# Chamber Bleed Auxiliary Power Unit

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**The use of gases bled from a propulsion unit as an energy source for auxiliary power units (APU's) has been investigated and shown to offer significant weight and envelope savings in comparison with conventional warm gas generators. The principal challenge associated with this use of chamber-bled gases lies in conditioning the hot, particle-laden gases to a state compatible with the energy transfer device (e.g., turbine, air motor). Filter designs which remove 100% of the metallic particles in the exhaust gas and which have efficiently reduced chamber gas temperature by thermal decomposition of a sacrificial material have been demonstrated. Four candidate coolant materials have been characterized by subscale testing. Heat transfer models have been formulated which adequately predict the performance of coolant bed designs. Two full-scale demonstration tests of a combined filter-cooler have been conducted. Approximately 8 hp was delivered to a hydraulic actuation system for the 21.4- and 40.3-sec test durations.**

## Introduction

MANY present and future missile systems require an energetic source of gas in such ancillary applications as auxiliary power unit drive and as the working media for pneumatically actuated valves. Solid propellant gas generators are most frequently used on conventional systems. The use of gases bled from the propulsion unit would be an attractive substitute for warm gas generators. Both the higher energy content of propulsion unit gases and their on-demand availability would contribute weight and envelope savings in comparison with present designs. The excessive flame temperature and the presence of large quantities of metallic particles constitute the technical obstacles to the use of these gases. The objective of this recently completed exploratory development program was the development and demonstration of adequate gas conditioning technology.

## System Evaluation

One of the principal advantages of the use of chamber-bled gas is the weight savings gained by elimination of the gas generator. This savings is accruable from two sources: first, the higher impulse of propulsion unit propellants contributes a higher specific energy (hp-hr/lb) than typical gas generator propellants; second, bleeding gases from the propulsion unit on demand as opposed to the constant bleed operation of gas generators results in more efficient designs.

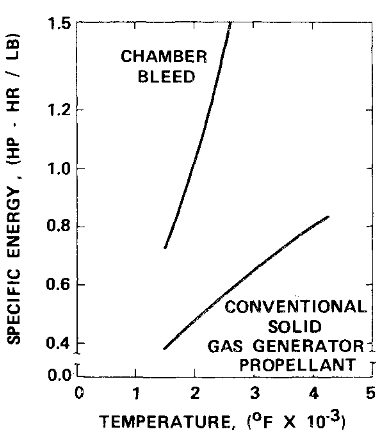


Fig. 1 Theoretical specific energy vs temperature.

Quantitatively, the performances of a typical solid propellant gas generator and a propulsion unit propellant cooled by decomposition can be compared in terms of specific energy (hp-hr/lbm) as shown in Fig. 1. Based on equal weights of coolant plus propellant gases and gas generator propellant, the chamber-bleed system has a theoretical specific energy of 1.4 hp-hr/lbm at 2500°F as compared with 0.56 hp-hr/lbm for a solid gas generator. In terms of weight savings, these curves show that equivalent gas energies are produced by decomposition cooling of chamber gases at a savings of 60% of the weight of a gas generator propellant.

Additional weight savings are available since chamber-bled gases are used only when needed. That is, whereas a gas generator must be designed for essentially constant mass flow, the chamber-bleed system can be operated only for the actual time required to supply the hydraulic horsepower dictated by the system's duty cycle. Figure 2 shows the total potential weight savings accruable from both the specific energy standpoint and from considerations of duty cycle. At the selected action time of 40 sec and load energy requirement of 15 hp, available weight savings vary from 8.5% of APU weight at 100% duty cycle to 13.5% at a 10% duty cycle. Those studies assumed that the hardware weight in the chamber bleed system; i.e., filter and cooler housing and gas control valve, would be equivalent to the gas generator inert weight.

The potential weight savings from these two sources was the motivating force for additional studies directed towards showing workable solutions to the problems of filtering and cooling gases bled from a propulsion unit.

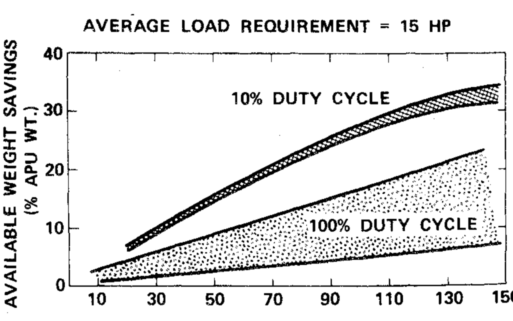


Fig. 2 Theoretical chamber bleed weight savings.

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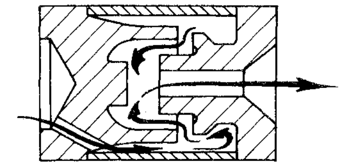

Fig. 3 Counter flow separator design.

## Filter Studies

The use of chamber-bled gases as an energy source for APU's in applications requiring small amounts of power (<3 hp) for short durations (<10 sec) is state-of-the-art on existing tactical systems. In these applications, chamber-bled gases are used to pressurize a blowdown (nonrecirculating) supply of hydraulic fluid and require no gas conditioning. Meaningful demonstration of advancements in gas conditioning technology requires the delivery of higher energy levels for longer durations. Consequently, the studies in this program were directed at supplying energy levels in excess of 5 hp for operating durations to 40 sec.

### Particle Filter Designs

An adequate particle filter is characterized by the following performance parameters and operating conditions.

1) Efficiency: At least 80%, and preferably a higher percentage, of all particles must be removed for reliable turbine operation.

2) Particle Size: The liquid metallic particles in a combustion chamber may range from submicron size (~0.1) to several microns.

3) Environment: The filter must be operable in the same high-pressure, high-temperature environment as the propulsion unit.

4) Particle Trap Volume: Sufficient trap volume in the filter must be provided to collect all particles during a 40-sec operation. The particle volume is computed on the basis of 50% of the bulk density of the metallic compound to account for the porosity which will exist in the filtered mass.

5) Pressure Drop: The maximum use of the available energy in the bleed gas stream requires that pressure drops through the filter be minimized.

Previous work in particle filters indicates that generally the efficient removal of small particles ($<10\ \mu$) from a gas stream requires larger pressure drops than are desirable in this application. However, since the metallic particles of concern (mainly alumina) are in a liquid state at typical combustion temperatures, they tend to agglomerate into larger sizes that are more readily filtered. Agglomeration, resulting from particle collision, is enhanced in a filter designed for turbulent gas flow.

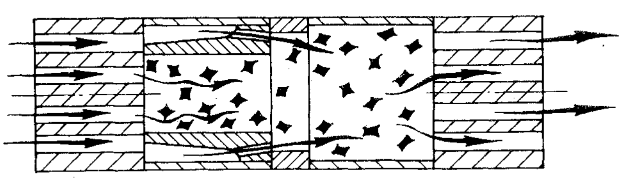

Fig. 4 Packed bed separator design.

Various filter concepts were considered and evaluated as to their relative performances with respect to the above-listed filter requirements. Since no analytical means exists to accurately evaluate the particle size distribution resulting after agglomeration, it was decided to select several of the more promising filter concepts for evaluation on a subscale static test.

The filter designs selected for static test evaluation may be classified as follows: 1) counterflow separator, 2) gas diffusion separator, 3) impact separator, and 4) porous material separator. An example of the counterflow separator is shown in Fig. 3. In this design, gas is admitted to the filter via an orifice plate. The flow stream is subjected to two sharp 180° turns before exhausting through a center port. A trap is provided at each turn to collect particles which, because of their high mass, are centrifuged from the gas stream. In addition, the turbulence of the gas stream at each turn will induce some particle agglomeration.

The gas diffusion separator is shown in Fig. 4. This filter consists of a bed of carbon berl saddles. The tortuous flow path through the bed provides high probability of particle collision (agglomeration) and the interstices between saddles form natural particle traps.

It is recognized that if the interstage volume in a multistaged filter is sufficiently large to permit the gas velocity to approach zero, the particle flow in that volume will be randomly oriented because of the absence of well-defined gas flow streamlines. The liquid metal particles entering this area will not decelerate as rapidly as the gas particles and will have a high probability of impacting and solidifying on a filter surface. The device based on this mechanism has been termed an impact separator. As will be shown in more detail in the discussion of the test results, the impact separator is predominantly important.

The final filter type selected for static test demonstration was a porous material filter. As was shown earlier, it may be expected that in a multistaged filter, filtration efficiency will increase, because of agglomeration, with the number of separator stages. Porous material filters appear to be most attractive as a final element to collect the fine particles which have not been trapped by previous stages.

### Filter Evaluation Test

Three multistaged filter assemblies were designed to evaluate the efficiency of the four filter concepts listed above and the dependency of efficiency on the location of each design. Figure 5 shows one of the filter assembly designs. This assembly includes each of the filter concepts selected for evaluation. Gases bled

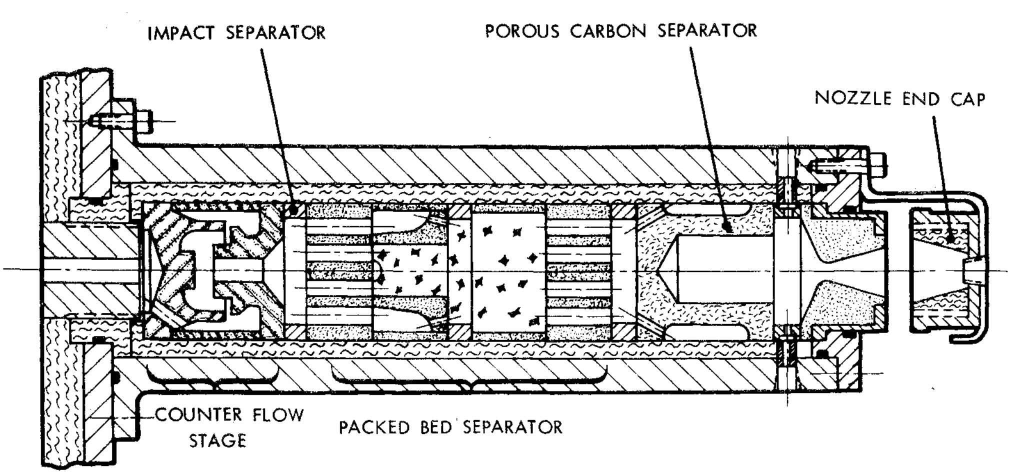


Fig. 5 Packed bed filter system.

from a low-velocity blast tube attached to the test motor enter the counterflow separator. Subsequent filter stages include a packed bed of berl saddles and a final stage of porous carbon. Each of these stages is preceded by an impact separator volume. Gases exit from the filter assembly through a nozzle sized to restrict gas velocity through the filter stages and to provide an analytical means for determining the quantity of gas which passes through the filter.

The test motor included a propellant characterized by a flame temperature of 6500°F and 40% by weight content of alumina ($Al_2O_3$). This motor was designed to operate at moderately high pressure for approximately 10 sec.

Two of the three assemblies tested exhibited 100% efficiency in particle filtering. The interstage impact separator volumes were most effective in removing metallic particles from the gas stream. This was particularly true when these volumes were preceded by a counterflow stage. The counterflow and packed bed stages were only moderately effective and appeared to separate particles principally by condensation. The porous final filter stages entrapped all particles presented to it although the quantity filtered was minimal.

It was concluded from this test that, in general, gases are best filtered before entering a cooling stage so that the particles are still in a liquid stage and subject to agglomeration. The most effective filter designs will maximize particle collection volume (50% of total filter envelope as a goal) and provide for turbulent flow to induce agglomeration. A porous final filter stage will entrap any remaining particles.

The successful demonstration of effective particle filtering solved one of the technical challenges associated with the controlled use of chamber-bled gases. The design technology gained in this program was used in another exploratory development program in which conditioned chamber-bled gases were used as the operating medium for pneumatically actuated hot gas valves. A combination of impact separators and porous carbon final filters were effective in removing all metallic particles from the gas stream in two static firings.

## Studies of Cooling Mechanisms

As previously discussed, the potential weight savings of a chamber bleed system over a conventional warm gas generator are due principally to the on-demand availability of the chamber gases. In addition, it is desirable to maintain the available energy content of the conditioned gases at the maximum attainable value. For this reason, the problem of gas cooling cannot be solved simply by heat soaking to inert parts; the energy thus dissipated is no longer available for useful work.

Thermal decomposition of a sacrificial material was selected as the cooling process to be studied. The literature cites many materials with reasonably well-characterized decomposition products and parameters. Solid blocks of coolant materials can be molded/machined into geometries which permit good predictions of heat transfer rates.

The properties of a large number of materials taken from the literature were evaluated. Some materials were eliminated because they could decompose into hazardous by-products. Others held little interest because of a low melt or sublimation temperature. Table 1 lists nine candidate materials which appear attractive when evaluated by a computerized heat transfer model. The specific energy of each material refers to the available energy of a gas mixture with a typical high-energy propellant at a mixture outlet temperature of 2000°F. These values compare with an available energy of a typical gas generator propellant of 0.275 hp-hr/lb propellant. The theoretical model used to predict cooler bed performance and the definition of the specific energy rating parameter are given in Appendix A.

### Binder Selection

Binder systems were evaluated as a means of providing structural integrity to compressive molds fabricated of the materials listed in Table 1. Criteria used in the selection of a binder system were: 1) compatibility with coolant molding process; 2) good erosion resistance at elevated temperature; 3) binder failure near the decomposition temperature of coolant; and 4) binder failure by an endothermic process.

Several binder systems selected on the basis of these criteria were evaluated in a series of laboratory tests. These tests were designed to qualitatively evaluate the structural and thermal characteristics of the binder systems when molded with candidate coolant materials. A coolant/binder system containing 10% Formvar exhibited performance characteristics superior to those of other binder systems tested. The most common failure mode of other binder systems was fracturing from thermal shock when exposed to an oxyacetylene flame.

**Table 1 Candidate coolants and theoretical specific energy**

| Coolant | Specific energy (hp-hr/lb at 2000°F) |
|---|---|
| Glycine | 0.77 |
| Oxamide | 0.625 |
| Succinic acid | 0.625 |
| Sodium bicarbonate | 0.286 |
| Tartaric acid | 0.457 |
| Melamine formaldehyde | 0.357 |
| Lactose | 0.72 |
| Delrin | 0.53 |
| Alpha-valine | Data not available |

### Coolant evaluation tests

The candidate coolant materials listed in Table 1, selected by analytical evaluation, were further screened by laboratory tests. The candidate coolant materials were molded with a 10% concentration of Formvar and subjected to an oxyacetylene flame for 30 sec. This test was intended only to show structural integrity of the coolant/binder system under high-temperature environments. No inlet or outlet temperature measurements were attempted. Melamine formaldehyde and alpha-valine (isovaleric acid) experienced multiple shear failures during this test and were eliminated from further testing. All other coolants exhibited good physical appearance after the test and experienced similar weight losses.

Final coolant evaluation consisted of a series of subscale static firings. The test motor, shown in Fig. 6, was designed to incorporate an end-burning grain of a propellant exhibiting plateau burning rate characteristics. All gases passed through a multi-perforated block of the candidate coolant materials. The nozzle was sized to operate in the plateau region of the propellant to provide commonality of test conditions for the various materials. Means were provided to collect condensable materials from the exhaust plume as a qualitative indication of erosion of the coolant

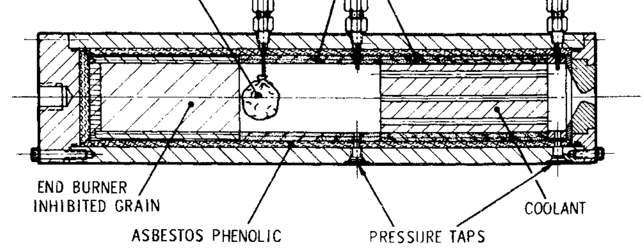


Fig. 6 Experimental test motor used in evaluation candidate.

materials. Pressure and temperature were measured to characterize coolant performance.

Seven coolant materials were evaluated in these static tests. A computerized heat-transfer program, developed for coolant performance analyses, showed good agreement between theoretical and measured values for operating pressure, outlet temperature, and amount of coolant consumption using the heat transfer coefficient as the correlating parameter. These classified data show heat-transfer coefficient to be sensibly independent of the individual material. Consumption rates predicted are generally marginally larger than measured rates as may be accounted for by extraneous heat losses. The one material which exhibited considerable erosion (Lactose) did lose more mass than was predicted for the measured operating conditions. The degree of correlation of data with predictions shows the theoretical model to be a useful design tool.

As a result of the coolant evaluation tests, four materials have been shown to be acceptable for use as coolants in a gas conditioning system. These materials, in order of preference, are; 1) glycine (amino acetic acid), 2) oxamide, 3) tartaric acid, and 4) succinic acid.

## System Demonstrations

The successful completion of the coolant evaluation test series and the demonstration of total particle filtration have shown separate solutions to the major problems of chamber bleed gas conditioning. It remained to demonstrate these combined devices under conditions simulating a tactical environment.

Two auxiliary power sections taken from surplus Tartar missiles were obtained for demonstration testing. The design of the demonstration test was influenced by the availability of the Tartar APU section. To avoid costly modification of the APU turbine, the test motor was designed to provide operating conditions for the turbine similar to those characteristic of the existing gas generator.

The design philosophy used for the demonstration test was to bleed gases radially from a high-velocity (subsonic) blast tube. The high particle momentum at the bleed station will minimize the particle content of the gases entering the filter/cooler. The reduced $Al_2O_3$ content of the filtered gases permits a substantial reduction in the required filter envelope. It was recognized that while the quantity of particles entering the filter/cooler would be reduced, the particles remaining would be in the submicron and small micron sizes. The efficient removal of these particles without incurring excessive pressure drops would be a significant test of filtering technology.

Two static demonstration firings were planned. The first test, designed for 20 sec duration, was intended to evaluate the particle separation efficiency of the high-velocity bleed probe and to appraise the performance of the combined filter/cooler for extended operating durations. The final 40-sec test was intended to demonstrate the state of development of gas conditioning technology over action times sufficient to satisfy tactical duty cycles.

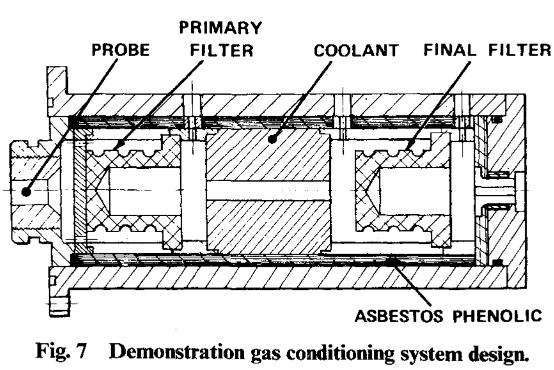


**Fig. 7 Demonstration gas conditioning system design.**

The filter/cooler design used in these tests was flightweight but housed in a heavyweight steel case as shown in Fig. 7. The primary filter consisted of a coarse grade of porous carbon. The coolant material was glycine with a Formvar binder system. The final filter was a fine grade porous carbon. Gases exiting from the filter/cooler were directed to the turbine of the Tartar APU. Hydraulic power generated in the APU was used by an existing actuator to deflect a cantilever spring sinusoidally. A second gas conditioning system was evaluated simultaneously. Gases conditioned by this system were exhausted to the atmosphere through a nozzle designed to match the flow rate required by the turbine.

The two demonstration tests were successfully conducted. The propellant used in both tests was characterized by a flame temperature of 5950°F and an alumina content of 23% by weight. The test motors were operated at average pressures of 550 psi and 575 psi for durations of 21.4 and 40.3 sec. The gas conditioning systems in both tests exhibited total particle filtration with most of the alumina collected in the primary filter stage. Additional envelope savings could be realized by minimizing the envelope of the final filter stage. Gas temperatures measured at the output of the filter/cooler were well below the maximum allowable value of 2500°F.

An average of approximately 8 hp was generated by the APU during both tests. This energy level is within the operating envelope for this APU and was achieved at a substantial savings in weight and envelope over the existing warm gas generator design.

## Conclusions

The technological problems associated with conditioning chamber-bled gases to a state suitable to such applications as auxiliary power units have been resolved. The successful demonstration of gas conditioning systems in this program has shown that total particle filtration and controlled efficient reduction in gas temperatures are a present day capability.

The problems remaining pertain to tailoring the technology to specific applications. Missile systems that remain propulsive to target or that have no post-propulsive control requirement may apply this technology directly. Integral rocket/ramjet missiles similarly can use chamber bleed systems; ram air can augment chamber gases after rocket burnout. However, many missile systems require electrical and/or hydraulic power for substantial periods after propulsion burnout. It remains to show whether in such a system chamber-bled gases may be applied. In suitable applications, this technology offers significant performance improvements by merit of demonstrated weight saving potential.

## Appendix: Analytical Coolant Survey

A thermodynamic heat transfer model of the cooling bed was generated. To permit relative ease of computation with reasonable accuracies, only first order of magnitude effects were considered. This model equated heat given up by the bleed gases to heat absorbed by the coolant by

$$\dot{m}_g \int_{T_I}^{T_o} C_{P_g} dT = \dot{m}_c \left[ C_{P_s}(T_D - T_A) + \Delta H_R + \int_{T_I}^{T_o} C_{P_c} dT \right]$$

where $\dot{m}_g$ = mass flow rate of particle-free bleed gas, lbm/sec; $\dot{m}_c$ = mass flow rate of decomposition products, lbm/sec; $\Delta H_R$ = heat of decomposition, Btu/lb; $C_{P_g}$ = heat capacity of particle-free bleed gases, Btu/lb-°R; $C_{P_c}$ = heat capacity of decomposition products, Btu/lb-°R; $C_{P_s}$ = heat capacity of coolant material, Btu/lb-°R; $T_I$ = coolant bed inlet temperature, °R; $T_o$ = coolant bed outlet temperature, °R; $T_D$ = coolant decomposition temperature, °R; and $T_A$ = ambient temperature, °R.

The rate of heat transfer to the coolant surface was approximated by

$$\dot{Q} = U_H A \left[\frac{(T_I + T_o)}{2} - T_s\right]$$

where: $\dot{Q}$ = heat flow rate, Btu/sec, $U_H$ = heat transfer coefficient, Btu/in.$^2$-sec-°F, $A$ = exposed coolant surface (in.$^2$), and $(T_I + T_o)/2$ = average gas temperature in coolant bed, °R. The combination of gases exiting through a nozzle (or into a turbine) is given by

$$\dot{m}_g + \dot{m}_c = C_{D_m} A_t P_o$$

where: $C_{D_m}$ = discharge coefficient of gas mixture, sec$^{-1}$, $A_t$ = nozzle area, in.$^2$, and $P_o$ = filter/cooler outlet pressure, psi.

To compare various candidate coolant materials analytically, a rating parameter was generated. This parameter, designated specific energy, is given by

$$\text{specific energy} = \frac{KT_m}{MW_m}\left(\frac{\gamma_m}{\gamma_m - 1}\right)\left[1 - \left(\frac{P_a}{P_o}\right)^{(\gamma_m - 1)/\gamma_m}\right]$$

where: $K$ = dimensionless constant, $T_m$ = mixture gas outlet temperature, °R, $MW_m$ = molecular weight of gas mixture, lb-mole/lbm, $\gamma_m$ = specific heat ratio of mixture, $P_a$ = ambient pressure, psi, and $P_o$ = filter/cooler outlet pressure, psi.

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# Damping of Axial Instabilities by Small-Scale Nozzles Under Cold-Flow Conditions

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**The damping of axial instabilities by a variety of small-scale solid rocket nozzles has been determined experimentally under cold-flow conditions using the modified impedance tube technique. The dependence of the damping upon the cavity depth and the secondary flow rate issuing from the cavity of a submerged nozzle, the geometry of the convergent section of a single-ported nozzle, and the number of nozzles present in a multiple-ported nozzle cluster has been determined. Measured data indicate that in the case of the submerged nozzle the cavity depth surrounding the nozzle has a significant effect upon the nozzle admittance while the secondary flow rate issuing from the cavity has negligible effect on the admittance. Tests conducted with conical, equal-radii-of-curvature and linear-velocity-profile nozzles showed that conical nozzles provide the most damping. Tests with multiple-ported nozzles indicated that quadruple-ported nozzles provide less damping for axial instabilities than single and dual-ported nozzles whose damping capabilities are approximately the same.**

## Nomenclature

$A$ = amplitude of pressure oscillation, psfa (rms)
$\hat{A}$ = constant
$c$ = velocity of sound, fps
$f$ = frequency, Hz
$F$ = nondimensional frequency defined as equal to $\omega r_c/\bar{c}$
$i$ = imaginary unit, $(-1)^{1/2}$
$L$ = length, ft
$M$ = Mach number
$p$ = pressure, psfa
$P$ = pressure amplitude, psfa (rms)
$q$ = secondary to primary flow rate ratio
$r$ = radius, ft
$S$ = cross-sectional area, ft$^2$
$T$ = period of oscillation, sec
$u$ = axial velocity, fps
$V$ = volume, ft$^3$
$y$ = nondimensional admittance, defined by Eq. (8)
$Y$ = admittance, defined by Eq. (7), ft$^3$/lbf-sec
$z$ = axial coordinate
$\alpha$ = nozzle admittance parameter, defined by Eq. (5)
$\alpha_N$ = nozzle decay coefficient, defined by Eq. (15), sec$^{-1}$
$\beta$ = nozzle admittance parameter, defined by Eq. (6)
$\gamma$ = specific heat ratio
$\Gamma$ = real part of nondimensional admittance
$\delta$ = pressure phase, defined by Eq. (14), rad
$\eta$ = imaginary part of nondimensional admittance
$\lambda$ = wavelength, ft
$\Lambda$ = nondimensional decay coefficient
$\rho$ = density of gas in the chamber, lbf-sec$^2$/ft$^4$
$\omega$ = angular frequency, rad/sec

*Superscript*
$(\bar{\ })$ = steady-state quantity

*Subscripts*
$c$ = denotes a chamber property
$N$ = quantity related to nozzle behavior
$1$ = perturbed quantity

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## Introduction

SOLID propellant rocket motors are often subject to combustion instabilities involving oscillations of the gases within the combustion chamber. Such instabilities can result in failure of