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DEBRIS CONTROL DESIGN ACHIEVEMENTS OF THE BOOSTER SEPARATION MOTORS

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ABSTRACT

The stringent debris control requirements imposed on the design of the Space Shuttle booster separation motor are described along with the verification program implemented to ensure compliance with debris control objectives. The principal areas emphasized in the design and development of the Booster Separation Motor (BSM) relative to debris control were the propellant formulation and nozzle closures which protect the motors from aerodynamic heating and moisture. A description of the motor design requirements, the propellant formulation and verification program, and the nozzle closures design and verification are presented.

INTRODUCTION

The Space Shuttle solid rocket booster separation system is designed to ensure safe separation of each of the Solid Rocket Boosters (SRBs) from the External Tank (ET) without damaging or recontacting the Shuttle Orbiter/ET during or after separation. Eight solid BSMs, four mounted in the SRB nose frustrum and four mounted externally on the aft skirt (Fig. 1), provide the impulse and momentum required to move each SRB radially outward from the ET. As the SRBs move outward from the ET, the slightly downward thrust vector of the SSME (Fig. 2) causes the orbiter to be exposed to the exhaust plume of the forward BSMs.

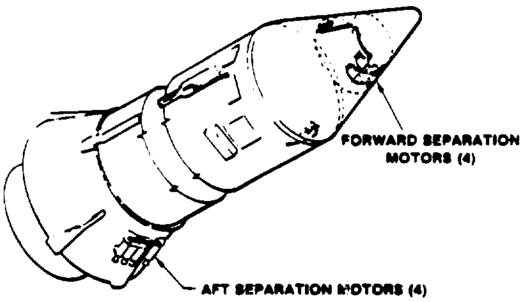

Figure 1. BSM Locations.

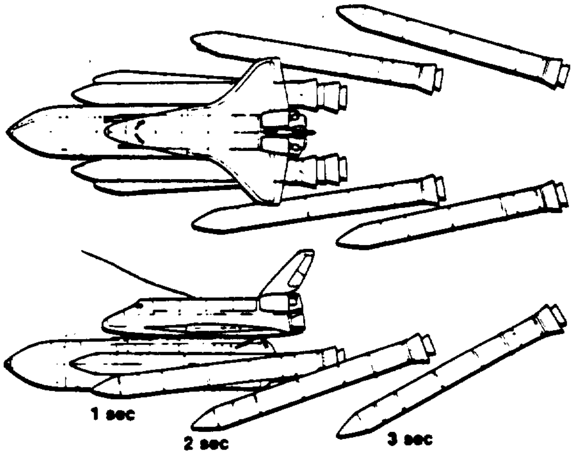

Figure 2. Computer Simulation of SRB Separation Sequence.

SRB separation nominally occurs at a flight time of 124 sec, an altitude of approximately 140,000 ft, and a mach number of 4.5. The initial conditions for separation (dynamic pressure, angle of attack, sideslip angle, and body angular rates) will be different for each flight depending on ascent winds, atmospheric conditions, SRB thrust tailoff mismatch, flight control system status, and SSME operating status. A set of design initial conditions was defined which reflected a composite of nominal and malfunction flight conditions and provided the basis for sizing the system. The BSM thrust and total impulse requirements were derived from these design initial conditions (Table 1).

DESIGN DRIVERS FOR DEBRIS CONTROL

Plume exposure tests of Orbiter and ET Thermal Protection System (TPS) materials conducted at the Air Force Arnold Engineering Development Center indicated that even short-term exposure of these

TABLE 1. BSM PERFORMANCE AND DESIGN REQUIREMENTS

o PERFORMANCE	
Thrust level (max), lbf	29,000
Web action time average thrust (min), lbf	18,500
Web action time impulse (min), lb-sec	14,000
Action time impulse (min), lb-sec	15,000
Web action time (max), sec	0.8
Ignition interval to 75% max thrust, msec	30 to 100
Time to thrust equal to or greater than web action average thrust (max), msec	200
Time from end of web action time (EWAT) to 50% of pressure at EWAT, msec	100
Maximum pressure at EWAT, psi	2,000
Propellant bulk temperature, °F	30 to 120
o DESIGN	
Weight (max), lb	154
Length (max), in.	34.6
Diameter (max) in.	12.88
Nozzle cant angle, degrees	20
Propellant stability additives (max) %	2
Propellant burning rate additives (max) %	1

materials to the solid rocket motor exhaust plume resulted in extensive material damage. TPS materials exposed to exhaust plumes in a manner that simulated the anticipated flight conditions relative to separation distance and exposure time experienced rather significant erosion and particle debris damage. The Orbiter insulation, consisting of rigidized silica fiber felt with a thin borosilicate glass coating, is designed for multiple reuses, and replacement of the TPS tiles is a costly process. Aluminum oxide particles and debris from sources such as igniter tape, igniter propellant, and nozzle materials eroded and fractured the TPS coating to the extent that similar erosion during flight would require replacement of the TPS.

The sensitivity of the Orbiter/ET TPS to exhaust plume debris resulted in relocation of the BSMs on the SRB and a reduced motor burning time requirement. The forward BSMs were moved from the SRB forward skirts to the nose frustum and oriented as shown in Figure 3. This location and orientation, combined with a maximum burning time requirement of 0.8 sec, minimizes exposure of the TPS to the plume during normal separation conditions. In a similar manner, the aft BSMs were moved to the SRB aft skirt and the nozzle canted 20 deg to eliminate plume impingement on lower surfaces of the Orbiter. Since the TPS can be exposed to the motor exhaust plumes for short periods in off-nominal or abort separations, additional design constraints were imposed on the BSM to minimize the amount of damage.

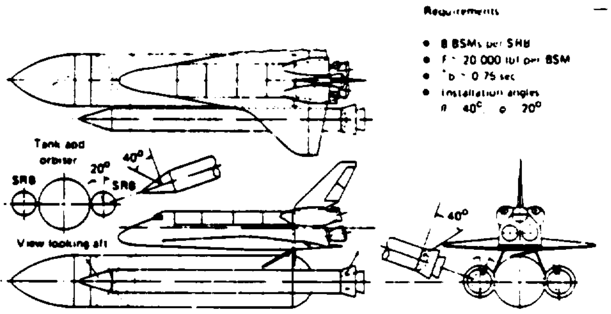

Figure 3. Shuttle Separation System.

PERFORMANCE AND DESIGN CONSTRAINTS

The BSM performance requirements reflect an emphasis on control of exhaust debris. The requirements that motor burning time shall not exceed 0.8 sec and that tailoff pressure shall decay to 50% within 100 msec were established to terminate the motor burning time and collapse the exhaust plume before the Orbiter could intersect the motor plume boundary. In addition, the contoured nozzle is designed to minimize the expansion of the gaseous and particulate plume at EWAT and during tailoff.

Control of exhaust debris is reflected in the design requirements for the igniter, nozzle, nozzle closures, and propellant. The nozzle and igniter were designed to preclude the generation of debris thus limiting the types of materials and coatings that could be used. Propellant particulate debris is controlled by limiting the amount of burning rate and stability additives to 1 and 2%, respectively. A similar constraint is imposed on the igniter propellant. Additionally, the igniter design was modified to eliminate the ejection of unburned igniter and boost charge particulates. The igniter design features a booster charge retainer with mylar sheet to contain the charge during handling and shipping and a radially perforated igniter case to ensure complete burning of the booster charge and igniter propellants before exiting the nozzle.

PROPELLANT FORMULATION

The selection of 1% and 2% limitations on the burn rate and stability additives represented a compromise between minimizing particulate debris and ensuring adequate combustion stability margin. Rigorous combustion stability requirements were imposed on the motor design and the development program to ensure stable operation of the motor. Two propellant formulations were selected for initial development testing, the baseline propellant containing 2% aluminum powder and an alternate containing a mix of aluminum and alumina. The baseline propellant selected for the BSM is an 86% solids/2% aluminum HTPB propellant with formulation and key properties as shown in Table 2.

TABLE 2. UTP - 19,048 BSM PROPELLANT

o FORMULATION	
Hydroxy-terminated polybutadiene binder, %	14.0
Iron oxide catalyst, %	0.25
Aluminum powder, %	2.00
Ammonium perchlorate, %	83.75
o PROPERTIES	
Theoretical specific impulse, sec	250
Theoretical density, lb/in.^{3}	0.0614
Burning rate at 1500 psia/70°F, in./sec	0.8
Pressure exponent	0.45
Tensile strength at 70°F, psi	200
Elongation at 70°F, %	40
End of mix viscosity (140°F), kps	5
Pot-life, hr	20
Autoignition temperature, °F	
10 sec	685
30 sec	570
60 min	420

Combustion stability was a major consideration in the design of the BSM since propellants with low solid particles in the exhaust tend to produce chamber pressure oscillations. The evaluation of combustion stability included (1) a preliminary stability evaluation based on an analysis of interactions between combustion and flowfield and (2) pulse tests in prototype and development motors to determine experimentally the stability of the motor. The stability of pressure disturbances of small amplitude is balanced between the combustion processes that supply energy to the disturbance and other processes that remove energy (i.e., nozzle, flow turning, and particulate damping). The evaluation of the mechanisms contributing to motor stability were evaluated using a combination of analytical techniques for particle and nozzle losses and flow turning and experimental data for pressure coupled response using T-burner results. The T-burner characterization program was conducted using the baseline propellant formulation. The tests were run at 1350 psia using the pulse-variable area method which had been used extensively for testing highly aluminized propellants. Cylindrical grains were used with area ratio variations from 2.67 to 6.67 and frequency variations from 480 to 900 hz. One series of tests was conducted with the grains preheated to approximately 130°F. The test results revealed a low response function for combustion driving indicating a reduced susceptibility towards instability in the motor.

The uncertainties involved in completely defining and characterizing the mechanisms effecting motor stability necessitated full-scale motor pulse tests. Four prototype and several development motors were pulsed at a 5% overpressure at 200 and 400 msec after ignition to demonstrate stability throughout web burn time. The results of these tests, which revealed a highly damped response to the overpressure, verified the stability of the propellant-motor combination over a wide frequency range in both the axial and transverse modes.

NOZZLE ENVIRONMENTAL COVER

The BSMs have their nozzle exit cones exposed to the atmospheric elements that exist at the Kennedy Space facility as well as the environments of launch. In order to preclude the ability of these environments from affecting the condition of components within the motor (such as, the propellant grain and igniter) it was necessary to provide a nozzle closure. This closure had to satisfy the following basic requirements:

1. Provide a humidity seal for the motor for a time period of 6 months on the launch pad.
2. Be hermetic (no leaks) when the closure is subjected to a differential pressure of 4 psi.
3. Protect the BSMs from all launch and ascent thermal and acoustic environments.
4. Open completely during the ignition transient time.
5. Do not produce any debris during ascent, separation, or booster re-entry that could possibly impact the Shuttle Orbiter.

The latter requirement is particularly challenging for the nozzle closure of the BSMs mounted within the nose cone of the Solid Rocket Boosters (SRBs). The location of the forward and aft mounted BSMs is shown in Figure 1. From Figure 2 it can be seen that the SRB nose cones are mounted forward of the Orbiter. Also, in order to obtain the outward and downward movement of the SRBs relative to Orbiter, it is necessary for these forward BSMs to have their nozzles pointed upward and inward toward the Orbiter. This creates a significant problem in that any portion of the nozzle closure that might be ejected during booster separation could severely damage the Orbiter and potentially cause loss of the mission. Thus, a major requirement imposed on the forward BSMs is that the nozzle environmental closure not only seal the motor from outside elements, open almost instantaneously during motor ignition, but that upon opening the nozzle closure must remain attached to the BSM and not allow any solid ejecta. Figures 1 and 2 show that the aft mounted BSMs are located aft of the Orbiter with their nozzles directed aft of the Orbiter. Therefore, nozzle closure debris from these motors is acceptable since it poses no threat to the Orbiter.

FORWARD BSM NOZZLE CLOSURE

A debris-free nozzle closure posed a unique design problem. Many propulsion systems have nozzle closures but they are simply ejected upon motor ignition. Therefore, no data/experience base existed – upon which the BSM program could draw information. Numerous concepts were evaluated including various kevlar reinforced rubber closures that were configured to petal open and then slide forward to avoid ablation of the petals by the BSM exhaust plume. This system had promising features but introduced potential hermetic sealing problems, aeroheating concerns, and possible flight dynamics interactions that would be difficult to simulate in ground testing.

After further evaluation of potential approaches it was decided to design and test a rigid metal cover that could be made to hinge open during motor ignition as shown in Figure 4. Motor ignition was required to open the closure because this nozzle cover concept was retrofitted to the existing booster separation system and no additional ordnance devices were to be considered. The resulting primary design requirements for the forward mounted BSMs nozzle closure were:

1. Protect the BSM from ascent aeroheating (1600°R).
2. Induce no modifications or additions to the existing electrical or ordnance systems.
3. No solid ejecta can emanate from the closure during all phases of booster flight from launch through water impact.
4. Nozzle closure must survive the aerodynamic heating, acoustic, vibration, and shock environments of the booster from launch through water impact.
5. Nozzle closure must open solely from the impetus provided by motor ignition.
6. Nozzle closures cannot interfere with either the closures or exhaust plumes of adjacent BSMs (Fig. 5).

7. The hinged cover must open a minimum of 145° in order to avoid interference with the BSM exhaust plume (Fig. 6).
8. The hinged cover must open a maximum of 180° in order to avoid impacting the skin of the SRB nose fairing.

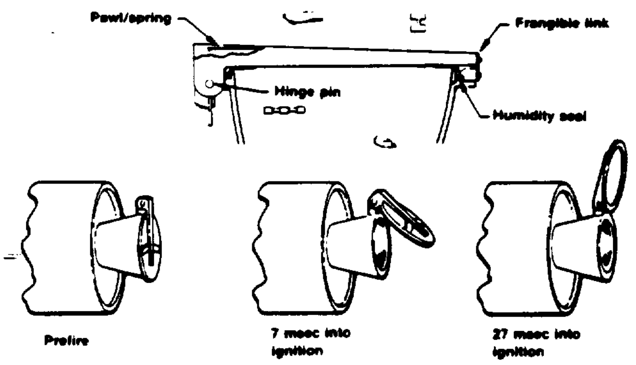

Figure 4. Basic Concept for Hinged Cover.

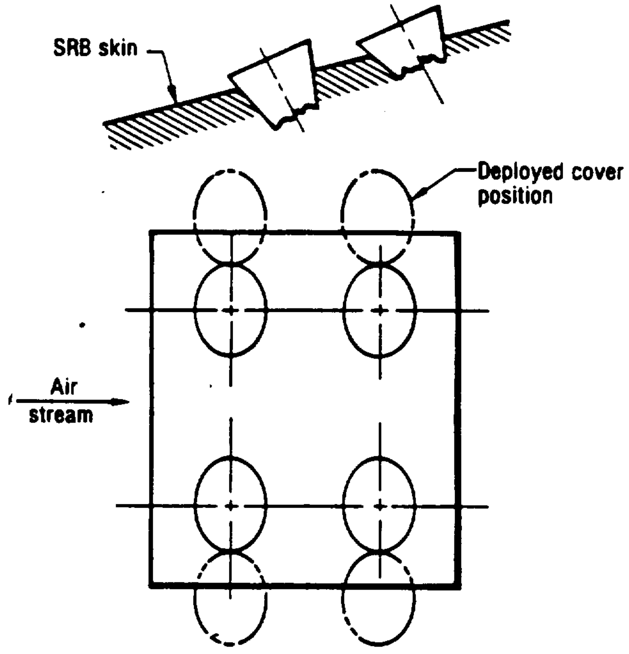

Figure 5. Forward BSM Nozzle Closure Relative Orientation.

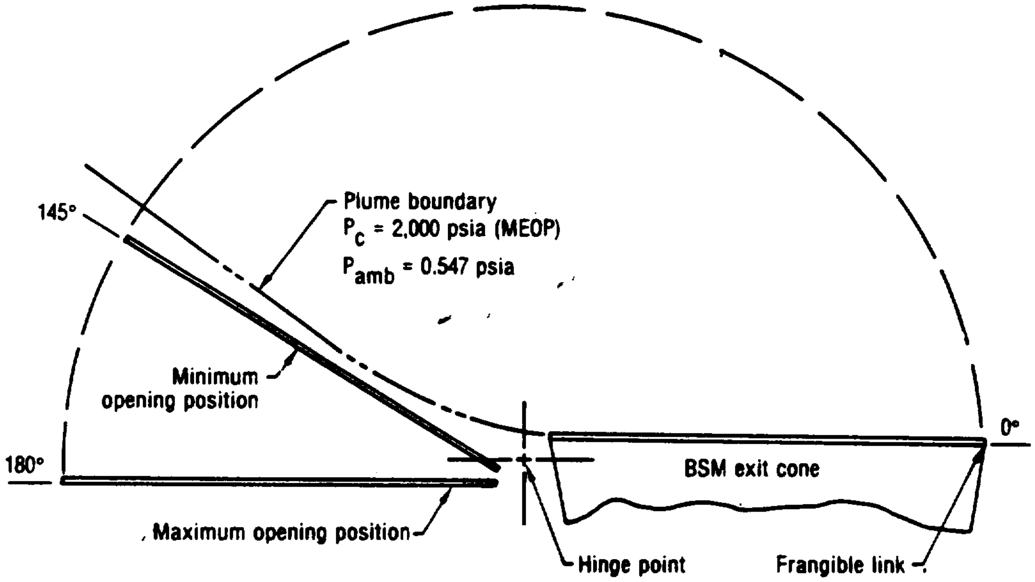

Figure 6. Forward BSM Nozzle Closure Allowable Opening Angles.

The primary design challenge for the hinged cover was to determine how the large amount of rotational energy could be absorbed in time to stop the cover between the angular position of 145 and 180 deg. Extensive study of the problem resulted in the use of a hinge-pin (axis of rotation) that would twist during cover rotation. This twisting action allowed absorption of a significant portion of the rotational energy. To absorb the remaining energy, a cantilevered secondary stop was incorporated which could accurately limit rotational travel to a maximum of 180 deg. To prevent springback to an angle less than 145 deg, a ratchet engagement device was used.

The metal hinged cover, shown in Figure 7, consists of a structurally reinforced disc supported at two points 180 deg apart. At one point, a hinge pin undergoes torsional plastic strain during operation. At the second point, 180 deg from the hinge pin, the disc is held closed by a stainless steel frangible link. At a given ignition pressure, the frangible link will break and the cover will swing open. During the opening process, the hinge pin will deform torsionally and absorb the accumulated rotational energy of the cover. At 151 deg the cover engages a locking ratchet, then finally comes to rest and locks at about 166 deg. At 155 deg the cover engages a deformable secondary stop (Fig. 8). Between 155 deg and 180 deg the cover energy is, therefore, being absorbed by both the torsion pin and the secondary stop.

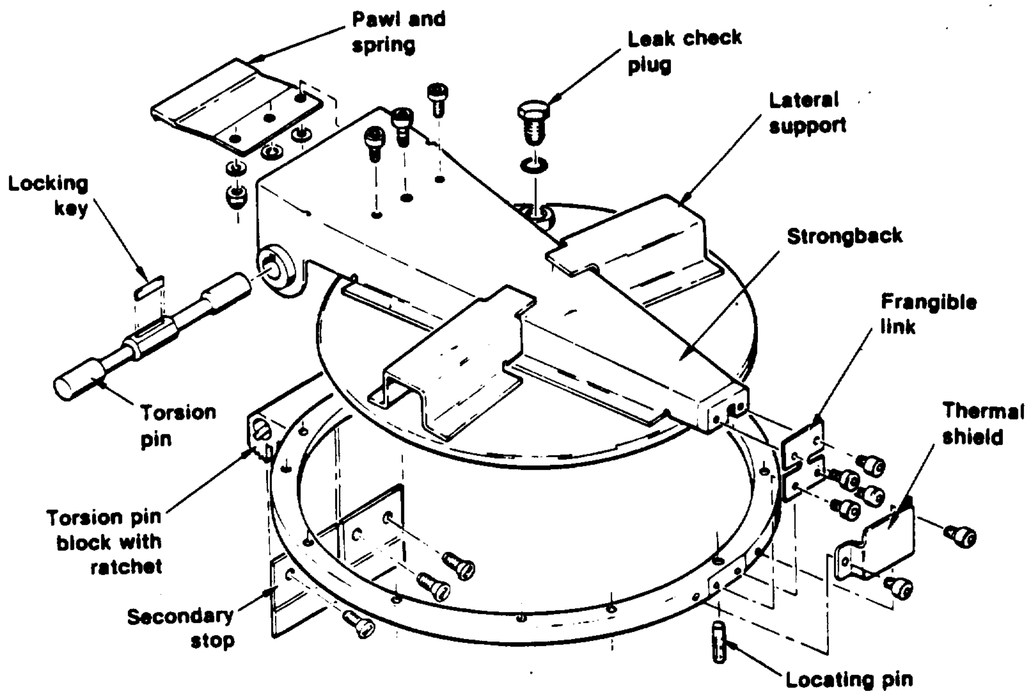

Figure 7. Exploded View of Forward BSM Nozzle Closure.

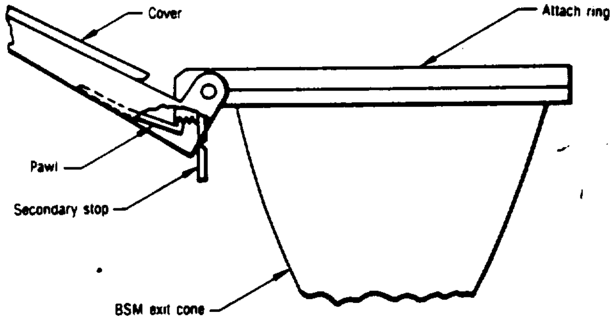

Figure 8. Open Cover Immediately Before Secondary Stop Engagement.

The cover plate is spin-formed from a flat sheet of 321 stainless steel. The strongback and lateral support structure, also 321 stainless steel, are spot welded to the cover plate. The subassembly is mated to the attachment ring by aligning the holes and the keyway in the stongback tabs to those in the torsion pin block, then inserting the torsion pin. After the cover is properly positioned, the torsion pin (304L stainless steel) is welded to the bosses on the strongback tabs. The frangible link is attached to the cover and the entire assembly is bolted to a flange on the exit cone. Figure 9 shows the cover assembled to the exit cone.

Major tasks for the hinged cover aeroheating shield were to demonstrate that the rotational energy given to the cover could be absorbed by the hinge pin via plastic torsional deformation without resultant fracture of the pin. Additional objectives were to demonstrate repeatable performance, large margins of safety, and zero debris during operation.

The frangible link was designed to fail during ignition. The torsion pin was sized to allow the cover to swing open to an angle greater than 145 deg (to clear the expanded plume) but less than 180 deg (to avoid impacting the SRB skin).

A series of component bench tests were performed to characterize the torsion pin and secondary stop energy absorption at the predicted high strain rates. A laboratory fixture was designed and built which could be preset to impart the required amount of torsional work to a flywheel simulating one-half

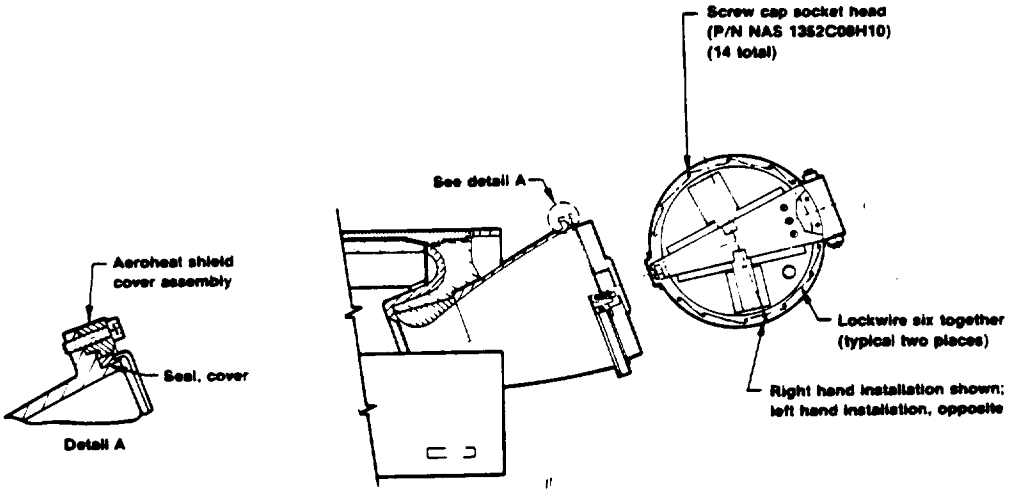

Figure 9. Hinged Cover Assembled to BSM Exit Cone.

of the mass properties of the hinged cover. The flywheel was restrained by a single torsion pin specimen simulating one-half of the hinged cover torsion pin and was set to contact a secondary stop specimen after approximately 145 deg rotation.

Twenty-five torsion pins and four secondary stop specimens were tested. The results demonstrated repeatable performance in that all the input energy was absorbed and the flywheel came to rest within the position range of 145 deg to 180 deg required for hinged cover operation. Twist angles of approximately 1,000 deg were required to fracture the torsion pin.

From the above results, component sizing data were generated to support a prototype hinged cover design. Three tests were conducted in which the hinged cover was assembled to an empty BSM motor case powered with only an igniter. The cover was tested also during two BSM motor firing tests. All tests were successful in that the cover opened to the predicted angles, no debris was ejected, and no physical degradation of hardware was observed.

Fifty-seven empty case tests and three motor firings were conducted on the hinged cover to evolve critical component dimensions, demonstrate repeatability, and verify large margins of safety. Vibration, structural, and leakage tests also were performed. The development tests and their objectives are given in Table 3.

TABLE 3. TEST OBJECTIVES SUMMARY

Test Category	Objective
Component sizing	Verify soundness of current design
	Establish dimensions for critical components
Repeatability	Demonstrate repeatable dynamic operation
Margin Test	Demonstrate survivability under all single point failure modes
Vibration	Verify cover remains intact under full ascent vibration spectrum
	Verify cover remains closed with frangible link omitted
	Verify cover remains intact and open during reentry
Structural	Verify integrity of ratchet pawl under simulated reentry loads
	Verify large margins in critical design areas
Leakage	Verify integrity of environment seal

Empty case tests consisted of a BSM, motor assembly with an igniter, and an epoxy filler to simulate propellant volume. It was determined that the same initiator system as would be used in flight was required to yield representative test results. Both Tabor and Kistler pressure transducers were used to provide the required frequency response. Pressure data were taken in the motor case and in the exit cone.

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The frangible link, torsion pin, and secondary stops were critical components requiring final design definition. Since these components were all functionally interrelated, many iterations were required for final sizing. To assist in this effort, NASA/MSFC-developed dynamics computer programs were used.

Initial hardware was sized from static test results, then incorporated into a cover assembly and tested. High speed photographic records were analyzed to determine the cover position versus time. These results were combined with the pressure data and the initial test conditions and input to a computer curve-fit program to determine the ratio of motor pressure to pressure against the cover (P/P_c) and the cover dynamics. The values of P/P_c, cover mass properties, and initial design/performance conditions were input to a dynamics program. The output of this program was compared to the observed dynamics of the cover and the value of the opening pressure was adjusted until predicted and actual test results agreed.

Component resizing is simulated by changing the initial design conditions and inputting these new values to the dynamics program. The output will determine the hardware dimensions for subsequent tests. Figures 10 and 11 show a typical cover (test 2-15) in the pretest and posttest conditions. In the test, the final opening angle was 168 deg.

Figure 10. Pretest Condition of Typical Hinged Cover Test.

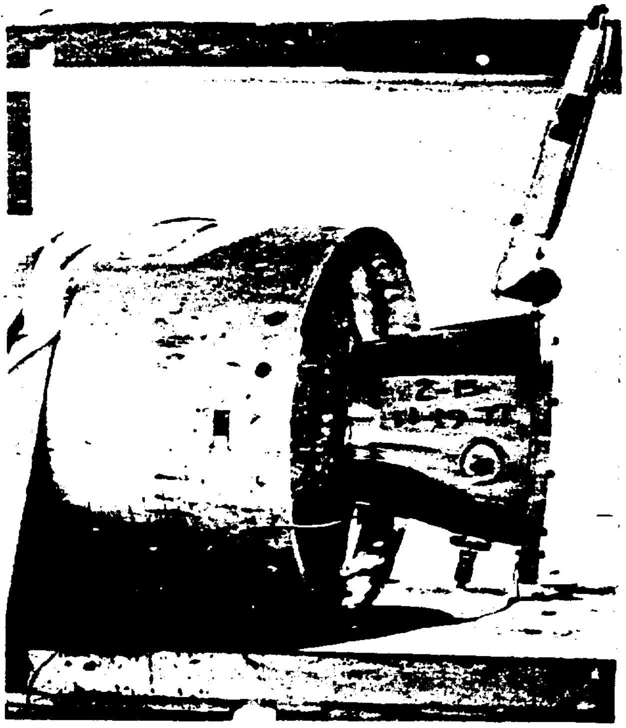

Figure 11. Post-Test Condition of Typical Hinged Cover Test.

A series of margin tests were conducted to verify that single point failure modes would not result in catastrophic failure. The results clearly demonstrated the cover's ability to survive under extreme test conditions. Vibration tests were conducted with the cover assembly attached to a BSM exit cone and successfully demonstrated large margins of safety. A series of structural tests were performed to verify large margins of safety during ascent and cover operation. Leakage tests with GN_2 verified the integrity of the environmental seal to 4 psi.

The design shown in Figure 7 has been incorporated into all flight BSM systems. To date, six Shuttle launches have been completed. All BSMs have performed as designed. Figure 12 shows the hinged cover properly intact after the recovery of one of these flights.

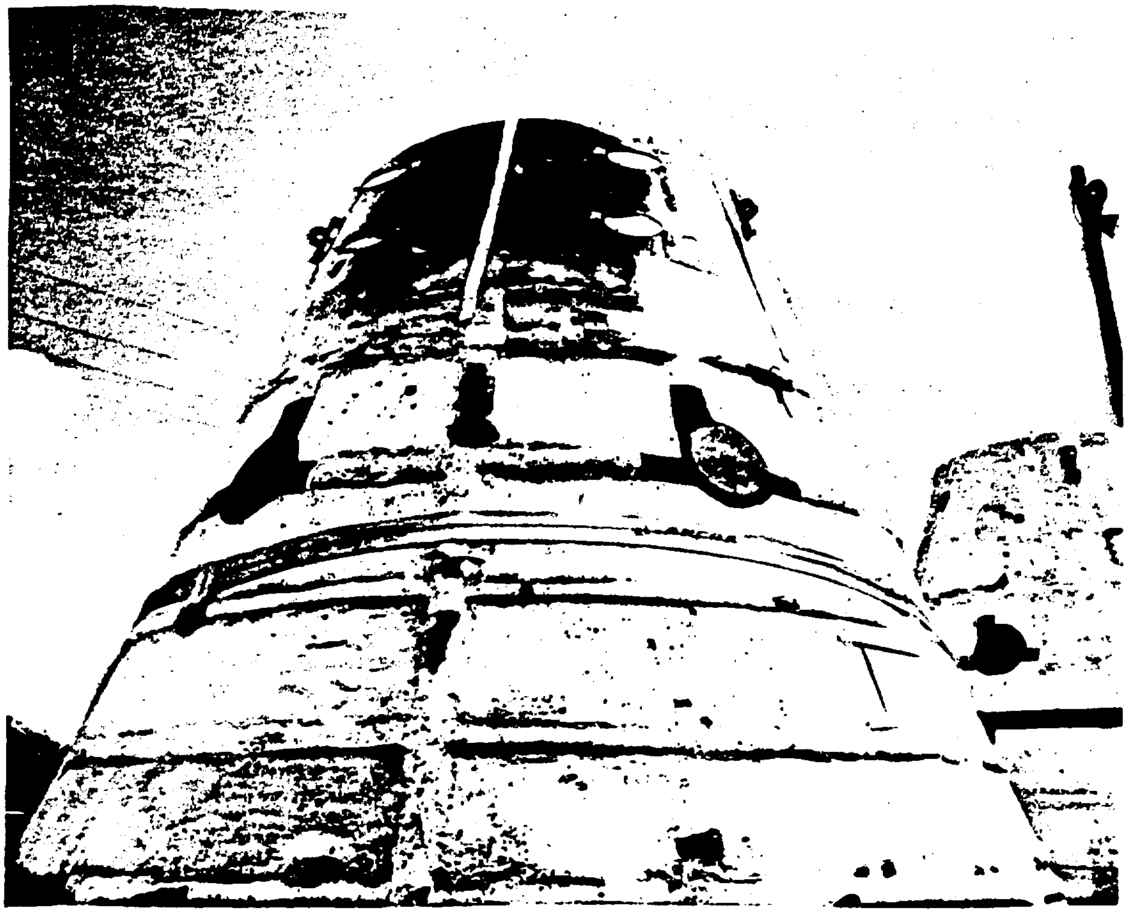

Figure 12. BSM Hinged Covers on Nose Cone of Recovered Shuttle Booster After Flight.

AFT BSMs NOZZLE CLOSURE

As previously mentioned, the aft mounted BSMs do not have a nozzle cover debris requirement since their nozzles are directed away from the direction of the Orbiter. The design of this cover simply involves clamping an 1100 series aluminum disc over the end of the nozzle. The disc has a circumferential notch to provide a clean rupture. The design is shown in Figure 13. Figures 14 and 15 show this closure pretest and posttest. All tests were successful and the design has been incorporated for flight. Figure 16 shows the aft mounted BSMs with their covers clearly ejected after ignition in flight on board the Shuttle SRBs.

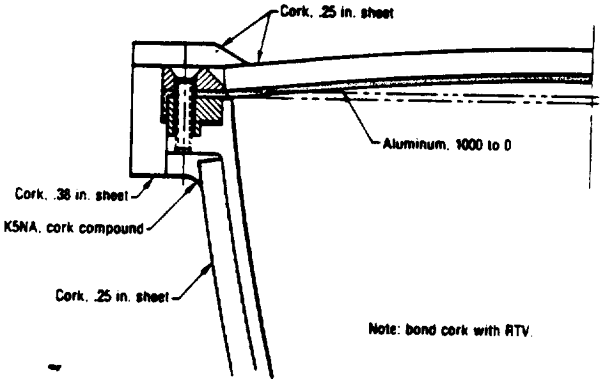

Figure 13. Aft Mounted BSM Nozzle Closure Configuration (After Proof Test).

Figure 14. Aft Mounted BSM Nozzle Closure - Pretest.

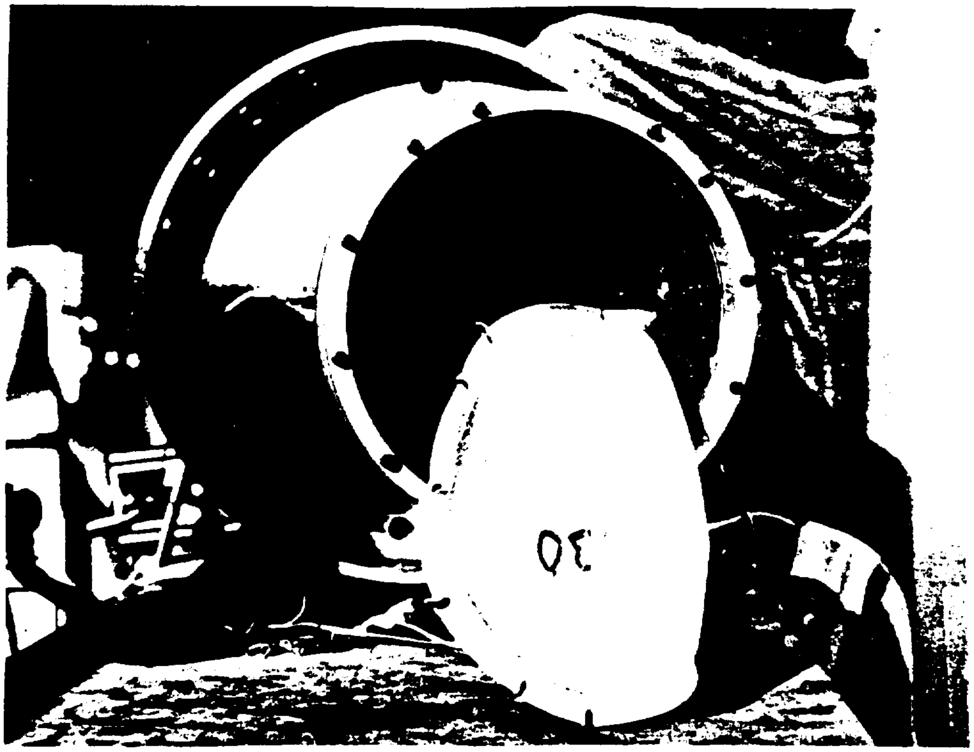

Figure 15. Aft Mounted BSM Nozzle Closure - Post-Test.

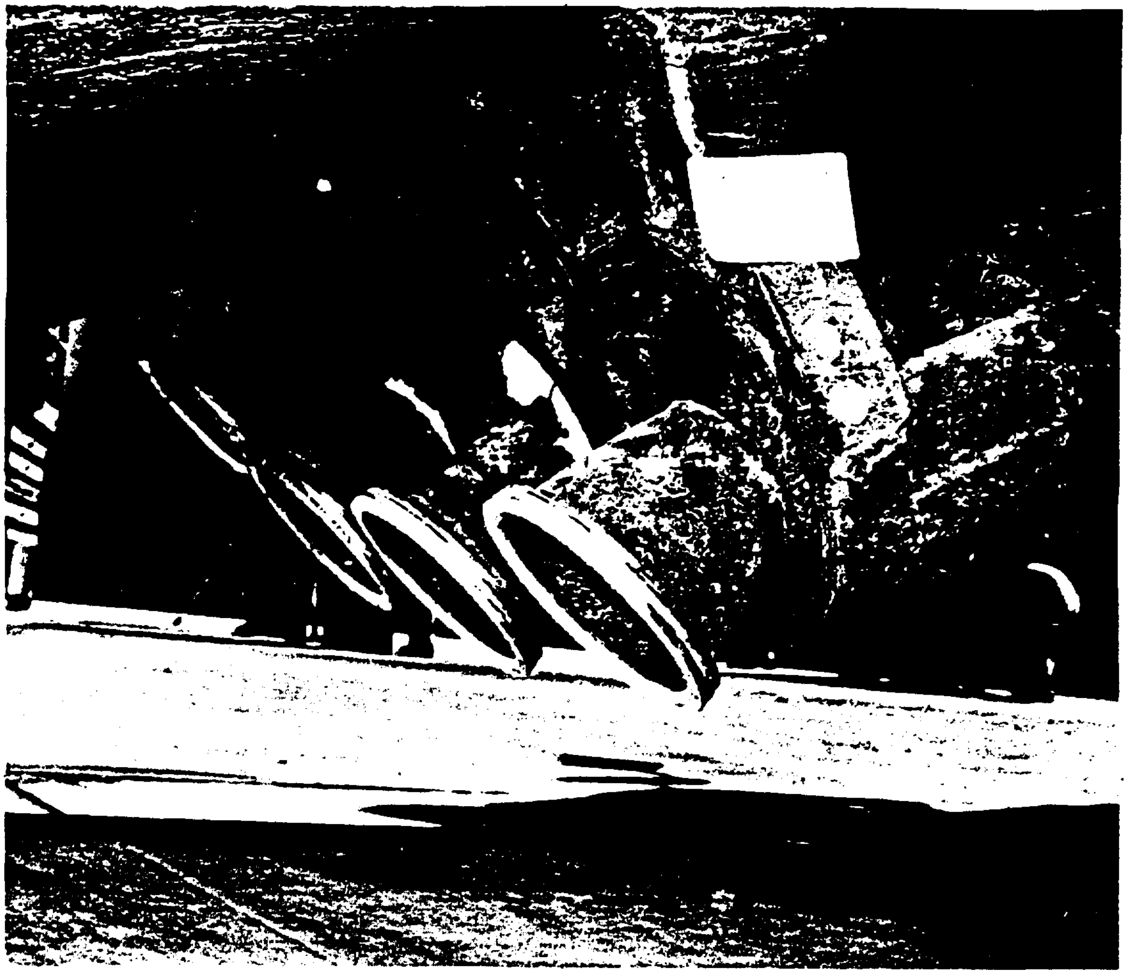

Figure 16. Aft Mounted BSMs After Recovery From Flight.

CONCLUSION

The seven successful flights of the Space Shuttle Transportation System (STS) have verified the design of the BSM relative to control of debris that would be damaging to the Orbiter. Post flight inspections have not revealed any Orbiter TPS damage resulting from BSM operation. The flight program has validated the BSM design approach and the extensive development and certification test program that was implemented to ensure debris free operation.