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# Evaluation of Bipropellant Pressurization Concepts for Spacecraft

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**An evaluation of pressurization concepts for bipropellant systems was conducted with an emphasis on demonstrating the technical feasibility of simple systems. A computer model was developed which incorporated thruster characteristics and various pressurization/feed system variables, including pressurant solubility. All the concepts can provide acceptably low propellant residuals, and the available thruster test data indicate that the requirements for blowdown operation can be successfully accommodated. Results of the evaluation show that the relatively simple bipropellant blowdown system, employing tank repressurization for larger propellant loads, should be an attractive alternative to the more complex and costly pressure regulated systems.**

## Nomenclature

$C_1, C_2$ = gas solubility constants
$m$ = dissolved gas mass
$P$ = pressurant gas partial pressure
$P_c$ = thruster chamber pressure
$P_i$ = initial ullage pressure
$P_I$ = thruster inlet pressure
$P_v$ = propellant vapor pressure
$T$ = propellant temperature
$V_i$ = initial ullage volume
$V_T$ = tank volume
$W$ = propellant mass
$\dot{w}$ = propellant flow rate
$\rho$ = propellant density

## Introduction

MONOPROPELLANT hydrazine propulsion systems are currently in wide use for spacecraft orbit adjust and attitude control functions. These systems have a history of very predictable, reliable operation, and their simplicity implies obvious cost advantages as well. However, two factors have contributed to the increasing consideration being given bipropellant propulsion systems for spacecraft applications. First, a desire to minimize weight and volume (which have a direct impact on Space Transportation System [STS] launch costs) favors the higher performance of bipropellant systems using the storable combination of monomethylhydrazine and nitrogen tetroxide. Second, the development and qualification of $\leq$5-lbf (22-N) thrusters has made it feasible to consider integrated propulsion systems which can perform all the necessary spacecraft functions using a common propellant supply.

The availability of bipropellant thruster test data at various duty cycles makes possible accurate performance and weight tradeoffs. For steady state orbit adjust firings bipropellant thrusters in the 100-lbf (445-N) class achieve specific impulses up to 310 s compared to approximately 235 s for catalytic thrusters. The average specific impulse for attitude control functions is more difficult to compare owing to duty cycle effects, but Fig. 1 shows the general characteristics for 5-lbf (22-N) class thrusters. The catalytic monopropellant thrusters appear to exhibit a much greater sensitivity to chamber temperature, so that for three-axis stabilization applications involving low duty cycles and low temperatures the bipropellant thrusters have an even greater advantage.

One area which has been troublesome in some monopropellant applications is the effect of duty cycle on thruster degradation. In particular, the thermal cycling and low temperature operation associated with three-axis stabilization attitude control has resulted in adverse effects, including catalyst attrition, catalyst bed compaction, injector tube clogging, and injector tube thermal choking.[1] Qualification testing of these thrusters usually involves representative duty cycles; however, ground testing cannot fully simulate the on-orbit environment, and abnormalities during a mission may result in a deviation from the expected thruster activity. It appears that the goal of duty cycle insensitivity for long-life spacecraft can be more easily met with bipropellant thrusters which do not exhibit the kind of catalyst bed degradation inherent in the monopropellant engines. Some concerns do exist regarding the effect of duty cycle on bipropellant chamber coating life or flow passage thermal environment, and it is expected that future testing will address these concerns. Some thrusters also experience mixture ratio shifts with varying inlet pressure or low pulse widths, and these factors must be considered in propulsion system modeling.

Bipropellant systems can be more effectively and reliably implemented if the complexity and the number of active components can be reduced. This paper will discuss an evaluation of several pressurization concepts for an integrated bipropellant system (incorporating both orbit adjust and attitude control thrusters), including blowdown, blowdown/repressurization, and pressure regulated types. Although the feasibility of blowdown systems has been

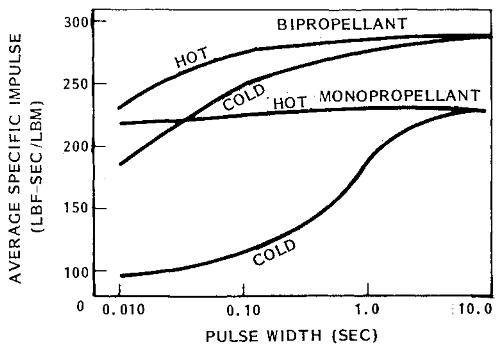


**Fig. 1 Thruster performance comparison.**

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previously discussed,[2] a detailed comparison with other concepts for the purpose of identifying system selection criteria has not been presented. The emphasis will be on demonstrating the technical feasibility of simple systems for spacecraft applications.

## Propulsion System Modeling

A computer model was constructed which incorporates pressurization/feed system and thruster operating characteristics. Variables which can be accounted for include tank volumes, propellant masses, loading conditions, on-orbit temperatures, pressurant gas saturation, tank repressurizations, percent of attitude control (ACS) usage, orifice or venturi control, and pressurization concept. Helium is assumed to be the pressurant gas since nitrogen involves serious disadvantages for blowdown systems.[2] The solubility of helium in each propellant is an important factor in blowdown systems with surface tension propellant management, and the amount of dissolved gas is expressed as

$$m = PW(C_I + C_2 T)$$

During thruster operation, dissolved gas is expelled along with the propellant, and with blowdown operation gas comes out of solution and into the ullage as pressure decays. Since it is assumed that propellant is used periodically during the mission, an isothermal blowdown with equilibrium solubility is assumed for this study. The gas equation of state is substituted into the above expression, and the resulting equation is integrated over the desired propellant usage. The amount of expelled gas is then

$$\Delta m = (C_I + C_2 T)\rho P_i V_i \ln\left(\frac{\rho V_T - W_2}{\rho V_T - W_I}\right)$$

Then, using the new value of total helium (dissolved plus ullage) a new gas pressure is determined based on the assumption of equilibrium solubility. When a tank repressurization is conducted the maximum calculated tank pressure immediately following that event is not based on equilibrium solubility since a period of time is required for this to occur. When the blowdown resumes, however, the readjustment is made, causing a slight reduction in tank pressure due to the increase in dissolved gas. The gas solubility in the propellant at loading is normally assumed to be zero since tank pressurization usually occurs shortly before launch and the time required for full saturation would probably be measured in weeks. However, the degree of saturation at loading can be specified in the model.

Existing bipropellant orbit adjust thrusters use orifice flow control for fuel and oxidizer so that the flow rate is expressed as

$$\dot{w} \sim \sqrt{P_I - P_c}$$

In the blowdown mode, this orifice control will maintain the same mixture ratio into the thruster for equal fuel and oxidizer inlet pressures. However, venturi flow control has been used successfully for accurate impulse delivery and propellant statusing on monopropellant hydrazine systems, therefore this option was incorporated in the bipropellant model. Known values for valve and injector pressure drops were used in determining whether a venturi could be used in the fuel and oxidizer lines for the orbit adjust thruster in the model. For operation at the design values of inlet pressure, mixture ratio, and thrust the venturi throat diameters determined indicated the cavitated flow condition could be maintained for a back pressure $\leq 85\%$ of the venturi inlet pressure. This condition was shown to be satisfied for inlet pressures down to 150 psia (1034 kPa), and the flow rate is expressed as

$$\dot{w} \sim \sqrt{P_I - P_v}$$

The use of a venturi would cause a shift in mixture ratio of 0.05 over a 150-350-psia (1034-2413-kPa) inlet pressure range, and the dependence on vapor pressure dictates another reason for relatively tight propellant temperature control. One advantage of the venturi is that it reduces the total range of flow rate into the thruster, so that operation over an inlet pressure range of 150-350 psia (1034-2413 kPa) with a venturi is equivalent to a range of 161-323 psia (1110-2227 kPa) for orifice control. The use of a cavitating venturi may be of greater significance for feed system stability (especially at low inlet pressures), since it is very effective in decoupling downstream pressure oscillations from the upstream flow.[3]

## Configurations

A description is provided for each of the pressurization concepts included in the evaluation. Each schematic shows all the major components required in the system design, under the assumption that each design meets the requirements of space shuttle compatibility and safety. The particular configurations shown provide three independent flow control devices (valves) in series while also providing redundancy in accessing the propellant supply. In the interest of simplification, a single thruster represents the orbit adjust and attitude control functions, and no attempt is made to display various feed system options. It is recognized that the actual design and number of components will be determined by the particular application.

### Simple Blowdown

Figure 2 shows a bipropellant blowdown system which employs a passive surface tension propellant management device. This type of system has been used extensively in monopropellant applications for some time, and it has come under consideration for bipropellant applications now that thrusters have been developed and tested in the blowdown

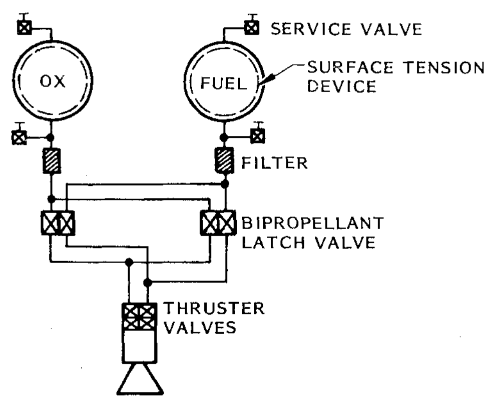


**Fig. 2 Simple blowdown configuration.**

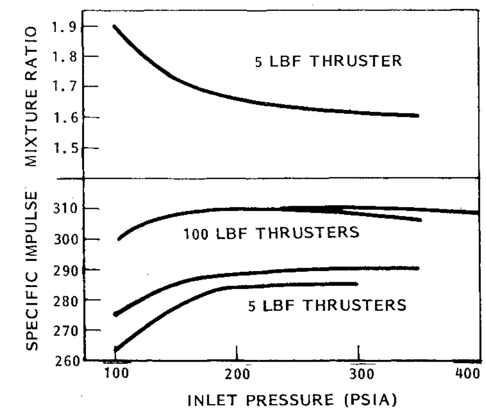


**Fig. 3 Bipropellant thruster characteristics.**

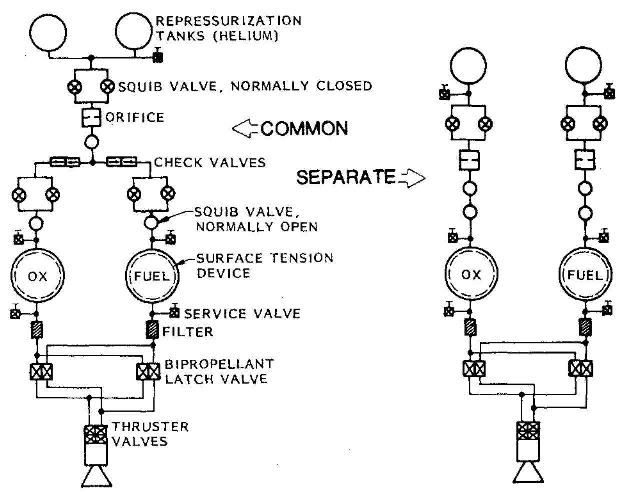


**Fig. 4 Common and separate repressurization configurations.**

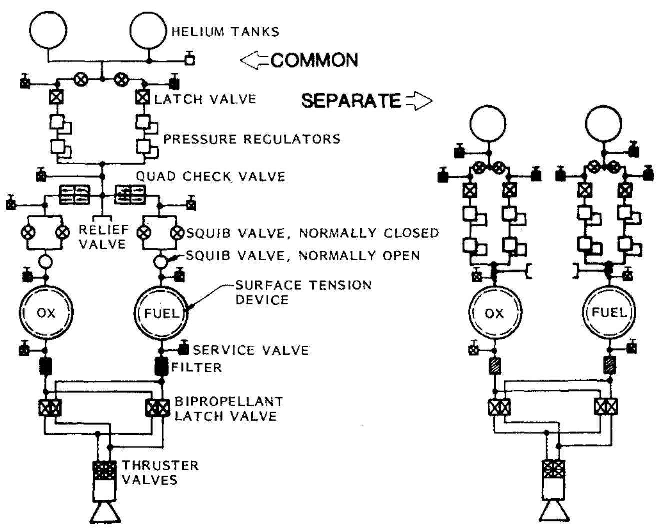


**Fig. 5 Common and separate regulated configurations.**

mode.[4-6] Figure 3 shows performance data which were obtained for two thrusters in each class which were tested over a varying inlet pressure range; mixture ratio vs inlet pressure was available for only one 5-lbf (22-N) engine. Propellant loading efficiency favors going to a low tank pressure, however the observed performance degradation and mixture ratio changes are significant at the low pressure levels. Therefore a range of 150-350 psia (1034-2413 kPa) was selected for the study. After taking into account expected loading tolerances and temperature ranges, the propellant tank loading was set at 55% full.

#### Common Repressurization

Repressurization of the propellant tanks allows for a greater propellant loading efficiency while maintaining an inlet pressure range consistent with thruster capabilities; this concept has been used successfully on monopropellant applications and techniques have been developed which provide a high degree of performance prediction accuracy. Figure 4 shows a configuration which involves simultaneous repressurization of the fuel and oxidizer tanks when the pressure in one of the tanks reaches a specified minimum value. The parallel squib valves downstream of the check valves provide positive vapor isolation prior to the repressurization. After that event is completed the normally open squib valves are fired closed to again achieve vapor isolation, particularly important if shuttle retrieval is anticipated. Using the same 150-350-psia (1034-2413-kPa) pressure range, the propellant tanks are loaded to 80% full. Either increasing the pressure blowdown range or adding a second repressurization would allow an increased propellant load.

**Table 1 Propellant loading results**

| Configuration | Initial pressure, psia | Load, % full | Loading ratio, oxidizer/fuel |
|---|---|---|---|
| Simple blowdown | 335 | 55 | 1.667 |
| Repressurization (common) | 320 | 80 | 1.658 |
| Repressurization (separate) | 320 | 80 | 1.650 |
| Regulated (common) | 220 | 90 | 1.650 |
| Regulated (separate) | 220 | 90 | 1.650 |

#### Separate Repressurization

Also shown in Fig. 4 is a configuration which involves the separate repressurization of each tank when some minimum pressure is reached in either one. The series redundant normally open squib valves upstream of each propellant tank are fired closed soon after the repressurization process is completed. These valves preclude vapor migration and condensation in the helium tanks while assuring comparable ullage volumes in the propellant tanks for the final blowdown. This particular concept also has an 80% propellant loading efficiency and provides complete isolation of fuel and oxidizer while eliminating the need for check valves.

#### Common Regulated

Pressure regulated systems can allow propellant loading efficiencies of 90-95% and the pressure setting can be selected based on known thruster capabilities. This simplifies combustion and feed system stability analyses and performance prediction procedures. The major disadvantages include number of active components, testing and checkout, leak points, complexity, and cost. The concept shown on Fig. 5 includes quad-redundant check valves for propellant isolation during the mission and squib valves for isolation prior to deployment and again prior to retrieval. Two series redundant pressure regulator legs are provided for reliability and an upstream latch valve can be used to isolate the regulator from high pressure gas if necessary. A relief valve protects against a gross regulator malfunction to prevent excessive propellant tank pressures.

#### Separate Regulated

The other concept in Fig. 5 has the same loading efficiency as the previous one, but provides complete separation of fuel and oxidizer segments. Check valves and some squib valves are eliminated, but more pressure regulators are required for the same redundancy. This separated concept also puts more of a premium on regulator repeatability for mixture ratio and residual control. The known influence of gas flow rate and inlet pressure on regulator outlet pressure is probably not significant here since both high pressure tanks would be expected to blow down equally.

## Results of Analyses

Based on the desired use of identical tanks for fuel and oxidizer, the oxidizer/fuel loading ratio was first assumed to be 1.65 at a temperature of 70°F (294 K). The performance model computer program was then used to determine the actual loading ratio which resulted in zero residuals for the assumed nominal conditions of 1) 70°F (294 K) propellant, 2) 20% ACS usage, 3) 0% gas solubility at loading, 4) 100%

gas saturation on-orbit, and 5) orifice flow control for orbit adjust thruster. Table 1 shows the initial pressure at loading, the propellant loading efficiency, and the optimum loading ratio for zero residuals. The loading pressures are slightly lower than the maximum operating pressure to account for loading tolerances and temperature effects. The results show that the configurations can be efficiently loaded, and each concept is either at or very close to the optimum 1.65 ratio for equal-volume loading. In the case of the separate repressurization configuration, the optimum loading ratio is achieved by making the initial fuel and oxidizer repressurization tank helium masses slightly different.

Figure 6 shows the tank pressure changes and mixture ratio variability for the simple blowdown case; gas solubility effects are the primary reason for the lower oxidizer pressure initially and the higher oxidizer pressure at the end of the blowdown. The fuel and oxidizer pressures stay relatively close, which results in a mixture ratio range which appears to be well within the capabilities of existing thrusters. Figure 7 shows the same information for the separate repressurization system, again showing the tight pressure control which can be achieved. The mixture ratio takes a significant shift when the tanks are repressurized, but the overall range during the mission is still within expected thruster capabilities. The ACS shift is larger than the orbit adjust since the ACS thruster used in the model exhibits a mixture ratio variability with inlet pressure. In order to evaluate the effect of off-nominal conditions or uncertainties, several of these cases were run while still using the nominal propellant load. Figure 8 shows the resulting mixture ratio shifts for the separate repressurization system for some of these conditions and illustrates the techniques which must be employed to determine thruster operating requirements for this kind of application.

Mission simulation runs were made for all the pressurization concepts to determine propellant residuals and mixture ratio ranges. These configurations are identified in the following tables as 1) simple blowdown, 2) common repressurization, 3) separate repressurization, 4) common regulated, and 5) separate regulated. Table 2 shows the residuals as a percentage of the total propellant loaded for various conditions, including gas saturation, temperature, loading errors, propellant usage, and pressure regulator accuracy. These residuals represent the propellant remaining in one tank when depletion occurs in the other. The purpose of this exercise was to determine the sensitivity of each of the concepts to these variables; cases were also run assuming venturi control for orbit adjust to see if benefits might be derived from this approach.

One general observation is that none of the concepts shows a great sensitivity to the selected parameters. The common regulated system appears to have a slight advantage since it is not affected by most of the uncertainties, including gas

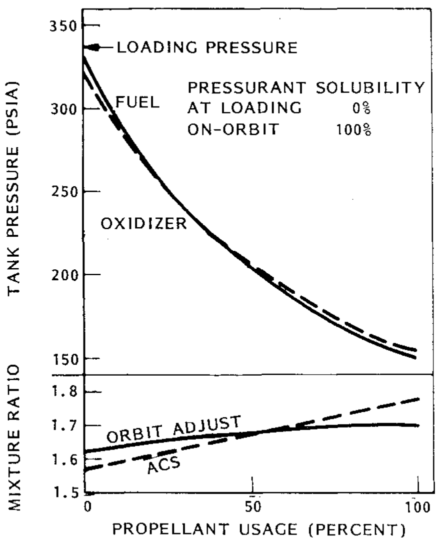


Fig. 6 Simple blowdown characteristics.

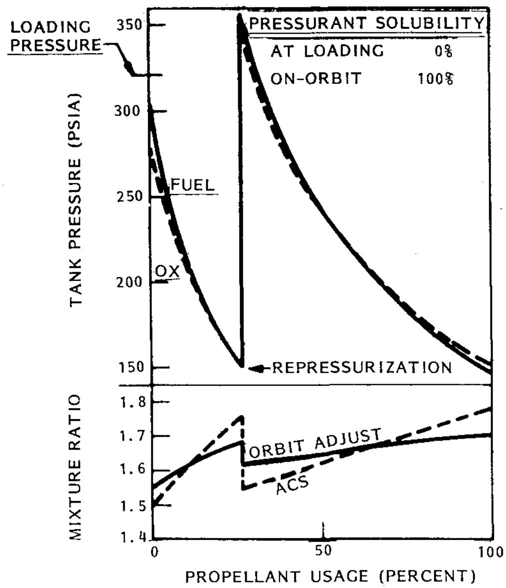


Fig. 7 Separate repressurization characteristics.

**Table 2 Propellant residual sensitivity**

| | Propellant residuals, % of total load — Conditions | | | | | |
|---|---|---|---|---|---|---|
| Configuration | Gas saturation at loading, 0 vs 100% | Oxidizer/fuel differential at loading, 10 psi | Oxidizer/fuel differential on-orbit, 10°F | Repressurization gas mass error, 1.5% | ACS usage, 20 vs 50% | Regulator differential on-orbit, 3 psi |
| Orifice[a] | 0.7 | 1.3 | 0.8 | ... | 0 | ... |
| Venturi[a] | 0.6 | 0.9 | 0.5 | ... | 0.1 | ... |
| Orifice[b] | 0.9 | 0.5 | 0.3 | 0 | 0 | ... |
| Venturi[b] | 0.7 | 0.4 | 0.2 | 0 | 0.1 | ... |
| Orifice[c] | 1.0 | 0.6 | 0.7 | 0.6 | 0 | ... |
| Venturi[c] | 0.8 | 0.4 | 0.5 | 0.4 | 0.1 | ... |
| Orifice[d] | 0 | 0 | 0.3 | ... | 0.2 | ... |
| Venturi[d] | 0 | 0 | 0.8 | ... | 0.2 | ... |
| Orifice[e] | 0 | 0 | 0.3 | ... | 0.2 | 0.8 |
| Venturi[e] | 0 | 0 | 0.8 | ... | 0.2 | 0.5 |

[a]Simple blowdown. [b]Common repressurization. [c]Separate repressurization. [d]Common regulated. [e]Separate regulated.

**Table 3 Mixture ratio ranges**

| Configuration | Orbit adjust thruster Nominal | Orbit adjust thruster Worst case | ACS thruster Nominal | ACS thruster Worst case |
|---|---|---|---|---|
| Orifice[a] | 1.62-1.70 | 1.59-1.74 | 1.57-1.78 | 1.52-1.81 |
| Venturi[a] | 1.65-1.66 | 1.63-1.68 | 1.57-1.78 | 1.52-1.83 |
| Orifice[b] | 1.54-1.71 | 1.50-1.77 | 1.49-1.79 | 1.44-1.84 |
| Venturi[b] | 1.60-1.68 | 1.58-1.70 | 1.49-1.79 | 1.44-1.84 |
| Orifice[c] | 1.55-1.70 | 1.50-1.78 | 1.49-1.78 | 1.44-1.85 |
| Venturi[c] | 1.60-1.67 | 1.58-1.70 | 1.49-1.79 | 1.44-1.83 |
| Orifice[d] | 1.66 | 1.66-1.67 | 1.64 | 1.64-1.65 |
| Venturi[d] | 1.66 | 1.64-1.67 | 1.64 | 1.64-1.65 |
| Orifice[e] | 1.66 | 1.64-1.68 | 1.64 | 1.62-1.66 |
| Venturi[e] | 1.66 | 1.64-1.67 | 1.64 | 1.62-1.66 |

[a]Simple blowdown. [b]Common repressurization. [c]Separate repressurization. [d]Common regulated. [e]Separate regulated.

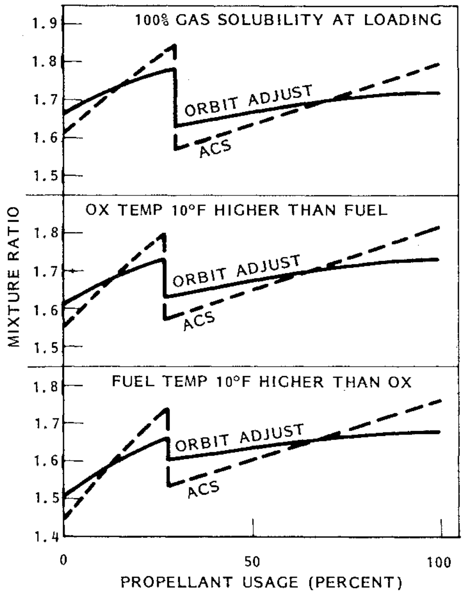


**Fig. 8 Mixture ratio shifts.**

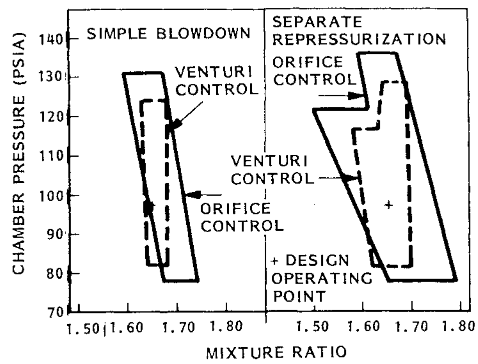


**Fig. 9 Orbit adjust thruster requirements.**

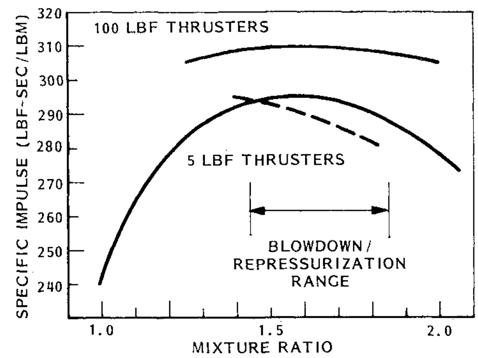


**Fig. 10 Effect of mixture ratio on performance.**

solubility, but the overall percentage advantage is not large. The use of a cavitating venturi minimizes the residuals for the blowdown/repressurization cases, but would not be favored for a regulated system owing to the influence of propellant temperature on vapor pressure and thus flow rate. It is very difficult to force the blowdown systems to high residuals owing to the self-regulating aspect; a higher flow from one tank will cause a more rapid pressure decay which will bring the system back toward its design point mixture ratio. Overall, the conclusion is that all the configurations offer acceptable residual levels, and this item would not be a major factor in system selection for this study.

Table 3 shows the mixture ratio range over which the thrusters are required to operate during the course of the mission; the worst-case range incorporates the extremes resulting from evaluation of all the variabilities and uncertainties. The pressure regulated systems are obviously more favorable since a constant pressure level is specified. As might be expected from the pressure excursions involved, the repressurization cases exhibit the greatest mixture ratio variability; for these cases, use of a cavitating venturi reduces the variability.

The output from the performance model is evaluated to determine the thruster operating and test requirements and to assess the thruster compatibility for a particular propulsion system configuration. The mixture ratio and flow rate requirements for the 5-lbf (22-N) thrusters do not appear excessive, since testing over these ranges has already been conducted. Fewer data are available for the 100-lbf (445-N) units, so these requirements are presented in more detail. Figure 9 shows the chamber pressure/mixture ratio envelope encompassing both the expected and off-nominal conditions; the cross locates the design operating point for the thruster. It is seen that the incorporation of venturi control significantly reduces the required operating range for the thruster, especially in the case of repressurization where the variability is greater. Testing over this envelope would be required to verify thruster compatibility with a particular configuration, and use of a venturi should minimize concerns regarding stability or thermal control. From a performance standpoint, it appears that mixture ratio ranges required for blowdown/repressurization concepts do not entail significant penalties. Data for both thrust levels are shown on Fig. 10, and the performance losses in the range 1.44-1.85 are minimal.

## Conclusions

The evaluation of pressurization concepts for integrated bipropellant propulsion systems has resulted in the identification of technical criteria which can be used in a system selection process. The analysis of residuals shows that all concepts provide acceptably low values, and the oxidizer/fuel loading ratio is nearly identical for each concept. Use of cavitating venturi flow control is suggested for orbit adjust thrusters operating in the blowdown mode; this technique, if it is compatible with thruster pressure drops, minimizes residuals and the required chamber pressure/mixture ratio range. For blowdown systems where the propellant and pressurant are in contact, gas solubility is a significant consideration.

The results of this evaluation show that blowdown systems appear to present a viable alternative to the more complex and costly pressure regulated system. Although system weight studies were not addressed in this paper, the simple blowdown concept is probably superior for modest applications since it does not require the high pressure tanks and other components inherent in the pressure regulated systems. Where large propellant loads exceeding several hundred pounds are required, repressurization of the tanks should make the blowdown concept competitive with pressure regulated systems. It is probable that more thruster testing will be required initially for the blowdown systems in order to demonstrate successful operation over the relatively wide inlet pressure and mixture ratio range, but available thruster test data suggests that these requirements can be accommodated. Therefore it is expected that the relatively simple bipropellant blowdown system employing surface tension propellant management will be an attractive concept for spacecraft propulsion.

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