ELECTRONIC REGULATOR:
BREADBOARD AND CONCEPTUAL SPACE FLIGHT VERSIONS

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ABSTRACT

The Electronic Regulator Project at TRW has constructed a breadboard system demonstrating pressure regulator operation over a wide range of flow conditions. The test hardware is composed of pneumatic-actuated, solenoid-controlled valves and associated tubing, gas volumes and transducers. System control, data recording and data reduction functions are controlled by a 486-class PC running Labview software.

This breadboard system has demonstrated that a single system, using several control modes, is versatile enough to be used across the TRW spacecraft product line, from the very low Xenon flows associated with an electric propulsion system, to the high Helium flows required in a constant thrust situation such as in the AXAF spacecraft. A conceptual flight version, composed largely of off-the-shelf parts, has been designed and evaluated relative to requirements of various TRW spacecraft.

INTRODUCTION

Most current space vehicles depend on propulsion systems to maintain and change their orbits, and to perform attitude control. In virtually all cases compressed gas is used to pressurize and expel propellants from the spacecraft tanks. Systems for pressurizing propellant tanks range from passive blow-down to utilizing pressurized gas, via a pneumatic mechanical regulator. For example, the AXAF spacecraft uses the latter, active approach to achieve its final orbital insertion and the former, passive pressurization technique during its operational life. While liquid propellant upper stages, such as the Centaur, typically use turbopumps, pumps are seldom used on long-duration spacecraft.

A variation of active pressure regulation onboard spacecraft was explored by the NASA/BMDO Clementine vehicle on its mission to the Moon in 1994. It flew a Bang-Bang regulator: valves placed between a high pressure gas supply and a low pressure tank. On command of the onboard computer, the valves were opened and gas was allowed to flow into the low pressure tank. Once the pressure in the downstream tank reached a predetermined quantity, the onboard computer closed the valves. This was repeated whenever the pressure in the downstream tank went below a minimum value.

Electronic regulators, as used on Clementine, allow change of the downstream set-pressures via simple software change. This allows exceptional system flexibility both in development and flight. In contrast, mechanical regulators typically have their set-pressures manufactured-in at the factory and may require mechanical tweaking of other parts of the propulsion system to insure appropriate downstream pressures. In addition to the increased system flexibility, the combination of flight-rated valves and pressure transducers that make up a conceptual electronic regulator typically cost less than a flight-rated pneumatic regulator. Orifice sizes are larger in an electronic regulator, reducing the chance of a system clog.

Three spacecraft, representing the fullest spectrum of gas flow requirements seen by TRW, were selected to define gas flow requirements for the electronic regulator (see Table 1).

TABLE 1. TRW REGULATOR REQUIREMENTS FOR CURRENT SPACECRAFT

Spacecraft	**AXAF**	**Generic LiteSat***	**Express**
Flow Rate Over Inlet Pressure Range (lbm/sec)	0 - 0.0025* (GHe)	0 - 0.000606 (GHe)	0.0000088-0.000026 (Xe)
Inlet Pressure Range (psia)	800 - 4500	500 - 4500	50 - 2175
Regulated Pressure Range (psia)	275 ± 8	400 ± 10	37 ± 3*
Maximum Lockup Pressure (psia)	291	410	50
Regulator Mass (lbm)	2.75	2.5	1.13

*Requirement for proper operation of spacecraft. Not specification value.

The reliability of a typical TRW mechanical regulator is greater than 0.999. An electronic regulator, to be usable for flight, must have a reliability comparable to this.

A conceptual flight version of an electronic regulator was designed using off-the-shelf, flight-qualified parts. The flight electronic regulator must be a standard, single unit that is able to meet all of the requirements of all of the above disparate mechanical regulators with little or no modification of the spacecraft. Each of the above systems will be compared to a similar system that makes use of an electronic regulator. The advantages in terms of cost, weight and flexibility will be assessed. To fully understand the issues involved and to verify design and algorithmic approaches, a breadboard system, comprised of non-flight components, was constructed in parallel with the flight regulator study.

MULTI-MODE ELECTRONIC PRESSURE REGULATION

The electronic regulator conceived for this paper (see Figure 1) is composed of two electromechanical valves in series, with a high pressure gas supply upstream and three pressure transducers downstream. A free volume exists between the two valves. A controller receives input from the pressure transducers and drives the valves to meet downstream pressure requirements. Depending on the flow desired, one of three operating modes, Bang-Bang, Bang-Wait or Burp, may be employed. The system can be tailored for different applications by increasing or decreasing the free volume between the valves and varying the set-pressures.

Systems that require high flows use a Bang-Bang operating mode, as previously described. Orifice size is maximum permitted by the valves to allow maximum flow in this mode.

For systems with moderate gas flow requirements, both valves are opened for a predetermined amount of time, then closed and pressure is measured. If pressure remains below the mode set-pressure, the process is repeated. This operating mode is entitled Bang-Wait.

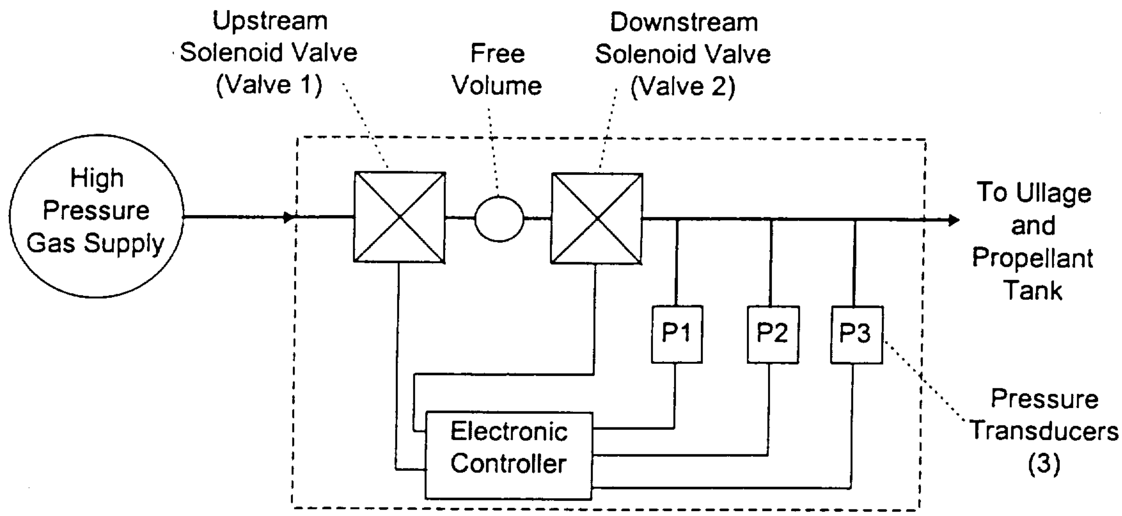

FIGURE 1. ELECTRONIC REGULATOR SCHEMATIC

The Alternating Valve (or Burp) operating mode of the regulator allows small puffs, or burps of gas into the low pressure side: the upstream valve is opened and closed, pressurizing the free volume between the valves and then the downstream valve is opened and closed sending a puff of high pressure gas downstream. This is repeated until the pressure sensors downstream read above the mode set-pressure. The procedure allows minute mass flows, such as those for electric propulsion systems, to be precisely regulated by the system.

Different set-pressures for each of the three control modes can be input into the controller for multi-tiered operation of the regulator. As an example, if 20 psi is the desired set- pressure, and a high degree of accuracy is required, then the Bang-Bang set-pressure might be 8 psi, the Bang-Wait set-pressure 15 psi and the Burp set-pressure 20 psi. Thus, the system can rapidly achieve 8 psi via Bang-Bang mode and a few psi of overshoot is acceptable. The system will then pressurize to 15 psi via Bang-Wait mode. Overshoot will be less than with the first mode, but still present. The last 5 psi will be covered slowly, but the end result of 20 psi will be achieved with high precision via the Burp mode.

The electronic regulator envisioned will not operate after a single valve failure, but remains fail-safe due to the normally-closed nature of the valves. Should one of the valves stick open, the system may continue to operate safely in the Bang-Bang and Bang-Wait modes. The remaining mode, Burp, will not be safely operable given this type of failure. Another unique failure mode of the electronic regulator is that of both valves failing closed due to a system power failure. Both valves may also fail open due to a computer error or crash. Precautions must be taken throughout development to eliminate the possibility of this. For high-priority missions multiple units may be set in either series, parallel or both to increase propulsion system reliability.

Similarly, mechanical regulators make use of series redundancy to prevent a fail-open case. They are fail-safe if they fail in the closed position.

BREADBOARD HARDWARE

A breadboard of the system verified the workability of an electronic regulator incorporating 3 tiered control modes (see photograph in Figure 2). The apparatus included both the electronic regulator itself and pressurant, ullage and dump systems. Valves used were Swagelok solenoid-controlled, pneumatically powered valves, connected to a 50 psi (3.4 X 10^5 Pa) pneumatic line. Pressures were measured with three Entran EPXM-V72-500p pressure transducers. Additional instrumentation measured temperatures and valve positions. Pressurized Nitrogen was the test fluid for all cases and also actuated the system pneumatic valves. All tests were performed at less than 50 psi (3.4 X 10^5 Pa).

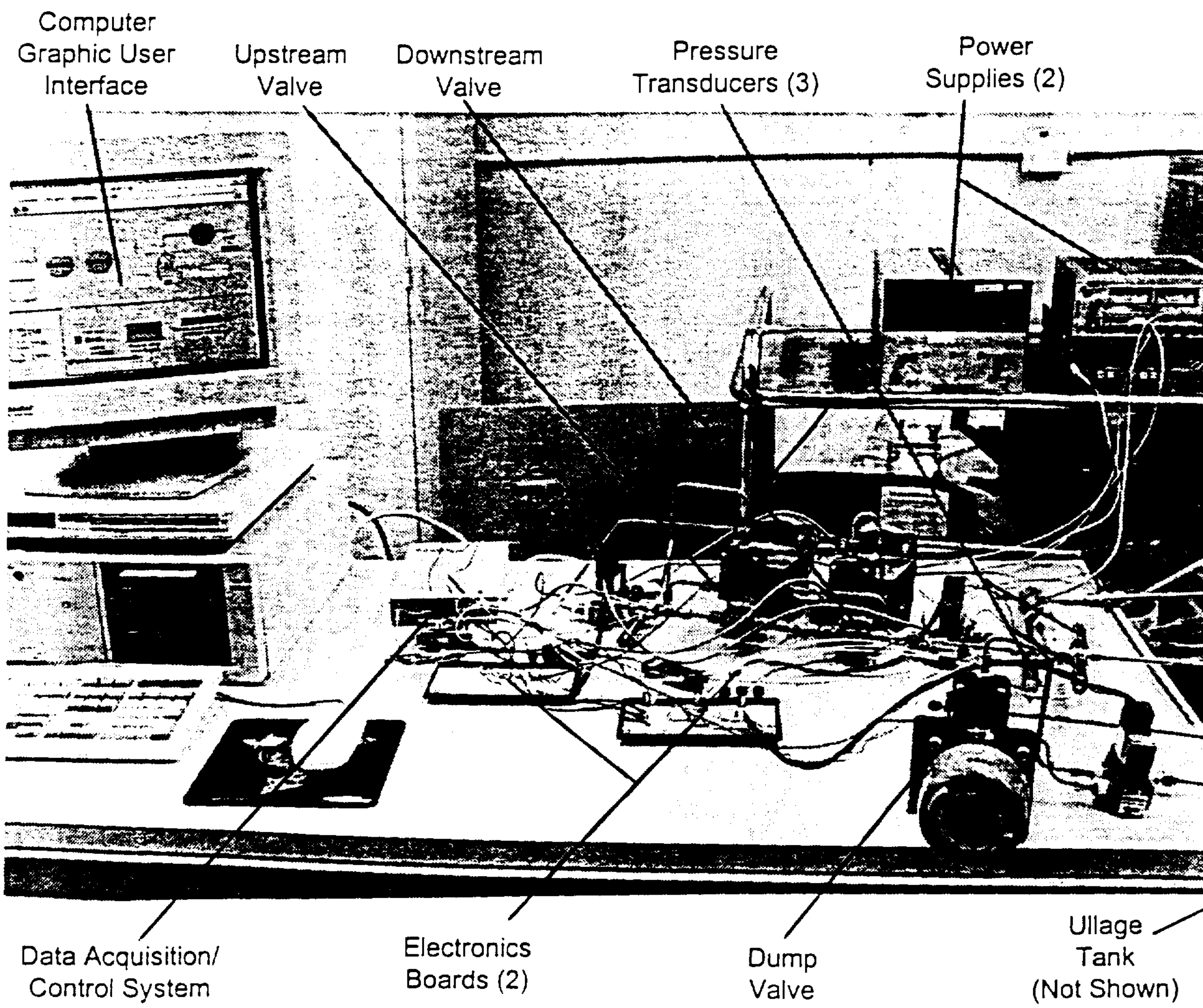

FIGURE 2. BREADBOARD SYSTEM PHOTOGRAPH

BREADBOARD SOFTWARE

Instrumentation and control software was written for the breadboard apparatus in the Labview/G programming language. Figure 3 shows the graphic user interface that allowed real-time adjustment and monitoring of the system. Outputs (including pressures, temperatures, valve commands and valve positions) were recorded into Microsoft Excel-compatible data files for later analysis.

The three operating modes were prioritized by the following algorithm:

1.) If $P_{Actual} < P_{Bang\text{-}Bang}$ actuate Bang-Bang mode until $P_{Actual} \geq P_{Bang\text{-}Bang}$,
2.) If $P_{Actual} < P_{Bang\text{-}Wait}$ actuate Bang-Wait mode until $P_{Actual} \geq P_{Bang\text{-}Wait}$,
3.) If $P_{Actual} < P_{Burp}$ actuate Burp mode until $P_{Actual} \geq P_{Burp}$.

This allowed the modes to be used in order of increasing accuracy. If one of modes was not wanted, the user could simply input the particular set pressure to zero, effectively bypassing that mode. While an upper and lower limit may be employed for each mode (for example, valve open if $P_{Actual} < P_1$ and valve close if $P_{Actual} > P_2$) that approach was not used in this system as it would add to the complexity of the system without any tangible benefit. For severely cycle-limited systems, this approach might be used to reduce the overall number of valve openings and closings.

Determination of actual pressure based on the three pressure inputs consisted of

1.) Discarding any obviously erroneous measurements, such as < 0 psi or > tank bursting pressure. In the event that all three transducers give erroneous results, the solenoid valves will not be cycled,
2.) Selecting the two closest of the remaining measurements,
3.) Taking the average of the two measurements. If only one of the valves gives a reasonable result (per step 1) that value is used.

To prevent pressure transducer noise from triggering the opening of the valves, three consecutive pressure data points were required to be below the maximum mode set-pressure before the valves were allowed to cycle.

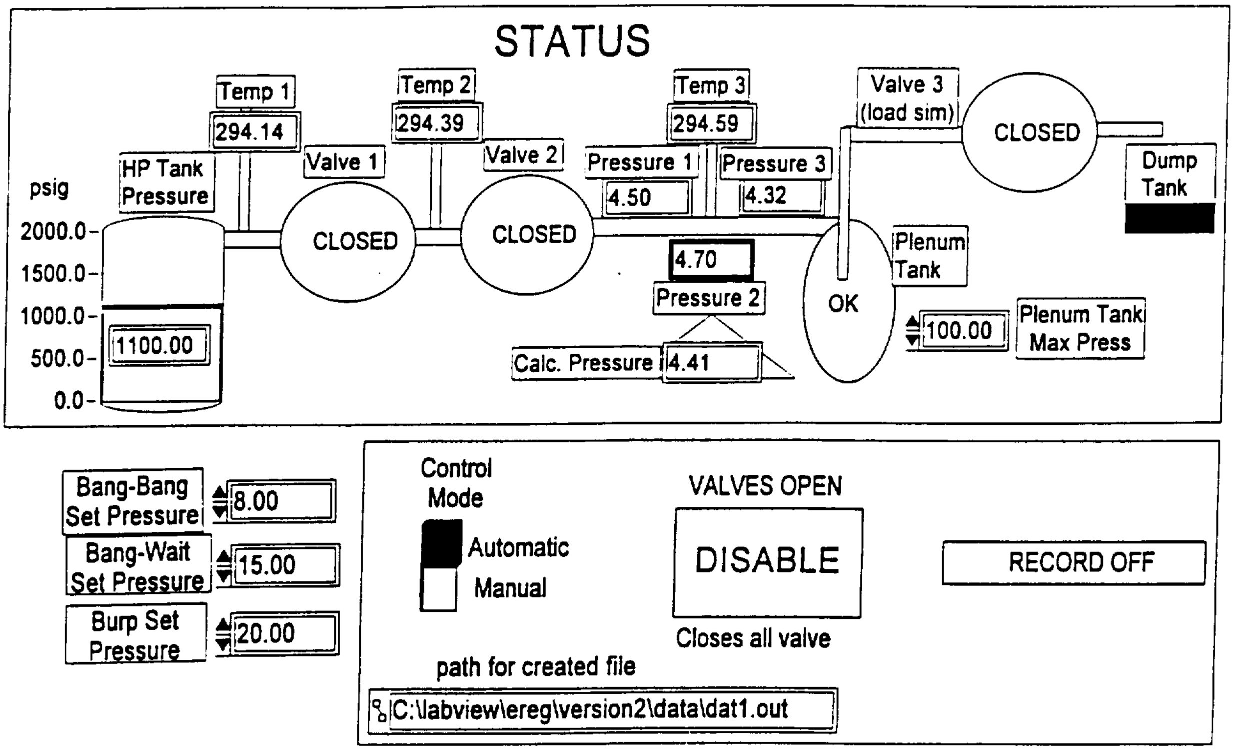

FIGURE 3. BREADBOARD GRAPHIC USER INTERFACE

BREADBOARD TEST RESULTS

Two tests were performed to verify proper function and operability of the breadboard system. The first test (Figure 4) shows the results of tiered, three mode operation into a 1010 in^3 (16.6 liter) volume. Bang-Bang set-pressure was 8 psi (6 X 10^4 Pa), Bang-Wait set-pressure was 15 psi (1.0 X 10^5 Pa) and Burp mode set-pressure was 20 psi (1.4 X 10^5 Pa). Note that the Burp mode appears particularly ineffective with this large a downstream volume, the individual gas pulses not noticeable above the system noise. The second test (Figure 5) shows the results of Burp mode operation into a small, 15.3 in^3 (250 ml) volume. Bang-Bang and Bang-Wait set-pressures were 0 psi (0 Pa), and Burp mode set-pressure was 5 psi (3 X 10^4 Pa).

The extremely slow system response (due to non-optimized code, and use of an antiquated 486 lab computer) necessitated low system pressures and very low flow rates. With fully optimized electronics and software, the system speed is only limited by the valve response.

The breadboard system accomplished its objectives of verifying system algorithms and design and demonstrating multi-mode electronic pressure regulation.

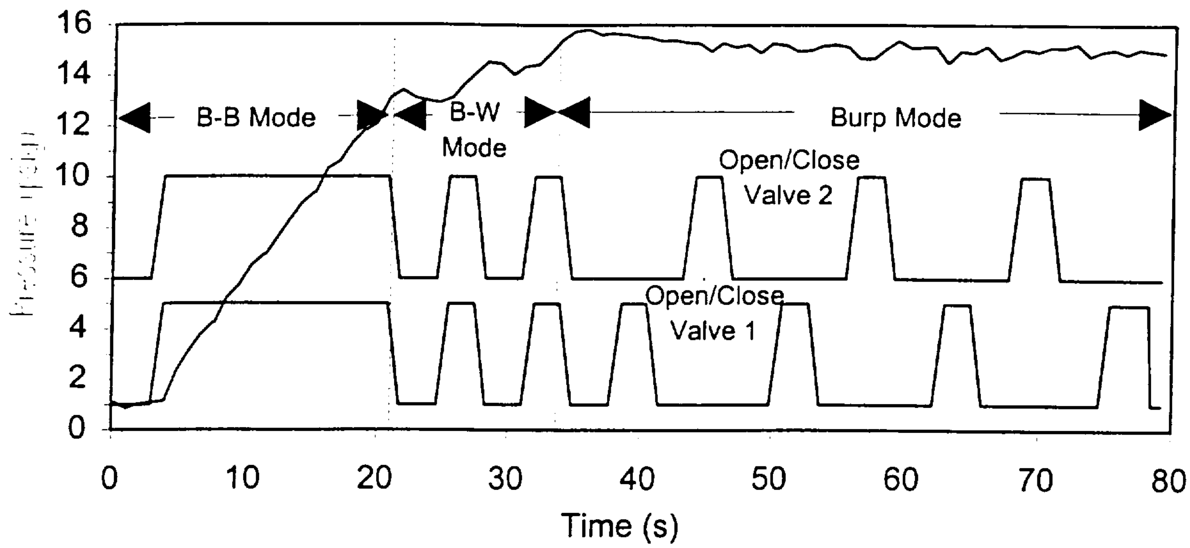

FIGURE 4. THREE MODE OPERATION OF BREADBOARD ELECTRONIC REGULATOR

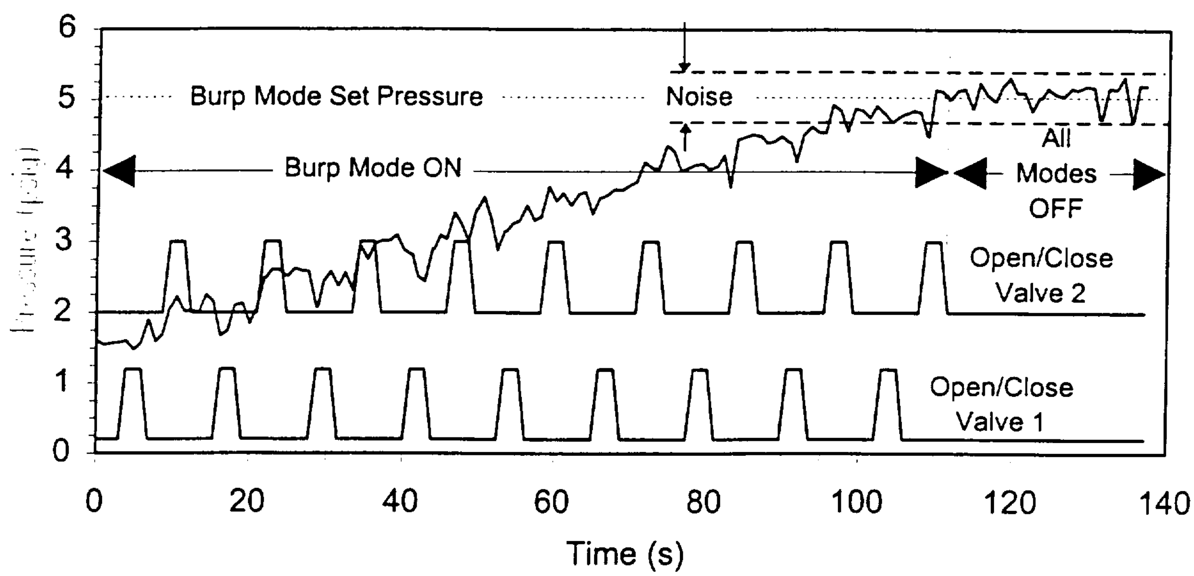

FIGURE 5. BURP MODE OPERATION OF BREADBOARD ELECTRONIC REGULATOR

FLIGHT ELECTRONIC REGULATOR SPECIFICATIONS

A conceptual flight version, composed largely of off-the-shelf parts, has been designed and evaluated relative to the requirements of the three TRW spacecraft in Table 1. Valvetech Corporation, a veteran manufacturer of spacecraft solenoid valves, and the manufacturer of the Clementine electronic regulator valves, has agreed to manufacture the valves and integrate the regulators for TRW. Valvetech is currently in the process of designing flight valves of this type for the TRW GeoLite mission. Only two pressure transducers are included with the flight electronic regulator envisioned. The model used is a TRW standard component and has already been flight qualified. An electronic port is included for a third pressure transducer so that the user may incorporate a third if extra redundancy is required. The two integral pressure transducers can be monitored by external devices allowing other pressure measurement devices to be deleted. While control of all valve functions by the spacecraft onboard computer is possible, this version has an electronic controller which allows the regulator to perform the valve cycling and calculations at an optimum speed, regardless of the spacecraft's own processing power and frame rate. Algorithms for the flight version are assumed to be the same as the breadboard version previously detailed. Specifications and components of the conceptual flight system are shown in Table 2.

TABLE 2. CONCEPTUAL ELECTRONIC REGULATOR COMPONENTS AND SPECIFICATIONS

Electronic Regulator System Components:

Valves: 1 dual-seat valve. (Valvetech Manufactured Item. TRW P/N EQ8-0366)

Pressure Transducers: 2 with wiring for 1 external transducer (TRW P/N EQ8-0299, currently in production)

System Controller (performs all internal calculations)

Inputs to Controller:	- Set-pressures (3) (optional)
	- Manual valve controls (2) (optional)
	- External pressure transducer (optional)
	- Power
Outputs from Controller: (optional)	- Raw Pressures (2)
	- Calculated Pressure
	- Set-pressures (3)

System Mass = 2.6 lbm

Valve Specifications: (TRW P/N EQ8-0366)

Flowrate: 0.0009 +0.0001/-0.0000 lbm/sec GHe at a delta P of 200 psid at 500 psia inlet pressure and fluid temperature of -10°F (Both seats open).

Pressure Tolerance: See Figure 6 for downstream pressure bands for various downstream volumes in the Burp mode. Other operating modes have pressure tolerances that are dependent on mode set pressure selections.

Maximum Xenon Throughput in Burp mode = 259 lbm (Assuming 3157 in^3 feed tank initially at 4500 psia, outlet at 40 psia, and 100,000 Burp cycles. This is cycle limited.)

Maximum He Throughput = 16.0 lbm GHe containing 0.001 g ACFTD

Maximum Number of Cycles per valve seat = 100,000 (dry)

Inter-Valve Volume: 0.141 in^3

Max Operational Pressure = 4500 psia

Proof Test Pressure = 6750 psia

Burst Test Pressure = 11250 psia

Power: 22.5 W maximum at 28 Vdc

Internal Leak Rate ≤ 5 scc/hr GHe at 300-4500 psia

External Leak Rate ≤ 1 X 10^{-6} scc/sec GHe at 4500 psia

Useful Life: 8 years of storage and 15 years of orbital operation

Vibration = 36.9 grms (Qualification Levels)

Shock = 2500 g peak in all three axis

Compatibility: Vapors of Hydrazine, NTO, gaseous Argon, Xenon, Krypton, He, N_2, DI water, IPA and other test fluids.

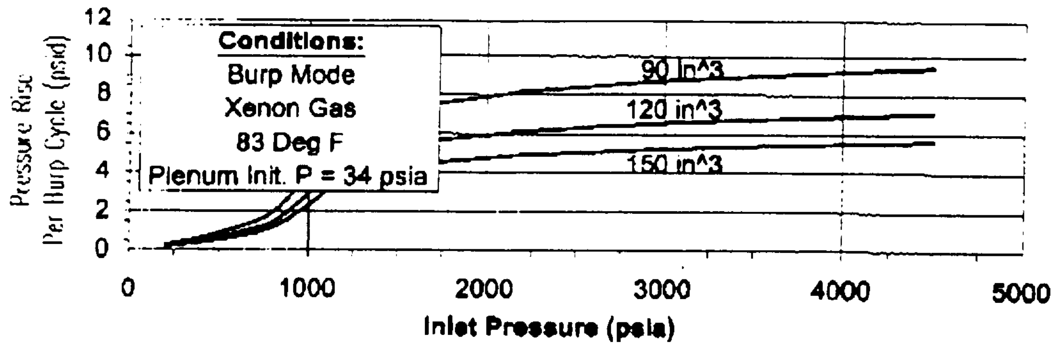

FIGURE 6. PRESSURE BAND VS. INLET PRESSURE FOR THREE PLENUM VOLUMES

Reliability was computed for two configurations of the electronic regulator: an AXAF-type application with three pressure transducers operating in the Bang-Bang and Bang-Wait modes and an electric propulsion system application using two pressure transducers and firing in the Burp mode only. Each system was assumed to operate for a cumulative one year over the spacecraft's life and to cycle each of the valve seats 80,000 times. Reliability of each of the individual components was estimated based on TRW's past experience with such components. Reliability was 0.999904 and 0.99735 respectively, for the two cases. While the second of the two reliability numbers is lower than current TRW reliability requirements (≥0.999), the exact mission scenarios used are fairly conservative. It is thought that given more realistic mission duty cycles, reliability requirements will be met.

ELECTRONIC VS. MECHANICAL: REGULATORS IN THREE APPLICATIONS

<u>AXAF</u>

The Advanced X-ray Astrophysics Facility, scheduled to be launched on the Space Shuttle this December, currently uses two high-flow mechanical regulators (each series-redundant) to pressurize the upper stage propellant feed system. A replacement of these with three electronic regulators is shown in Table 3. The two mechanical regulators are utilized one at a time. To allow the two mechanical regulators to be replaced with three electronic ones each with one-half the required flow capacity, the system was changed to allow all three regulators to operate at the same time. In the case of a failure of one electronic regulator the remaining two will be adequate to complete the mission. It is assumed for this application that the propellant tank pressure transducer is connected as the electronic regulator's third pressure transducer, allowing additional system redundancy.

TABLE 3. COMPARISON OF AXAF MECHANICAL TO ELECTRONIC REGULATOR

	AXAF w/ Mechanical Regulators (2 units)	AXAF w/ Electronic Regulators (3 units)
Total Regulator Mass (lbm)	5.5	7.8
Regulator Normalized Cost (FY 98)	1	0.41

LITESAT

TRW has built many lightweight satellites, or LiteSats, over the last decade including STEP's 1-4, ROCSAT and KOMPSAT. This LiteSat is an amalgam of TRW experience. Typically these systems use simple blowdown techniques to achieve monopropellant tank pressurization. Blowdown uses gas trapped within a tank to expel the liquid propellant from the same tank. Tank pressure, and consequently thruster inlet pressure and thruster Isp, decreases as the fluid is expelled from the tank. A typical LiteSat uses a blowdown pressure ratio of 4:1 for a tank that contains 180 lbm (81.6 kg) of propellant and starts life at 400 psia (2.76×10^6 Pa). Pressurant gas is Helium. Table 4 is a comparison of the typical LiteSat blowdown system to both mechanical and electronically regulated systems. The monopropellant thrusters are assumed to be fired in 50 msec pulses. Note that the addition of the electronic regulator, and its associated pressure transducers, allows the deletion of the propellant tank pressure transducer.

TABLE 4. COMPARISON OF LITESAT BLOWDOWN TO MECHANICAL/ELECTRONIC REGULATORS

	Typical Blowdown	Mechanical Regulator	Electronic Regulator
Effective Isp (sec)	134	160	160
Total Impulse (lbf-sec)	24,100	24,100	24,100
Tank Mass (lbm)	19	16.5	16.5
Propellant Mass (lbm)	180	151	151
Pressurant Gas (lbm)	0.18	0.71	0.71
High Pressure Bottle (lbm)	-	4.25	4.25
Tank Pressure Xducer (lbm)	0.58	0.58	-
Mechanical Regulator (lbm)	-	2.5	-
Electronic Regulator (lbm)	-	-	2.6
Net Mass (lbm)	199.76	175.54	175.06
Normalized Cost (FY 98)	1	1.65	1.35

EXPRESS

This spacecraft contains an experimental TRW Xenon electric propulsion system. A low pressure mechanical regulator is currently baselined to supply Xenon at 37 psia (2.6×10^5 Pa) from a 2175 psia (1.500×10^7 Pa) feed bottle. The Burp operating mode of the electronic regulator, with the addition of 120 in^3 (1970 cc) ullage downstream of the regulator, can be used for the same purpose. The pressure tolerance in this mode for the electronic regulator is ±3 psi (2×10^4 Pa), which is acceptable for the Express propulsion system. This tolerance is proportional to the inter-valve volume within the regulator and can be reduced, or the ullage tank shrunk, by reducing the volume. Table 5 is a comparison of the two units. It is assumed that the inclusion of the electronic regulator allows the deletion of another onboard pressure transducer. Mechanical regulator costs are based on other TRW mechanical regulator purchases as specific program costs are unavailable.

TABLE 5. COMPARISON OF EXPRESS MECHANICAL TO ELECTRONIC REGULATOR

	Express Mechanical Regulator	Express Electronic Regulator
Mech Regulator (lbm)	1.12	2.6
Pressure Xducer (lbm)	0.58	-
Ullage mass (lbm)	-	4.25
Total mass (lbm)	1.70	6.85
Normalized Cost (FY 98)	1	0.65

SUMMARY AND CONCLUSIONS

This examination of the utility of electronic pressurant regulators on spacecraft was composed of two parts:

- Demonstration of a breadboard unit was successfully completed and showed the effect of control modes and system algorithms on gas flow.

- A conceptual electronic regulator, with different control modes, can meet disparate requirements, from the high flows of liquid propellant upper stages, to the moderate flows in LiteSat propulsion systems, to the low flows of electronic propulsion systems. It allows greater flexibility than a mechanical system, from development through flight operations. Reliability was shown to be comparible to present mechanical systems. Use of an electronic regulator may decrease system cost and weight, though each application must be looked at individually to determine advantages and disadvantages.

Final design of a flight electronic regulator, including the implementation of the three operating modes into the electronics of the system, and integration of flight components into a single electronic regulator unit, will be addressed in the next phase of this program.