Dual-Chamber Rocket Motor Operating Characteristics

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An experimental investigation was conducted to determine the operating characteristics of the dual-chamber rocket motor. Axisymmetric and two-dimensional apparatuses were used with airflow to simulate the actual flow. Without special design considerations, the sustainer exhaust was found to always shock down within the booster cavity except for very short booster lengths. In shock-down operation thrust was found to be insensitive to booster cavity length. With nozzle throat area ratios and booster diameters sized properly, supersonic flow could be maintained within the booster cavity, substantially increasing thrust. Practical design geometries for actual motors operating in the supersonic flow mode appear quite feasible, especially for a nozzleless booster motor.

Nomenclature

A = area
C_F = thrust coefficient
d,D = diameter
F = thrust
h = height
L = length
$\dot{m}$ = flow rate
p = static pressure
P = stagnation pressure
T = temperature
γ = specific heat ratio
λ = nozzle divergence loss factor

Subscripts

a = ambient conditions
B,b = booster
e = nozzle exhaust
j = jet
max = maximum theoretically possible
N = nozzle
s = sustainer
SD = shock-down
SS = supersonic flow
TH = theoretical value

Superscript

$*$ = nozzle throat conditions

Introduction

TACTICAL missiles have utilized most often solid fuel rockets due to their ease of handling, Demands for higher performance have necessitated new advances in propellants and metallurgy, and pressures have risen steadily. New innovations have become necessary in order to improve overall performance for a propulsion system which has become a mature technology. Boost-sustain motors have been used to meet the demand for medium-range, air-launched tactical missiles.

Boost motors utilize high pressures, high burn rates, and thus short burn times to accelerate tactical missiles to their normal operating speeds, and to provide rapid separation from the launch vehicle. This generally has necessitated an internal-burning grain and a large nozzle throat area. Sustainer motors, on the other hand, require longer burn times and operating pressures determined by the desired boost-sustain thrust ratio. Current demands are for thrust ratios up to 20:1. A particular problem occurs when large thrust ratios are required for the boost-sustain motor. If both modes of operation use the same large boost nozzle, then the sustainer necessarily would operate at very low pressures with often unacceptably low burning rates. To obtain adequate pressures and flow rates under these conditions often requires internal-burning grains with correspondingly shorter burn times.

Several possible alternatives are available. In principle, the burning rate of the sustainer motor propellant could be increased enough to allow the use of an end-burning grain with small surface area. In practice, however, high burning rates are difficult to obtain at low pressures. Separate boost and sustain motors could be employed with the booster ejected after burnout. This is done readily on ground/ship-launched missile designs, but would present difficulties for air-launched systems, which usually utilize one set of aft-mounted fins for trajectory control.

Another alternative is the variable area nozzle, which requires some form of actuation. This, by itself, leads to increased complexity, weight, and expense, not to mention the technical difficulties associated with the high temperatures involved. New technology may permit this concept in the future.

The dual-chamber concept provides yet another solution. In this configuration the sustainer motor exhausts through its nozzle into the empty booster cavity. A typical design might incorporate a booster cavity which is nearly 50 sustainer exhaust nozzle diameters in length. From available literature,[1-3] free jets have been observed to shock down to subsonic flow within 8-10 diameters. Little is known about the behavior of confined jets. For long booster cavity lengths the sustainer motor exhaust would enter the booster cavity, shock down, and merely act as a gas generator for the booster nozzle. This in itself may provide sufficient performance advantages over the conventional (one-nozzle) boost-sustain design. However, if the jet impinges on the booster cavity walls, severe problems could arise from high heat-transfer rates. This could adversely affect thrust performance, with the increased need for insulation and weight.

The dual-chamber geometry might also be designed to prevent shock-down. This involves designing the nozzles and booster cavity such that they operate similar to a blow-down supersonic wind tunnel. In this mode of operation the sustainer exhaust would expand (with minimum or no shocks)

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to the booster cavity wall and flow supersonically into the booster nozzle. In order to operate in this manner, particular values of nozzle area ratio and booster cavity length are required. These requirements may or may not be compatible with particular motor geometry restrictions. Operation in the supersonic mode may also require the sustainer exhaust nozzle to be specially contoured to the booster cavity diameter. This may impose severe weight penalties.

When calculating the necessary area ratios, several operating requirements must be met.

1) The sustainer nozzle throat must be small enough to produce the desired high sustainer chamber pressure.

2) The booster throat area must provide adequate booster pressure and loading fraction.

3) The booster throat pressure during sustain operation must be kept greater than ambient pressure to prevent flow separation and to allow "starting."

4) The booster cavity length probably should be sufficient to allow the sustainer exhaust to expand to the wall.

Another alternative for the dual-chamber concept employs the ejection of the booster nozzle. Here the sustainer motor may be optimized for expansion to atmospheric pressure. Thrust is again provided at sustainer pressures commensurate with long burn times using end-burning grains. However, expansion of the sustainer exhaust to the boost cavity wall could affect base pressure greatly and thereby cause thrust to vary appreciably with altitude.

The purpose of this investigation was to determine the operating characteristics of the dual-chamber concept through a systematic investigation of the pertinent design (nozzle shape and size, booster cavity lengths, etc.) and operational (pressure, etc.) variables.

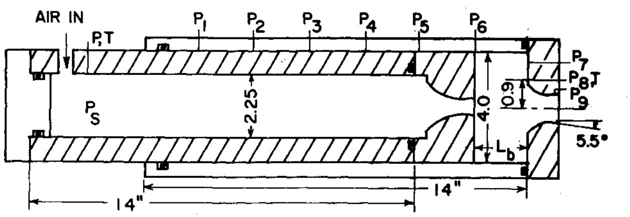

Fig. 1 Schematic of test apparatus.

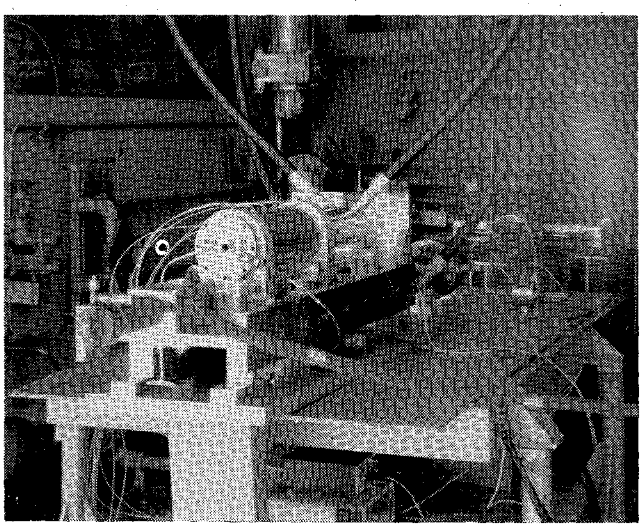

Fig. 2 Photograph of apparatus on thrust stand.

Experimental Apparatus

The axisymmetric motor simulator (Figs. 1 and 2) was mounted on a thrust stand. The length of the low-pressure section could be varied by actuation of a hydraulic jack mounted on the aft end of the thrust stand. Three configurations were employed (Table 1) in order to provide a wide range of booster-to-sustainer throat area ratios. Configuration 1 employed a sustainer nozzle that provided expansion to slightly greater than the shock-down pressure. Configuration 2 was significantly overexpanded and configuration 3 provided ideal expansion to the shock-down pressure.

The schlieren apparatus was a two-dimensional device with glass sides in which the simulated booster cavity length, sustainer nozzle size, and booster nozzle size could be varied. A schematic of the apparatus is shown in Fig. 3. Details of the apparatus are presented in Ref. 4. For each configuration tested, sustainer nozzle stagnation pressure (P_s) and booster cavity wall-static pressures were recorded and a schlieren photograph was obtained.

Results and Discussion

Shock-down Operating Characteristics

In this portion of the investigation, the variable-length axisymmetric apparatus was used to determine the effects of booster and sustainer nozzle throat diameters and area ratios, booster cavity length, and removal of the booster nozzle on the obtainable thrust and the axial pressure distribution. In addition, the two-dimensional schlieren apparatus was used to provide visual information on the booster cavity flowfield for selected configurations.

The three basic configurations presented in Table 1 were tested. Thrust was measured as booster cavity length was decreased continuously from 9.28 to 0.35 in. At intermittent lengths the booster length was held constant and the pressure distribution recorded.

Details of the experimental procedures and the complete data set are presented in Refs. 4 and 5. Representative data will be presented subsequently.

Booster Nozzle Attached-Axisymmetric Tests

Measured thrust as a function of booster cavity length is presented in Fig. 4 for configuration 1 (Table 1). Also shown are the theoretical values of thrust.

With the booster cavity in the full-forward position F_{TH} was calculated using the sustainer stagnation pressure and nozzle exhausting to ambient pressure. With the booster

Table 1 Apparatus dimensions and test conditions

Configuration	d_s^*	d_{e_s}	d_b^*	d_{e_b}	P_S	P_{SD}	P_{e_s}	P_{e_b}	A_b^*/A_s^*	F_{TH_s}	F_{TH_b}	F_{max}
1a	0.239	0.273	0.527	0.615	1500	308.5	320.7	60.2	4.86	90.7	88.0	104.2
b	—	—	—	—	1000	205.7	213.8	40.1	—	60.2	57.2	68.0
c	—	—	—	—	500	102.8	106.9	20.0	—	29.7	26.4	31.8
2a	0.273	0.465	0.527	0.615	1500	402.5	76.5	78.5	3.73	130.9	116.2	135.0
b	—	—	—	—	1000	268.4	51.0	52.3	—	86.4	76.0	88.6
3a	0.273	0.465	1.221	1.330	1500	75.0	76.5	20.0	20.0	130.9	96.6	128.0

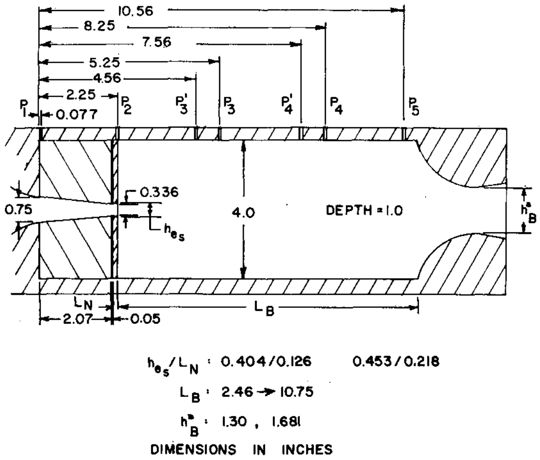

Fig. 3 Schematic of two-dimensional schlieren apparatus for shock-down mode of operation.

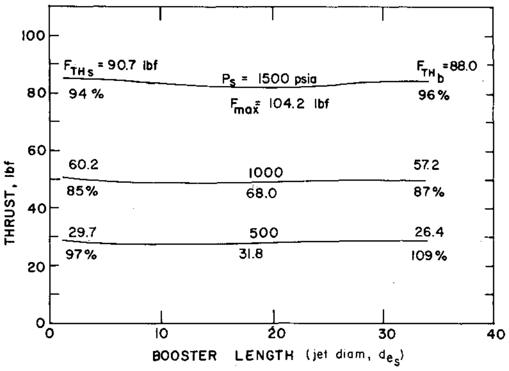

Fig. 4 Thrust vs booster cavity length, configuration 1, booster nozzle attached.

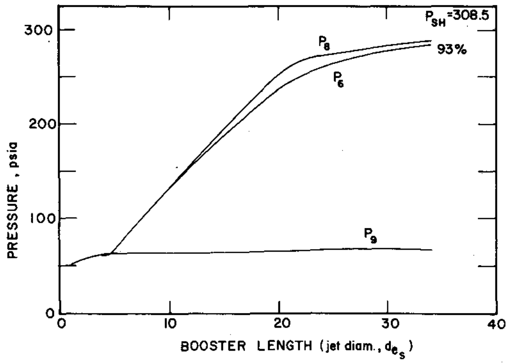

Fig. 5 Static pressures vs booster cavity length, configuration 1, $P_s = 1500$ psia, booster nozzle attached.

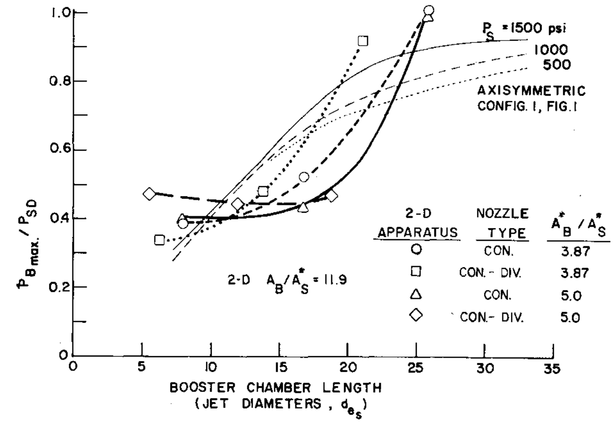

Fig. 6 Variation of booster cavity pressure with booster length.

cavity fully extended F_{TH} was calculated using the shock-down pressure and the booster nozzle exhausting to atmospheric conditions. The maximum possible theoretical thrust (F_{max}) was calculated using the sustainer stagnation pressure and assuming isentropic expansion from the sustainer nozzle throat to the booster nozzle exit diameter and ambient back pressure. For this calculation it also was assumed that no flow separation occurred in the booster nozzle.

Wall pressure variations with booster cavity length are presented in Fig. 5 for configuration 1.

Only minor variations occurred between the pressures along the booster cavity wall. For this reason only data for P_6 are presented. Pressure tap P_9 (Fig. 1) was located in the diverging section of the booster nozzle at an area ratio of 1.237. The overall area ratio was 1.362. Pressure tap P_8 was located on the booster nozzle plate.

The differences between the sustainer and booster theoretical thrusts were small (3-13%) for this configuration and resulted in very minor variations in thrust with booster cavity length. However, at no time did thrust increase dramatically to approach the maximum theoretically possible thrust. Thus, the sustainer exhaust jet never remained supersonic and never attached smoothly to the booster nozzle contour.

Wall static pressure approached the shock-down stagnation pressure (85-93%) for long cavity lengths ($>20d_{e_s}$) and decreased with decreasing cavity length. For lengths less than approximately 18-20 sustainer exhaust diameters pressure decreased rapidly. However, booster nozzle static pressure (P_9) remained essentially constant. This indicated that an approximately constant stagnation pressure was provided to the booster nozzle and is in agreement with the observed constant thrust. The large booster contraction ratio ensured that if the cavity flowed full, then the wall static and the stagnation pressures would be nearly identical. A stagnation pressure of 285 psia corresponds to the recorded value of P_9 in the exhaust nozzle for long booster lengths (Fig. 5). This value is in agreement with the value of 287 psia for P_8. Some jet penetration of the booster nozzle throat (i.e., if the booster cavity did not flow full) for the longest lengths could result in the observed differences between P_8 and the theoretical shock-down pressure. In any case, the high values of P_6 and P_8 indicated that the sustainer exhaust jet always shocked down to subsonic flow in the booster cavity.

Figure 6 presents the fraction of shock-down pressure obtained at the outer wall as a function of booster cavity length. It will be assumed that 1) when P_6 (or P_8) $\approx P_{SD}$ the expanding jet had reached the booster cavity wall and 2) when P_6 began to decrease rapidly, the core of the jet began to penetrate the booster nozzle throat (for configuration 1 the latter occurred for $P_6 \approx 0.7P_{SD}$ and lengths of 16-20 sustainer exhaust diameters, or 4.4-5.5 in.). When the jet clears the booster nozzle entirely it will pump the booster cavity to its minimum pressure. With these assumptions Fig. 6 implies that the jet may have spread in an approximately linear manner independent of sustainer pressure (since pressure ratio remained fixed) to lengths of approximately 18 exhaust diameters. After 18 diameters of length the jet spread more slowly and approached a maximum diameter asymptotically. In the latter stages, the jet spreading was slower for lower sustainer nozzle stagnation pressures.

Although the small difference between sustainer and booster theoretical thrust prohibited observation of marked

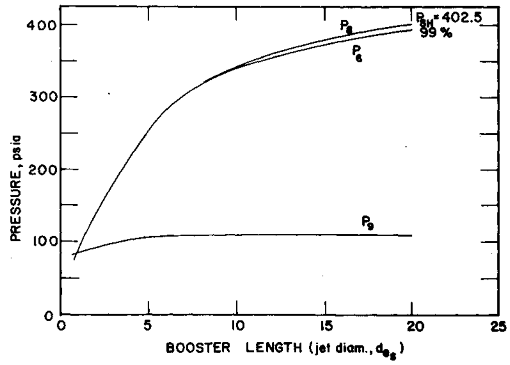

Fig. 7 Static pressure vs booster cavity length, configuration 2, $P_s = 1500$ psia, booster nozzle attached.

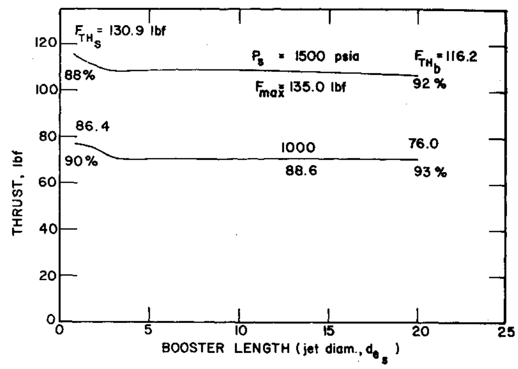

Fig. 8 Thrust vs booster cavity length, configuration 2, booster nozzle attached.

variations in thrust with booster cavity length some variations were observed for very short lengths. Figure 5 shows that booster nozzle static pressure (P_9) decreased more rapidly for lengths less than approximately five sustainer exhaust diameters, indicating that the jet most probably penetrated the booster nozzle without wall contact for these very short cavity lengths.

Configuration 2 operated in an extremely overexpanded condition. The behavior (Fig. 7) was similar to that obtained with configuration 1. However, sustainer jet shock-down apparently occurred more rapidly for the overexpanded conditions, allowing the jet to spread to the cavity wall and the resulting booster cavity wall static pressures to reach shock-down stagnation values for maximum booster lengths. In this case the exhaust jet was much larger and more nearly equal in diameter to that of the booster throat. Seventy percent shock-down occurred at approximately six exhaust jet diameters (or 2.8 in.) and the subsonically expanding jet apparently reached the booster wall. Configuration 2 also exhibited a noticeable thrust increase (Fig. 8) for booster lengths less than approximately 3.5 exhaust jet diameters (1.6 in.), apparently when the sustainer exhaust jet began to clear the booster throat completely.

Configuration 3 was designed for optimum sustainer jet expansion to the shock-down pressure but actually operated in an underexpanded mode due to the lower booster cavity pressures which were obtained. The jet core penetrated the large booster nozzle at the maximum lengths obtainable with the apparatus. The jet apparently cleared the booster nozzle for lengths shorter than approximately seven jet diameters (3.3 in.).

The above results indicate that without specifically designing the area ratios and lengths (as discussed below) the dual-chamber configuration will operate in a completely shock-downed manner except for very short booster lengths.

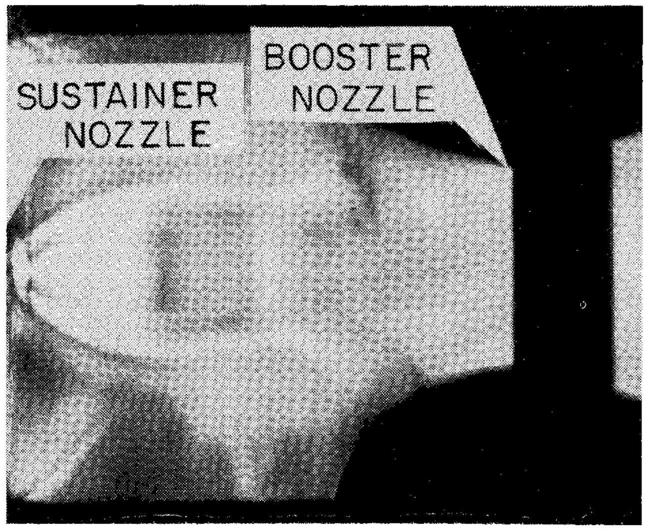

Fig. 9 Schlieren photograph, converging sustainer nozzle, $L_b = 8d_{e_s}$, $P_s = 195$ psia, $A_B^*/A_s^* = 5.0$.

Thrust variation with length does not appear to be of major significance. The behavior for the shorter lengths, where the jet clears the booster exhaust nozzle, may be of significance in the design/operation of integral rocket-ramjets, which use very short coupled ramjet combustors. Jet spreading to the booster cavity wall (as occurred with configuration 2) may present significant heat-transfer problems.

Booster Nozzle Attached-Schlieren Observations

Fourteen tests were conducted in this portion of the investigation. Figure 6 presents the fraction of shock-down pressure obtained in the booster cavity as a function of booster cavity length expressed in sustainer nozzle exit heights. Also shown are the data obtained with configuration 1 of the axisymmetric apparatus, which was the closest in operating conditions to the two-dimensional schlieren tests. The schlieren pictures (for example, Figs. 9 and 10) showed that the length required for the sustainer exhaust jet to shock-down to subsonic flow was 8-11 nozzle exhaust diameters for all tests conducted. This result was the same as that obtained for axisymmetric flow. The jet began to penetrate the booster throat for booster cavity lengths less than approximately 17 sustainer nozzle exit diameters (16-20 for axisymmetric flow, Fig. 6). When jet penetration of the booster throat occurred the booster cavity wall static pressures were pumped down in a manner similar to that obtained for axisymmetric flow. When the booster cavity length was sufficient to prevent jet penetration of the booster throat a normal two-dimensional jet behavior occurred, i.e., the jet would "flip" to one side and oscillate slightly in position with time. When the jet behaved in this manner booster cavity wall static pressure reached the shock-down pressure near the end of the chamber (Fig. 6). The core of the expanding subsonic portion of the jet never reached the booster cavity wall (except when the whole jet flipped to one side) for the lengths investigated.

Booster Nozzle Removed

With the booster nozzle removed, configuration 1 provided an extremely underexpanded sustainer exhaust flow. The difference of 10 lbf between the theoretical thrust and the measured thrust in the full-forward position (no booster cavity) was attributed to drag on the thrust apparatus (Fig. 11). As the booster cavity length was increased thrust dropped slowly until 18 exhaust diameters, where it decreased rapidly with length to a minimum of 28.6 lbf. This drop in thrust was directly attributable to less than atmospheric pressures within the booster cavity for lengths greater than 16 exhaust

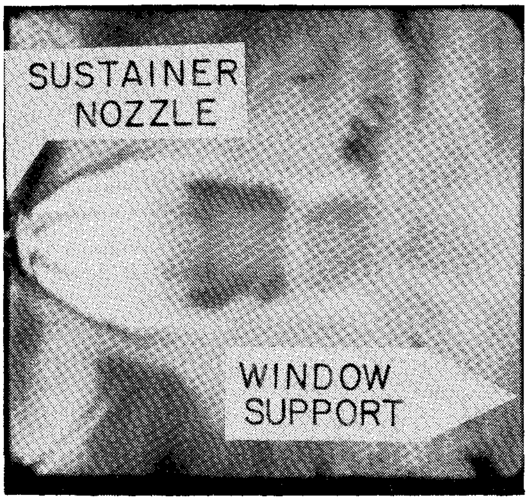

Fig. 10 Schlieren photograph, converging sustainer nozzle, $L_b = 17\ d_{e_s}$, $P_s = 195$ psia, $A_B^*/A_s^* = 5.0$.

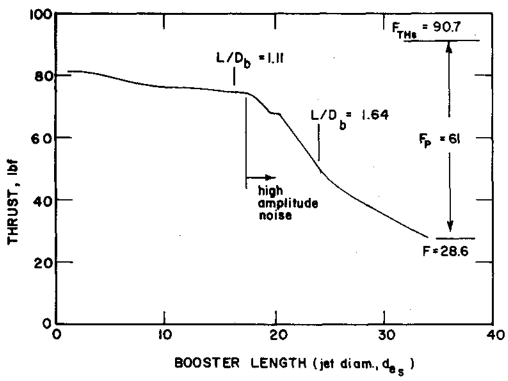

Fig. 11 Thrust vs booster cavity length, configuration 1, $P_s = 1500$ psia, booster nozzle detached.

diameters (Fig. 12, $L/_{D_b} = 1.11$ corresponds to $16d_{e_s}$). At the full-aft position, pressure on the forward booster wall was approximately 10 psia. This resulted in a negative thrust of 61 lbf and was approximately equal to the difference between theoretical and measured thrusts.

A large thrust variation would occur with altitude if the aft nozzle was ejected. The altitude performance would be improved significantly over the "nozzle-on" performance, but this wide variation in thrust may not be acceptable for tactical missiles. It is worth noting that the rapid thrust decay (Fig. 11) began at a length of approximately 18 exhaust diameters. Large high-frequency oscillations in thrust also occurred for lengths greater than 18 exhaust diameters. The top curve in Fig. 12 also shows that atmospheric pressure existed in the cavity for shorter lengths. Apparently the jet expanded to the wall at this location. Interestingly, this was approximately the same length at which jet pumping began with the booster nozzle attached.

Supersonic Flow in the Booster Cavity

The primary purpose of this portion of the study was to determine the effects of the sustainer and booster nozzle geometries on the maintenance of supersonic flow within the booster cavity. No attempt was made in this initial study to examine a wide range of booster/sustainer throat area ratios or booster cavity length/diameter ratios. The specific area ratios and flow rates selected were chosen to be as near a "practical design" as posible within the airflow rate/pressure

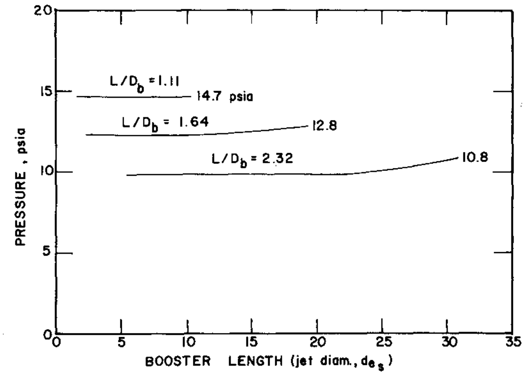

Fig. 12 Static pressure vs booster cavity length, configuration 2, $P_s = 1500$ psia, booster nozzle detached.

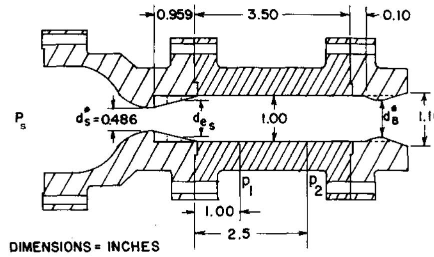

Fig. 13 Schematic of dual-chamber motor—supersonic flow in booster cavity.

limitations of an existing blow-down air supply system. Both axisymmetric and two-dimensional schlieren tests were conducted.

The booster/sustainer nozzle throat area ratio required to maintain supersonic flow in the booster cavity depends upon the sustainer nozzle area ratio and the stagnation pressure losses (shocks, wall friction, etc.) throughout the apparatus. In addition, sufficiently low ambient pressure (or sufficiently high sustainer pressure) must be present. The minimum area ratio requirements are readily calculated.[6] Increasing losses (oblique shocks, longer booster cavity, etc.) would increase the required area ratios. In an actual dual-chamber design, A_B^*/A_s^* would be dictated primarily by motor operating requirements (thrust ratios, etc.) and available propellant ballistic properties. In this investigation only airflow was utilized. For actual propellant exhaust products (γ closer to 1.2) and a specified sustainer throat diameter, larger booster cavity and booster throat diameters are required. This also results in a larger required booster nozzle contraction ratio. Thus, actual motor designs would have more favorable geometry for high propellant loading than those required in this investigation, which used airflow.

In order to reduce the axisymmetric booster cavity Mach number to 3.0, its diameter was reduced to 1.0 in. This reduction was required in order to be able to "start" and maintain supersonic flow within the booster cavity while remaining within the flow rate limitations (i.e., $p_B^* > p_a$ and $p_{e_B} > 0.5p_a$). Figure 13 is a schematic of the apparatus. A 15 deg half-angle cone was installed to allow the sustainer nozzle flow to expand smoothly to the booster cavity diameter. This nozzle was truncated for subsequent tests until only a converging nozzle remained. Table 2 summarizes the geometric variations and test conditions employed for each configuration investigated. Configuration 1 had the theoretically required[6] area ratios. The booster throat area was increased 13% for configurations 2-5 and 39% for configuration 6.

Table 2 Test conditions for supersonic flow in axisymmetric booster cavity

Configuration	d_B^*, in.	d_s^*, in.	d_{e_s} in.	A_B^*/A_s^*	$(A_e/A^*)_B$	$(A_e/A^*)_s$	A_{e_B}/A_s^*	p_{e_B}/P_s	$(p_e/P_s)_B$	P_s, psia
1	0.848	0.486	1.00	3.045	1.683	4.234	5.123	0.0202	0.1285	305,487
2	0.90	0.486	1.00	3.429	1.494	4.234	5.123	0.0202	0.1615	495,585
3	0.90	0.486	0.872	3.429	1.494	3.219	5.123	0.0202	0.1615	302,410, 486,619, 708
4	0.90	0.486	0.667	3.429	1.494	1.884	5.123	0.0202	0.1615	328,407, 506,606, 711
5	0.90	0.486	0.486	3.429	1.494	1.00	5.123	0.0202	0.1615	299,390, 499,615, 711
6	1.00	0.486	0.486	4.234	1.210	1.00	5.123	0.0202	0.2542	197,297, 392,493, 578,685

$$F_{SD} = \lambda C_{F_{SD}} P_{SD} A_B^* = \lambda C_{F_{SD}} \left(\frac{A_S^*}{A_B^*}\right) P_s A_B^*$$

$$F_{SS} = C_F P_s A_S^*$$

$$C_{F_{SD}} = C_{F_{SD}} \left[\gamma, \left(\frac{p_e}{P}\right)_B, \left(\frac{A_e}{A^*}\right)_B\right]$$

$$C_F = C_F \left(\gamma, \frac{p_{eB}}{P_s}, \frac{A_e}{A_s^*}\right)$$

Table 3 Configurations 2-5 (see Fig. 14)

Configuration (see Fig. 14)		d_{e_s}, in.	P_s, psia	F, lbf	p_1, psia	p_2, psia	Theoretical $p_{B_{SS}}$, psia	P_{SD}, psia
2	○	1.00	495	127	13.5	20.2	13.5	144.3
			585	153	15.9	23.9	15.9	170.6
3	△	0.872	302	72	9.0	12.8	8.2	88.1
			410	99	11.8	15.8	11.2	119.6
			486	125	14.2	20.6	13.2	141.7
			619	158	16.7	25.3	16.9	180.5
			708	181	20.2	30.0	19.3	206.5
4	□	0.667	328	73	10.4	13.6	9.0	95.6
			407	94	12.8	16.9	11.1	118.7
			506	121	15.9	21.0	13.8	147.5
			606	146	18.9	25.0	16.5	176.7
			711	172	22.1	29.2	19.4	207.3
5	◇	0.486	299	63	65.9	70.2	8.2	87.2
			390	83	84.8	90.2	10.6	113.7
			499	111	108.5	115.2	13.6	145.5
			615	140	133.9	142.2	16.8	179.3
			711	165	153.3	165.6	19.4	207.3

Figure 14 presents measured thrust as a function of sustainer pressure for configurations 2-5 with axisymmetric flow (Table 2). Also shown on the figure are the theoretical values for 1) thrust with full supsersonic flow and with shock-down, 2) booster cavity shock-down pressure (P_{SD}), and 3) booster cavity pressure for full supersonic flow with no losses ($P_{B_{SS}}$). Measured values of booster cavity pressure (p_1 and p_2, Fig. 13) are also presented.

As the sustainer nozzle was truncated in increments the booster cavity flow transitioned from nearly shock-free supersonic flow to a full shock-down behavior.

As the sustainer nozzle was truncated the shocks increased in strength, increasing the booster cavity static pressure and reducing the thrust. Configuration 4 apparently maintained supersonic flow (low p_1 and p_2) in the booster cavity, but the shock losses reduced the thrust to near theoretical shock-down values. When the sustainer nozzle was convergent, full shock-down conditions apparently were obtained. In this case the shock losses were apparently too great to allow "starting" of the flow through the booster throat.

For configuration 6, the booster throat area was again increased (39% greater than theoretical and 23% greater than configurations 2-5) to allow for "starting" with the larger shock losses obtained with the converging sustainer nozzle. Supersonic flow was again attained in the booster cavity, although with losses large enough to reduce the thrust significantly.

The thrust obtained with $P_s = 600$ psia and $A_B{}^*$ 13% larger than theoretical is shown in Fig. 15 as a function of sustainer nozzle area ratio. Data from the previous figures have been used by "correcting" the "near 600 psia" runs to 600 psia.

These results indicate that full supersonic flow can be obtained in the booster cavity of the dual-chamber rocket configuration. Maximizing the obtainable thrust required increasing the area ratio (and therefore weight) of the sustainer nozzle. With a converging sustainer nozzle, supersonic flow can be maintained and thrust increased above shock-down values. However, the booster throat area required becomes quite large. A nozzleless booster would probably be required in this case.

The configurations tested in this study were of limited scope. It should be noted that shock-down dual-chamber configurations that have been tested to date[7] have employed $A_B{}^*/A_s{}^*$ values only slightly greater than those used in

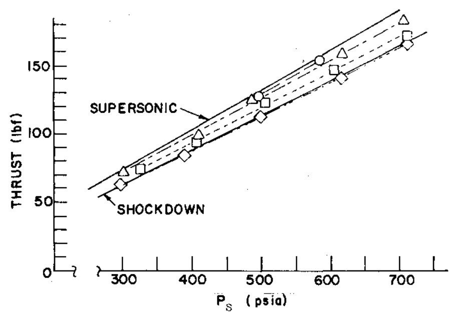

Fig. 14 Thrust obtained with sustainer nozzle truncation.

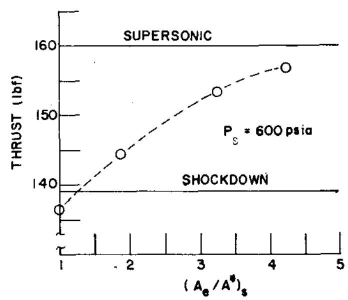

Fig. 15 Thrust variations with sustainer nozzle area ratios.

configuration 6 (Table 2). However, much longer and larger diameter booster cavities have been employed in the actual motors. The larger diameter would result in slightly higher booster cavity Mach numbers (approximately 4.5 with $\gamma = 1.2$) and the longer lengths would increase losses. These changes would require further increases in the booster nozzle throat area above that theoretically required. Shock impingement on the booster cavity wall also may require local increases in insulation material. However, a nozzleless booster cavity with a Mach number of approximately 3.5 would allow $A_B/A_s{}^*$ to be as large as approximately 21 ($\gamma = 1.2$) and would have a theoretical booster cavity pressure of 8.5 psia (with $P_s = 1500$ psia). Shock and friction losses would increase this pressure somewhat, providing a reasonable exhaust pressure at sea level for the supersonic flow.

Conclusions

1) Sustainer exhaust shock-down occurs within 8-11 jet diameters within the booster cavity, as it does in free-jet conditions.

2) Sustainer exhausts begin to penetrate the booster nozzle throat (for the geometries tested) for booster chamber lengths less than approximately 17 jet diameters, resulting in rapid decreases in booster cavity static pressure with decreasing cavity length, while thrust remains unaffected.

3) Sustainer exhaust jets will generally clear the booster throat for booster chamber lengths between 3 and 7 jet diameters.

4) Two-dimensional schlieren results generally confirmed the behavior found in the axisymmetric apparatus.

5) Sizing the booster nozzle throat slightly greater than theoretically required allows supersonic flow to be maintained within the booster cavity and results in significant gains in thrust over the shock-down behavior.

6) Sustainer exhaust nozzle truncation increases shock losses and reduces the obtainable thrust, but supersonic flow can be maintained with a converging sustainer nozzle.

7) Practical designs appear feasible for an actual motor in which supersonic flow is maintained within the booster cavity. Nozzleless boosters would enhance the obtainable performance gains.

Acknowlegment

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