Minimum-Response-Delay Controllable Solid-Propellant Gas Generators

J. Cohen,* L. C. Landers,* and R. L. Lou†
Aerojet Solid Propulsion Company, Sacramento, Calif.

A minimum response delay in controlling the flow rate of solid-propellant gas generators is achieved through the use of propellants having inverse pressure dependence of burning rate (negative n exponent). These propellants have flame temperatures as low as 2100°F and an n value less than −2.5. Because of the low pressure exponent, these propellants also have low temperature sensitivity. Higher-energy propellants, with and without metal fuels, have been formulated which also have a negative exponent and are proposed for applications where higher flame temperatures can be tolerated.

Nomenclature

A_t = cross-section area of nozzle throat
A_p = propellant burning surface
K_n = area ratio, A_P/A_t
$\dot{m}$ = mass-flow rate
n = pressure exponent in burning rate law equation: $r = CP_c^n$
P_c = chamber pressure
P_L+, P_H+ = positive-exponent propellant low and high pressures for $\dot{m}$ throttling
P_L-, P_H- = negative-exponent propellant low and high pressures for $\dot{m}$ throttling
r = linear surface regression rate
π_K ≡ $(\partial \ln P_c/\partial T)_{Kn} = (\partial \ln r/\partial T)_{Pc}[1/(1-n)]$

Introduction

FLOW control for a solid-propellant gas generator can be accomplished readily by regulating combustion pressure at the nozzle, thereby causing the propellant burning rate to vary. The feasibility of the technique depends on the availability of propellants with a high sensitivity of burning rate to pressure, i.e., a high value of pressure exponent n in the burning rate equation $r = CP_c^n$. The higher the (absolute) value of n, the greater the range of flow control which will be achieved with a given change in operating pressure.

Although flow control can be achieved with either positive-exponent or negative-exponent propellants, the negative-exponent propellant confers several important advantages. The first advantage is increased speed of throttling response, due to the combustion-chamber vent-area change being always in the same sense as the desired mass-flow throttling. The second advantage is that the exponent is not limited to absolute values less than 1.0, as it is for positive-exponent propellants. Stable motor operation is theoretically achievable with any negative value of n and has been demonstrated in motors using propellants with n as negative as −4.0. This high sensitivity of burning rate to pressure provides a high effectivity in mass flow control via pressure throttling. The third advantage is that the sensitivity of motor operating pressure to the ratio of burning surface and vent area K_n is reduced greatly which increases reproducibility of motor performance. Finally, the temperature sensitivity of motor operating pressure π_k is reduced greatly. These advantages have been demonstrated in firings of motors containing up to 80-lb grains.

Presented as Paper 76-691 at the AIAA/SAE 12th Propulsion Conference, Palo Alto, Calif., July 26-29, 1976; submitted Aug. 5, 1976; revision received Jan. 3, 1977.
Index categories: Fuels and Propellants, Properties of; Solid and Hybrid Rocket Engines.
*Senior Chemistry Specialist, Propellant Development.
†Manager, Propellant Development.

Comparative Propellant Properties

Throttling Response

Figure 1 shows a comparison of the method of throttling both positive- and negative-exponent propellants. Two curves are shown to depict the characteristic changes in the mass-flow rate $\dot{m}$ as it changes from $\dot{m}_{min}$ to $\dot{m}_{max}$ for increasing chamber pressure with a positive-exponent propellant and the contrasting shift from $\dot{m}_{max}$ to $\dot{m}_{min}$ for the negative-exponent propellant, dashed vs solid lines, respectively. The pressure ranges over which the propellants achieve the throttling are represented by P_L+ to P_H+ for the positive exponent and P_L- to P_H- for the negative exponent.

For the example shown in Fig. 1, a throttling ratio of 2.7 in high to low $\dot{m}$ is achieved for a pressure range of 500 psi (1000 to 1500 psi) with a practical negative-exponent propellant ($n = -2.5$), whereas a pressure range of 1400 psi (600 to 2000) is required for the positive-exponent propellant using an optimistically high value of 0.8 for n. The smaller pressure range and higher burning rate sensitivity to pressure permit the use of less complex and lower weight hardware for the negative-exponent propellant compared to the hardware for a positive-exponent propellant.

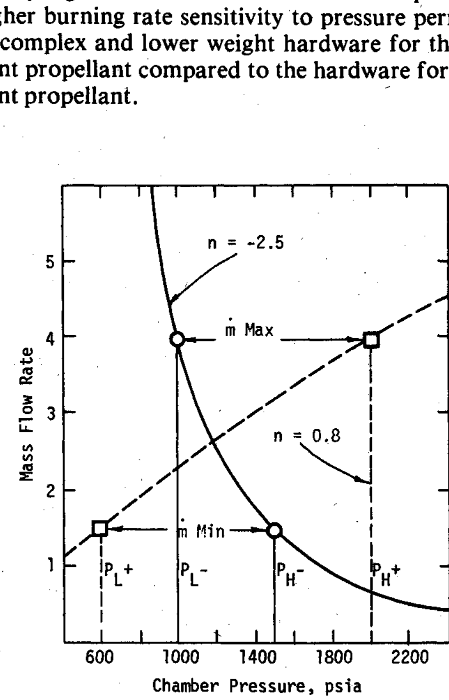

Fig. 1 Pressure effectivity for flow control.

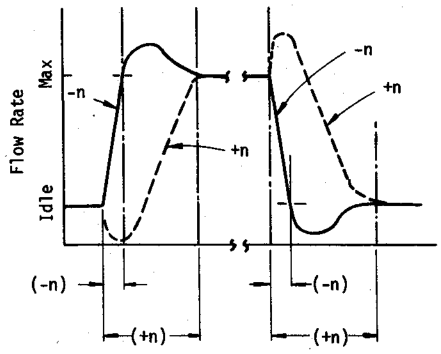

Fig. 2 Characteristic throttling times, negative and positive n propellants.

Response Delay

Figure 2 shows a comparison of the characteristic throttling for positive- and negative-exponent propellants for both increasing and decreasing flow. For the positive-exponent response (shown dotted on the figure) a command to increase flow results in a decrease of nozzle area. This nozzle action momentarily chokes the gas flow, and an initial drop or undershoot in gas flow occurs until the propellant burning rate increases and equilibrium gas flow is re-established. A command for a flow decrease results in increase in the nozzle area, thus the gas flow increases at first, producing a flow spike until the pressure can be vented to the new operating condition. These momentarily opposite corrections to gas flow add time delays in the overall response.

In motor operation with a negative-exponent propellant, however, the vent area change is always in the *same* sense as the desired throttling, i.e., it is increased for increasing flow rate and decreased for decreasing flow rate. For this type of response (shown as solid lines in Fig. 2) an increase in vent area causes an initial increase in flow rate through the vent; now the resulting decay in chamber pressure causes the propellant burning rate to increase (burning rate change is inverse to pressure change) and the higher mass flow is maintained. When the vent area is decreased, an immediate decrease in flow rate through the vent occurs; now the resulting increase in chamber pressure causes propellant burning rate to decrease, and the lower flow rate is maintained. Thus, with a negative-exponent propellant, the initial response of the system is always in the same sense as the desired throttling, so that there is no initial overshoot or undershoot to cause a response delay. The overall control system response thus is not degraded by the propellant response when using a negative-exponent propellant and response delays are then a function only of the hardware limitations.

With a negative-exponent propellant, a small over- or undershoot occurs at the completion of a flow change (shown exaggerated in Fig. 2 for the sake of clarity). These effects are not functionally a problem, however, because they occur only at the completion of the flow responses and, if need be, can be damped by the control system. Actual experience shows the overflow to be less than 3% and the underflow to be less than 4% of the control level.

Table 1 Effect of pressure exponent on I_{sp} when throttling

Throttling ratio	n	Pressure ratio	I_{sp} ratio (theor.)
3	0.8	2000/506	262/234
10	0.8	2000/112	262/185
3	0.9	2000/590	262/238
10	0.9	2000/155	262/200
3	−2.5	1288/2000	254/262
10	−2.5	796/2000	245/262

K_n Sensitivity of Pressure

The sensitivity of operating pressure to the burning-surface/throat area ratio K_n is reduced greatly with a negative-exponent propellant. For a motor with a fixed nozzle, this would reduce greatly the magnitude of excursions of motor operating pressure caused by grain imperfections or by passage of ejected inert materials (insulation, etc.) through the nozzle. For a controllable motor with a variable nozzle, this would reduce greatly the specific impulse shift when "idling" as shown in Table 1.

Temperature Sensitivity of Pressure

The temperature sensitivity of motor operating pressure π_K is reduced greatly because π_K is proportional to the quantity $1/(1-n)$, provided that the temperature sensitivity of burning rate $\partial \ell n r/\partial T$ does not change greatly. The extremely low temperature sensitivity observed in micromotor tests of a representative negative-exponent propellant is shown in Table 2. The π_K value is only one-fifth the typical value of $\sim 0.002°F^{-1}$ exhibited by positive-exponent propellants. This reduction in π_K improves the delivered specific impulse at the lower extreme of operating temperature because of the higher operating pressure at that condition, compared with a positive-exponent propellant. This is illustrated in Table 3, which shows that the I_{sp} decreases by less than 1% between 180 and −75°F operating temperatures for the low π_K propellant, compared to a decrease of over 6% for the conventional positive-exponent propellant with π_K of 0.0021%/°F.

Combustion Description

The inverse dependence of burning rate on pressure, the negative pressure exponent, is attributed to a combustion process which involves the establishment of a more-or-less stable binder melt layer on the burning surface. The action of the fuel-melt layer as a barrier to the propagation of combustion has been described by Steinz, et al.[1] as producing local flame extinguishment and by Schmidt[2] as a local thermal barrier. The local extinguishment concept requires a transverse flame transfer at the burning surface to maintain combustion and results in an average surface regression rate which is lower than when the entire surface has been ignited. A thermal barrier to deep ignition or flame transfer would act to reduce further the average burning rate. The addition of a fusible salt such as $(NH_4)_2SO_4$ adds to these effects by producing a deeper thermal barrier and by suppressing dissociation of the NH_4ClO_4 through mass action of the NH_4^+ ion.

Table 2 Temperature sensitivity of nonaluminized negative-exponent propellant (84% AP)

Grain	Temp., °F	K_n	$\bar{P}_b$, psia
10	+180	176.1	717
1	+80	177.1	658
9	−75	176.1	645
π_K	−75 to +80	0.00013°F^{-1}	
	+80 to +180	0.00087°F^{-1}	
	−75 to +180	0.00042°F^{-1}	

Table 3 Reduction in I_{sp} loss due to reduction in π_K

	Operating pressure		I_{sp} (theor.)	
π_K	180°F	−75°F	180°F	−75°F
.0021°F^{-1}	1000	585	246.6	232.3
.00042°F^{-1}	1000	898	246.6	244.3

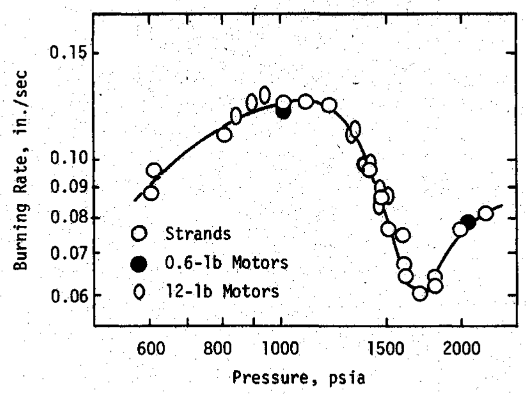

Fig. 3 Gas generator propellant burning rates, negative *n* under 1500 psia.

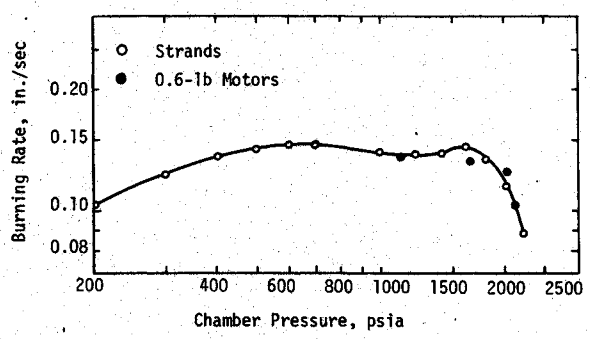

Fig. 4 Gas generator propellant burning rates, negative *n* over 1500 psia.

The local flame extinguishment actually can be observed at the surface of burning strands in a combustion bomb equipped with a viewing window. The flame transfer is seen to occur when isolated propellant sites, previously extinguished, are reheated to ignition by nearby combustion sites which subsequently are extinguished when they burn away into the melt zone. The breakup of the burning surface into the discontinuous condition just described occurs only for the pressure range when the burning rate does not have a fixed dependence on pressure in accordance with the exponential equation of the burning rate law. At other pressures the strand combustion is seen as a continuous flame burning normal to the surface.

In order to examine the propellant condition in support of the observations with strands, stop-fires have been conducted with grains containing $(NH_4)_2SO_4$ after some partial burn in a motor. The extinguished surface is pitted by shallow craters 3 to 6 mm in diameter, in conformance with a combustion mechanism based on ignition transfer such as just described and observed in the strand burning. The apparent burning rate for these propellants, then, is the average surface-regression rate, which is, in turn, proportional to the fraction of the surface actually undergoing combustion at a given time. The extent to which the burning fraction covers the surface is pressure dependent and therefore acts in place of

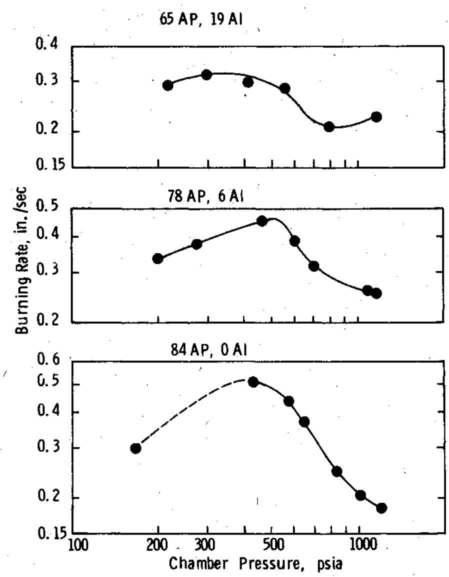

Fig. 5 Small motor burning rates of typical negative-exponent PU propellants with Al.

the usual pressure dependent burning processes. At a critical pressure level the combustion energy is believed to balance the endothermic and insulation processes[1,2] in the burning surface and the combustion becomes continuous over the entire surface. At still higher pressures the burning-rate/pressure relationship is in accordance with the usual exponential burning-rate dependence on pressure. No consistent explanation has been derived for this pressure threshold, which is susceptible to tailoring as described in the following discussion.

Ballistic Properties

The negative-exponent propellants developed for gas generator applications are based on the use of a polyurethane binder-fuel, ammonium perchlorate oxidizer, and burning rate control additives. The propellant burning rate and to some extent the pressure range for negative *n* operation are tailored by the selected additives and by control of oxidizer and additive particle size. The thermodynamic properties typical for this group of propellants are a specific impulse of 189 lbf-sec/lbm and combustion flame temperatures of 2100° F (chamber at 1000 psia) and 1030°F (exhaust at sea level).

Examples of the burning-rate pressure relationships with negative exponent are shown in Figs. 3 and 4 for negative *n* between 1000 and 1600 psia and between 1600 and 2200 psia, respectively. The burning rates measured in both strands and motors are plotted for comparison and are seen to be in good agreement (open vs closed symbols, respectively). The motor results were obtained with neutral-geometry internal-burning grains. Firings with 5.0-lb internal-external burning grains confirm these data with essentially identical results.

Negative-exponent propellants with higher performance have been formulated using ballistic solids consisting of AP or AP + Al. The properties for typical negative-exponent compositions are shown in Table 4. The negative-exponent

Table 4 Properties for typical negative-exponent propellants

Composition, %								
AP	Al	Combustion modifier	PU	I°_{sps} [a]	I°_{sps} [b]	ρ, lb/in.^{3}	TDR [c]	n [d]
65	19	1	15	261.6	248.0	0.064	1.53	−0.50
78	6	1	15	253.5	245.5	0.062	1.80	−0.73
84	0	0-1	15	246.6	240.8	0.061	2.62	−0.98

[a] Theoretical. [b] Delivered for 1000-psia chamber and 14.7-psia exhaust, 0° nozzle half-angle. [c] Turn-down ratio; ratio of r_{max}/r_{min} in negative-exponent region. [d] Average value between r_{max} and r_{min}.

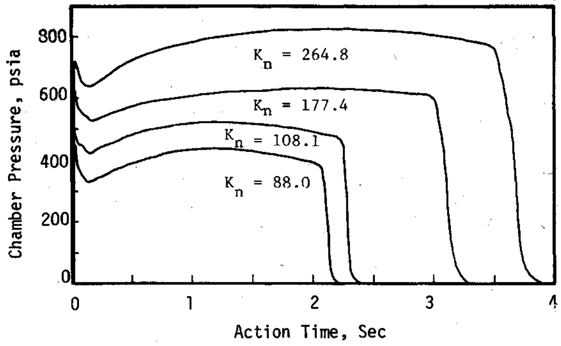

Fig. 6 Negative-exponent propellant with 6 wt% Al, motor firings.

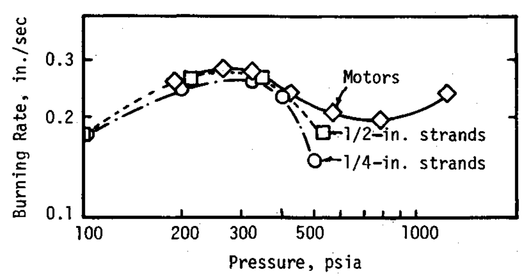

Fig. 7 Motor vs strand burning rates, aluminum fuel propellants.

characteristics become more pronounced as the Al content is decreased, although this is accompanied by decreases in specific impulse and density. The ballistic properties of these propellants are illustrated further in Figs. 5-7.

Micromotor test data (internal and end-burning 290-g grain) plainly show the negative-exponent characteristics. The burning rate vs pressure data (Fig. 5) show the pressure regime in which there is an inverse dependence of burning rate on pressure, and the pressure-time oscillograms for firings with the 6% Al propellant (Fig. 6) dramatically show that, in this pressure regime, the motor duration increases with pressure.

It is noteworthy that for the high-energy propellants, the burning rate vs pressure data obtained from strand-burning tests can be highly misleading (Fig. 7). The strand data indicated the negative-exponent characteristics to be much more pronounced than actually was observed in the motor firings, and increasing the strand diameter gave only a minor improvement. In addition, the strand tests indicated the possibility of a limiting pressure, above which combustion would not be sustained, but this was not borne out by the micromotor tests. This experience shows that motor data are required to characterize reliably the whole range of negative-exponent burning-rate relationships with pressure.

On-Demand Gas Generator Test Results

A demonstration of on-demand mass-flow control using a negative-exponent propellant was made using a pintle nozzle to control chamber pressure. The 10-in. diam by 30-in. long motor used an 80-lb grain in internal plus end-burning configuration with a 21-sec firing duration. The propellant area was designed to be nearly neutral during the firing to provide accurate information for calculation of the burning rate. The nozzle throat area vs pintle position was calibrated over the whole range of pintle travel planned for the firing. The pintle movement was programmed to give high- and low-rate travel with the annular throat area varying between 0.21 and 0.43 in.,^{2} including stepwise dwell positions. The pintle control functioned as planned throughout the motor firing, and the motor performance was close to predicted in both pressure and burning rate.

In addition to verifying the predicted propellant and motor performance, the firing demonstrated dependable high rates of flow change with essentially zero time delay using only

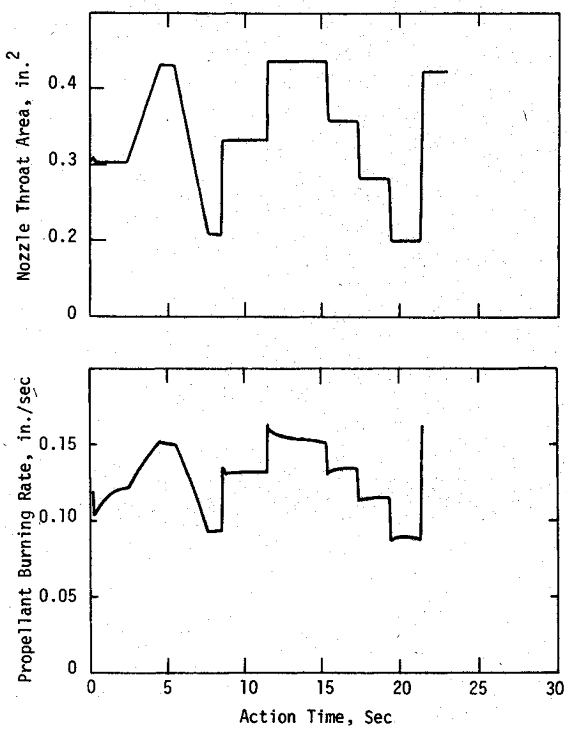

Fig. 8 Burning rate and nozzle throat area vs time, 80-lb grain, controllable pintle nozzle.

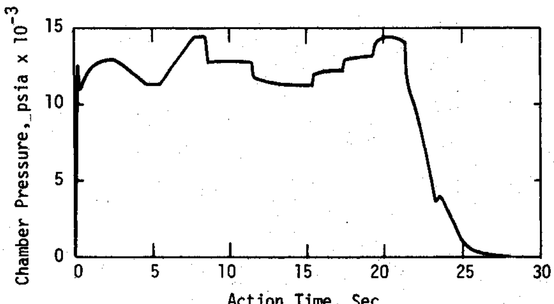

Fig. 9 Pressure vs time, 80-lb grain, controllable pintle nozzle.

simple experimental tooling in the motor hardware. The absence of time delay in the flow rate response to the varied flow demand is shown by the correspondence of pressure and burning rate to the nozzle area modulation as shown in Figs. 8 and 9. The time delay to initiate the shifts from a high to lower or from low to higher flow condition is essentially zero in all cases. The maximum value for the response lag is 8 msec, since no delay could be found between the pintle position signal and the pressure signal within the 125-cycle recording frequency used for the digital oscillograph.

The A_t, r, and P_c data shown in Figs. 8 and 9 are taken from the oscillograph records without smoothing. The A_t

Table 5 Controlled motor vs strand burning rates

Time,	P_c,	Burning rate, in./sec	
sec	psia	Strand	Motor
1	1200	0.142	0.113
2	1300	0.135	0.121
5	1130	0.150	0.152
8	1450	0.095	0.093
10	1280	0.13	0.132
14	1120	0.15	0.153
17	1230	0.14	0.137
20	1450	0.095	0.090

values are obtained from the pintle position oscillogram calibrated for the corresponding annular throat area both before and after the firing. The propellant burning rates are calculated for each 8-msec interval of the firing using the corresponding A_t and P_c values in the mass-balance equation: $r = C_w P_c A_t / A_p \rho$. The C_w was obtained from 5-lb motor firings, and A_p was calculated point-to-point for the firing using partial integrals for grain consumption vs the predicted grain-profile change. The A_p estimate is valid since the designed burning-area variation during the firing was less than $\pm 2\%$ from the mean area.

A 1.5-sec induction interval is observed at the start of the motor firing for the initial nozzle setting and a pressure rise from 1100 to 1300 psia occurs during that time. This induction interval is a part of the grain ignition interval and is characteristic for the low-flame-temperature propellants if ignition occurs at a pressure within the negative-exponent P_c range. An overshoot in burning-rate change is seen at the termination of each nozzle area change, but it occurs after the demand to initiate a change in gas flow is satisfied. This type of overshoot in gas flow easily can be cut off by commonly used systems with damped controls.

The burning rates obtained in the firing agree with the strand and 5-lb motor rates for the propellant used in the 80-lb motor. The burning rates at reference intervals in the firing are listed in Table 5 for comparison with the strand data which were used to predict the motor performance. No significant differences were obtained after the ignition interval explained earlier. The average value of n for this motor firing is -2.7, which is an important verification of the propellant performance under controlled mode operation.

Conclusions

Significant benefits are obtained by using a propellant with a negative-pressure exponent of burning rate, compared to a conventional positive-exponent propellant.

1) For negative-exponent gas generators or controllable thrusters, the benefits are a higher throttling ratio for a given pressure change and a faster response with elimination of inverse flow-responses to flow-change commands.

2) For negative-exponent controllable thrusters, another benefit is the greatly improved average I_{sp} efficiency.

3) For a negative-exponent propellant in a fixed-nozzle motor, the benefit is an increase in effective specific impulse due to the dramatically reduced sensitivity of operating pressure to ambient temperature.

References

[1]Steinz, J. A., Stang, P. L., and Summerfield, M., "The Burning Mechanism of Ammonium Perchlorate Based Composite Solid Propellants," Princeton University, Princeton, N. J., Interim Rept. No. AM8830 (DDC), Feb. 1969.

[2]Schmidt, W. G., "The Effect of Solid Phase Reactions on the Ballistic Properties of Propellants," NASA CR-66757, May 1969.