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Unique Nozzle Cover for the Shuttle Booster Separation Motors

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The stringent requirements imposed upon the shuttle booster separation system led to the development of two unique nozzle cover concepts with potential applications in other space propulsion systems. Major requirements were to 1) protect the booster separation motors (BSM's) from the ascent aerothermal environment; 2) provide a humidity seal for the BSM during storage and readiness on the launch pad; 3) open completely during the ignition transient; and 4) produce no debris during ascent, separation, and booster reentry. The nozzle cover concepts included 1) a frangible reinforced elastomeric cover with a retraction mechanism to remove the cover sections away from the plume, and 2) a stainless-steel cover hinged by a plastically deforming torsion pin. The paper discusses the design features of both systems, the dynamics computer model for the hinged cover, and the extensive testing which led to the selection and qualification of the hinged cover approach. The plastic behavior of the selected materials under high strain rates is also discussed.

Introduction

IT was determined analytically that the space shuttle's forward booster separation motors (BSM's), shown assembled to the solid rocket booster (SRB) in Figs. 1 and 2, will require shielding from the ascent aeroheating environment to preclude premature ignition.

Additionally, it was required that the aeroheating shield be retrofitted to the existing separation system without modifications or additions to the ordnance and electrical subsystems. This constraint made it necessary to utilize BSM ignition pressure to remove the aeroheating shield; however, due to the extremely fragile nature of the shuttle orbiter thermal protection system (TPS), no ejected debris was allowable during shield removal and BSM operation. The combination of these requirements in addition to others outlined in Table 1 has resulted in a unique set of design constraints.

Two basic approaches were identified: 1) an elastomeric frangible/retractable cover, and 2) a metal-hinged cover.

The frangible retractable cover (Fig. 3) consists of a Kevlar-reinforced rubber membrane attached to a pentagonal ring. The membrane has five radial grooves each originating from a vortex of the pentagonal ring and extending to within 1 in. of the center of the membrane. At a given pressure, the membrane will tear along these grooves, resulting in five pie-shaped petals, each attached to the pentagonal ring. The ring is spring-loaded to the aft closure so that upon fracture of the membrane, the assembly is pulled forward, thus removing the petals from the BSM exhaust plume.

The metal-hinged cover, shown in Fig. 4, consists of a structurally reinforced disk 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 disk is held closed by a strainless-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 166 deg. At 155 deg the cover also engages a deformable secondary stop. Between 155 deg and 180 deg the cover energy is therefore being absorbed by both the torsion pin and the secondary stop.

Aeroheating Shield Feasibility Development

During the early phases of the program, both the frangible/retractable and the hinged-cover approaches were successfully demonstrated against the following requirements: 1) the shield must be removed solely by means of the igniter pressure; 2) the shield must be completely removed within the ignition transient; and 3) during removal no debris is to be ejected. The following is a summary of this early development.

Frangible/Retractable Aeroheating Shield

Major tasks for the frangible/retractable aeroheating shield were 1) to develop a membrane that would fracture under ignition pressure in a predetermined repeatable manner, and 2) to develop a reliable retraction system. Figure 5 outlines the design evolution of the frangible membrane. As shown in the

Table 1 BSM aeroheating shield basic requirements

Protect BSM from ascent aeroheating environment (1600°R)
Induce no modifications or additions to the existing electrical or ordnance subsystems
Eject no debris during shield removal and motor operation
Shield must survive the aerothermal, aerodynamic, and vibration environments during liftoff, boost, and separation
Shield must be removed solely by the ignition pressure
No interference between removal of shield and removal of adjacent shields in BSM cluster

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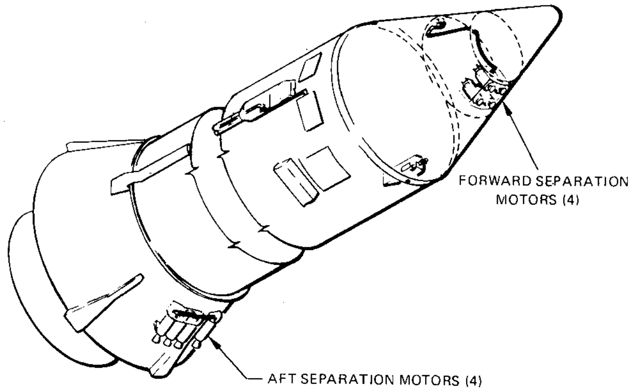

Fig. 1 BSM locations on space shuttle's solid rocket booster.

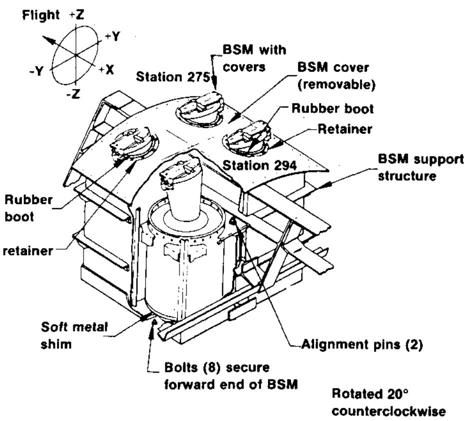

Fig. 2 Forward BSM's assembled to SRB with aeroheat shields.

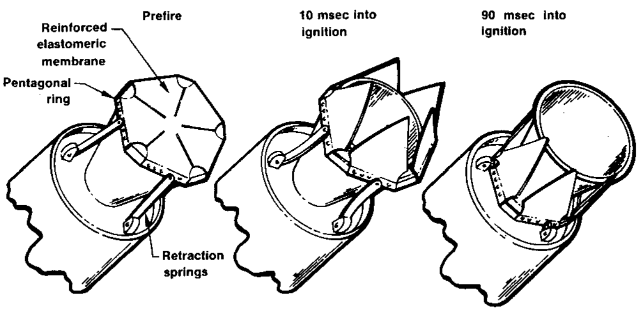

Fig. 3 Basic concept of frangible/retractable aeroheating shield.

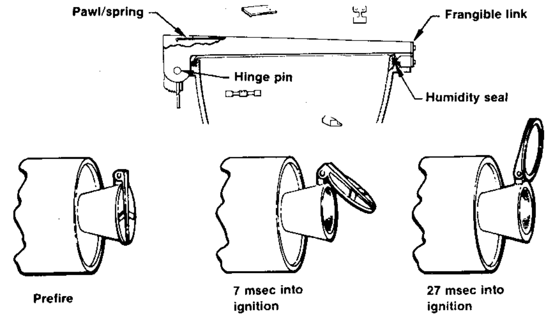

Fig. 4 Basic concept for hinged cover aeroheating shield.

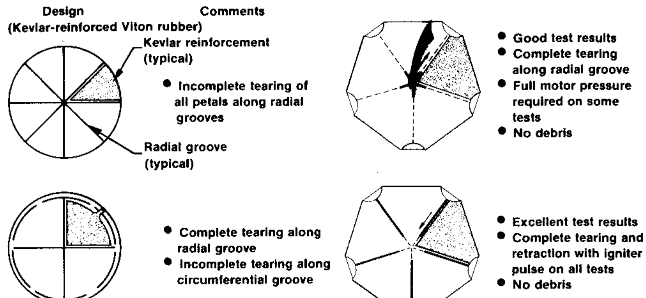

Fig. 5 Evolution of frangible seal.

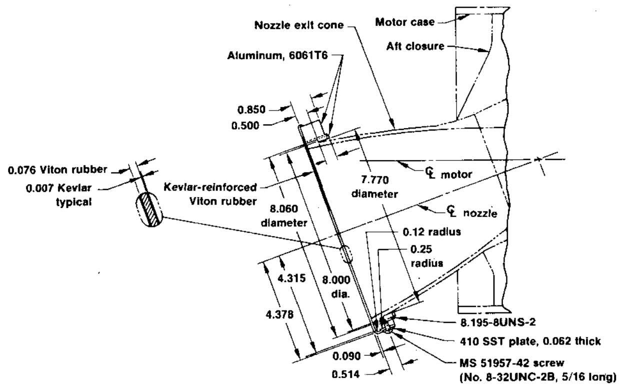

Fig. 6 Frangible cover assembled to BSM exit cone (all dimensions are in inches).

figure, a Kevlar-reinforced Viton rubber attached to a pentagonal ring provided the best results. The design is shown in Figs. 6 and 7.

The retraction system used four negator springs which are attached to the pentagonal ring and aft closure. These springs are similar to that used in a tape measure, and were chosen because of their large active length and their ability to collapse to a small package. Test results for the final design of the frangible/retractable aeroheating shield are summarized below:

Break pressure, psi	45-50
Complete opening, ms	5-25
Full retraction, ms	80-140

Thermal predictions indicated that shield average temperatures of 325°F in the radial groove areas were likely during ascent aeroheating. Since the Viton's physical properties would be seriously degraded at these temperatures, a thermal protection layer was required. Preliminary materials screening tests were conducted at CSD, and final screening tests were conducted using a hypersonic wind tunnel (Ref. 1, Appendix B). Analysis of the test data resulted in the final selection of a 1/8-in. layer of PD-200 (an open-celled silicone foam) as insulation for the aeroheating shield.

Additional empty-case tests were conducted which verified that the cover still opened properly without ejecting any debris when the PD-200 insulation was bonded to its outer surface.

A seal was vibration tested on a development motor at AETL. Cracks developed along the Kevlar-Viton interface near the radial grooves. It was later determined that the cracks, although much smaller, existed before testing. Additionally, excessive tension was applied to the seal during installation on the exit cone.

Hinged Cover Aeroheating Shield

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

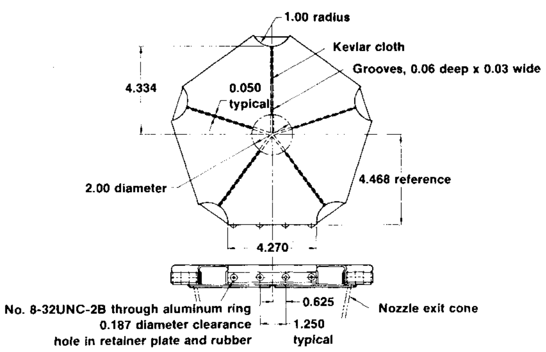

Fig. 7 Frangible cover for BSM nozzle (all dimensions are in inches).

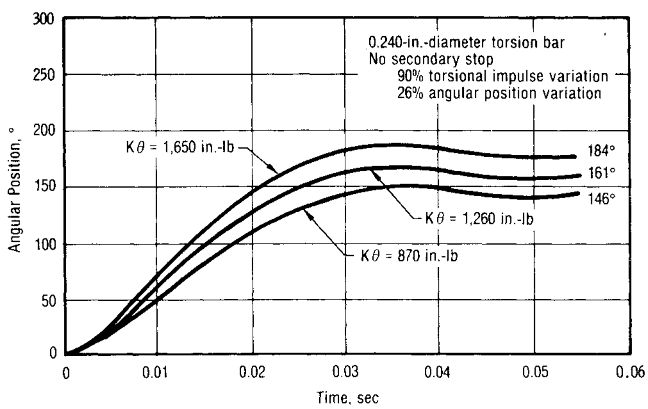

Fig. 8 Component bench-test results.

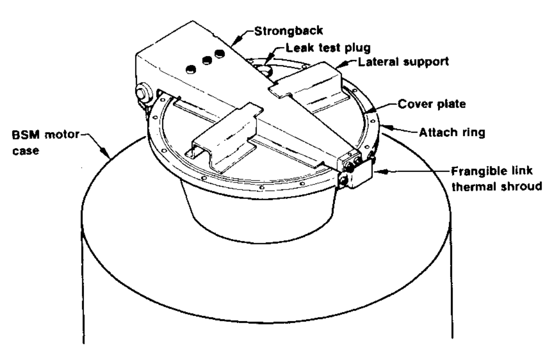

Fig. 9 Cover assembly (assembled view).

objectives were to demonstrate repeatable performance, large margins of safety, and zero debris during operation.

In the prototype hinged cover, the frangible link was designed to fail at a motor pressure of 17.5 psi; 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 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, summarized in Fig. 8, demonstrate repeatable performance in that all the input energy was absorbed and the flywheel came to rest within the

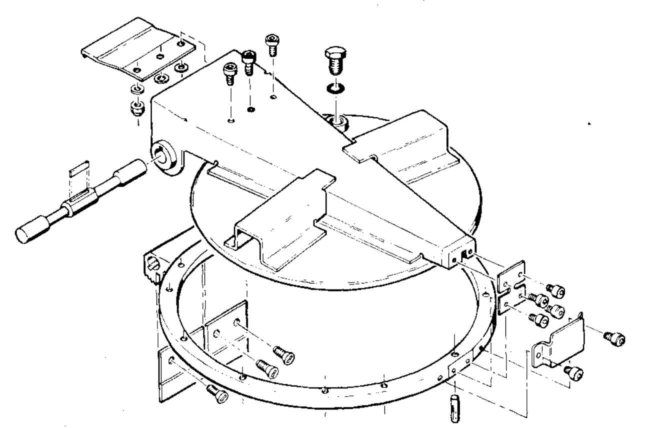

Fig. 10 Cover assembly (exploded view).

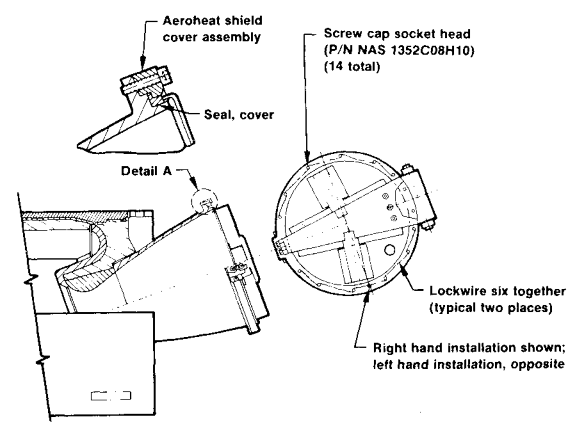

Fig. 11 Aeroheating shield assembled to BSM exit cone.

position range of 145 deg to 180 deg required for hinged cover operation. Twist angles of approximately 1000 deg were required to fracture the torsion pin.

From the above results component sizing data were generated to support the prototype hinged cover design. Three tests were conducted in which the hinged cover was assembled to an empty BSM motor case refurbished with only an igniter. The cover was also tested 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.

A vibration test of the prototype hinged cover was performed at AETL. In the lateral vibration axis (across the frangible link waist and parallel to its surface) the frangible link failed. It was determined that a restraining pin and/or a higher strength link would be required to preclude this failure in future tests.

Final Selection and Advanced Development

Design

Although both cover approaches were successfully demonstrated, the hinged cover was the final selection since it was determined that it involved less technical risk in meeting all program objectives within the allotted time. This determination was based partially upon the inherent predictability of the metallic components in the hinged cover over the elastomeric components in the frangible/retractable cover.

Upon selecting the hinged cover for advanced development, additional design requirements evolved. These included the following:

1) When closed, the cover must provide a humidity seal to the motor for six months on the launch pad; no leaks are

allowed when the cover is subjected to a differential pressure of ±4.0 psi.

2) The frangible link must be protected from direct thermal impingement during ascent.

3) Redundancy or large margins must be provided to assure that the cover hardware remains attached under worst-case operating loads.

4) A locking mechanism must be provided to hold the cover open after ignition.

5) The cover should be a separate subassembly to provide ease of assembly to the motor.

6) Positive clocking should be provided to prevent installation errors.

The advanced hinged cover design and its major components are shown assembled and disassembled in Figs. 9 and 10, respectively. Figure 11 shows the cover assembled to the exit cone. The cover plate is spin-formed from a flat sheet of 321 stainless steel. The strongback and lateral support structure, also 321 stainless steel, is spot-welded to the cover plate. The subassembly is mated to the attachment ring by aligning the holes and the keyway in the strongback tabs to those in the torsion pin block, and 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.

Testing

Fifty-seven empty-case tests and three motor firings were conducted on the aeroheating shield to evolve critical component dimensions, demonstrate repeatability, and verify large margins of safety. Vibration, structural, and leakage tests were also performed. The development tests and their objectives are given in Table 2.

Empty-Case Testing

Empty-case tests consisted of a BSM, a motor assembly with an igniter, and an epoxy filler to simulate propellant volume (Ref. 1, pp. 3-16 through 3-18). It was determined that the same initiator system to the igniter as would be used in flight was required to yield representative test results. In particular, the cover dynamics revealed a high sensitivity to the pressure profile during the first 12 ms of the ignition transient. Therefore, dual through bulkhead initiators (TBI's) were required. 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.

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, dynamics computer programs were used. The role of these programs in component sizing and testing is shown in the design iteration logic flow in Fig. 12.

Table 2 Test objectives summary

Test category	Objective
Component sizing	Verify soundness of current design
	Establish dimensions for critical components
Repeatability	Demonstrate repeatable dynamic opeation
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 re-entry
Structural	Verify integrity of ratchet pawl under simulated re-entry loads
	Verify large margins in critical design areas
Leakage	Verify integrity of environmental seal

Initial hardware is sized from static test results, then incorporated into a cover assembly and tested. High-speed photographic records are analyzed to determine the cover position vs time. These results are combined with the pressure data and the initial test conditions and are 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 are input to a dynamics program. The output of this program is compared to the observed dynamics of the cover and the value of the opening pressure is adjusted until predicted and actual test results agree.

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. Figure 13 is a curve fit for test 2-29. In this case, the cover opened 160 deg in 27.0 ms. The dimensionless pressure calculation based on a torsion pin average torque of 831 in.-lb is given in Fig. 14. The actual resistance torque of the hinge pin is a function of strain rate; however, a value of 831 in.-lb was found to be the best average value for a 0.275-in.-diameter torsion pin. Figure 15 shows the actual and predicted velocity profiles.

A series of repeatability tests were conducted (Ref. 1, p. 3-38). The results indicated an average opening pressure of 53.4 psi ± 1.82 psi and yielded a final opening angle of 165.4 deg ± 4.51 deg.

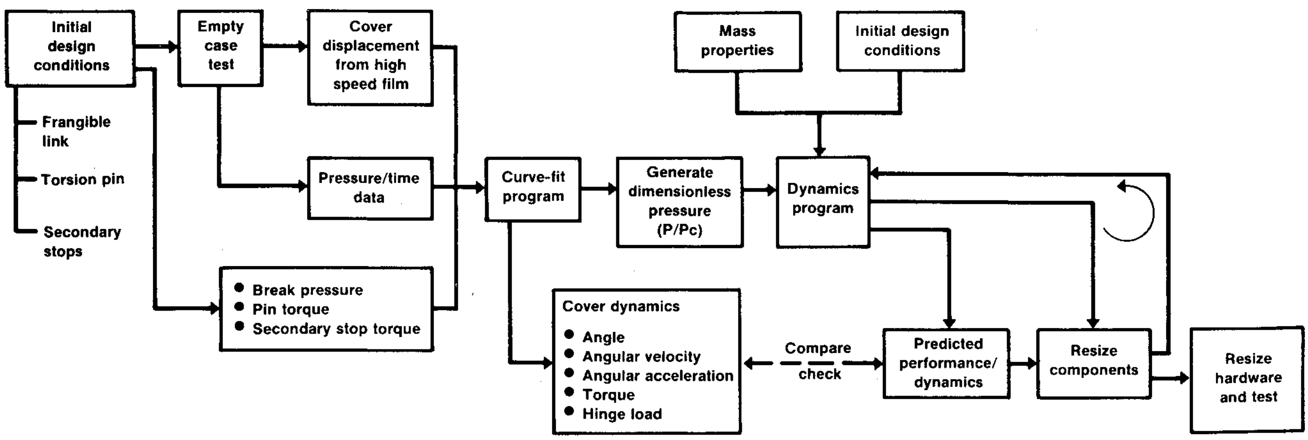

Fig. 12 Design iteration logic.

Table 3 Margin test results

Test description	Peak pressure, psi	Pressure rise time, s	Final opening angle, deg	Comments
No frangible link 2-3	50		160	Cover vibration tested without link 207-in. gap between cover and seal
2-32	47	0.0065	160	No gap between cover and seal
2-43	32	0.0110	124	Full demonstration motor firing Very small gap (0.015 in.) between cover and seal Single TBI
Two frangible links (stacked) 2-44	70		165	Frangible link attach bolts failed
One secondary stop removed 2-36	53	0.0078	160	
Both secondary stops removed 2-37	29	0.0088	155	Pressure data questionable
No key in torsion pin 2-40	54	0.0071	162	Backup set screws retained torsion pin
Torsion pin cut on one side 2-42	60	0.0068	182	Hardware intact
Removed one side of cover tab 2-45	47	0.0066	180	Cover cocked and bent opposite tab Crack on weld No debris
No key or set screws on torsion pin (free-swinging hinge) 2-46	60	0.0062	188	Full motor firing Two TBI's Weld cracked on one side Cover survived with no ejection of debris

Table 4 Vibration tests—aeroheating shield[a]

Test sequence (first unit)
Ascent vibration spectrum (cover closed)
Radial and tangential—unpressurized
Radial and tangential—pressurized to 15 psi
Longitudinal—unpressurized
Longitudinal—pressurized to 15 psi
Remove cover from vibration fixture and conduct open-case test
Re-entry vibration spectrum (cover open)
Longitudinal
Radial and tangential
Test sequence (second unit)
Ascent (cover closed)
Radial and tangential—unpressurized
Radial and tangential—pressurized to 15 psi
Longitudinal—unpressurized
Longitudinal—pressurized
Longitudinal—frangible link removed
Open-case fired without frangible link (test 2-31)

[a] All of the above tests were successful.

A series of margin tests (Ref. 1, pp. 3-38 through 3-44) were conducted to verify that single-point failure modes would not result in catastrophic failure. The results, shown in Table 3, clearly demonstrated the cover's ability to survive under extreme test conditions. With the exception of test 2-43 (a demonstration motor-firing), all covers opened beyond the altitude plume boundary. A thermal analysis indicated that the cover would survive if it received direct impingement on its outside surface from the plume of an adjacent BSM. The analysis also indicated that the cover would melt if it received impingement from its own plume in addition to the adjacent plume. This condition would result in hazardous debris. Test 2-43, however, represents a double-point failure mode in that a frangible link and a TBI were omitted. Subsequent tests verified that either one of these failure modes taken individually will always result in opening angles beyond the plume boundary. Additional failure mode studies concluded that failures were precluded by design redundancies, large margins of safety, or a large successful test base (Ref. 1, pp. 3-56 through 3-62).

Vibration Testing

Vibration tests were conducted with the cover assembly attached to a BSM exit cone. The test sequence is shown in Table 4. For each axis the cover was tested, first with ambient pressure on both sides of the cover, then with 15 psig in the exit cone chamber. This was considered necessary since it was possible that ambient pressure could be retained in the exit cone during ascent. After completing the ascent vibration spectrum, the cover was removed from the fixture and successfully tested on an empty motor case. After the test, the cover was reinstalled on the vibration test fixture and subjected to the reentry vibration spectrum.

After successfully completing the above tests, a second series of tests were conducted with an alternate frangible link design. After completing the ascent vibration spectrum, the frangible link was removed to simulate a frangible link failure and the cover was vibrated in the longitudinal mode (along the BSM axis). The cover was then tested on an empty case

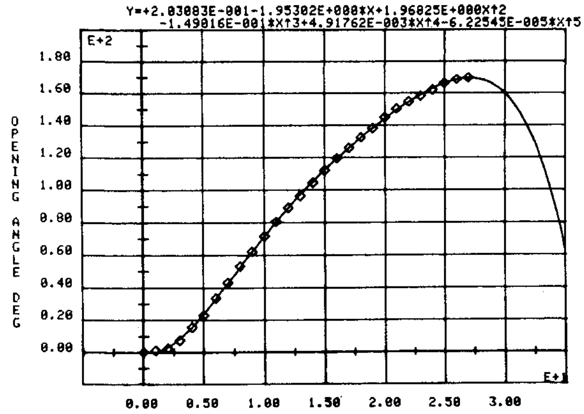

Fig. 13 Curve fit for test 2-29.

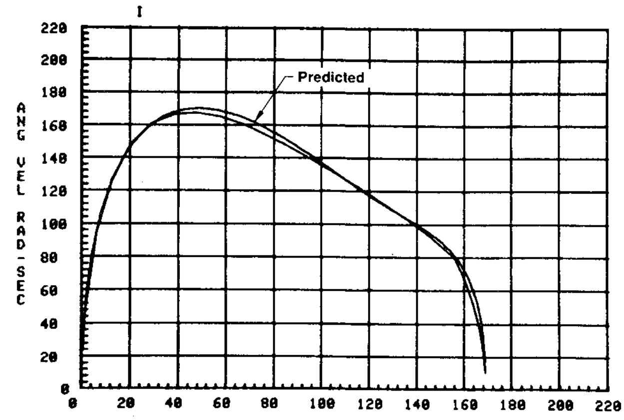

Fig. 15 Predicted vs actual velocity profile (test 2-29).

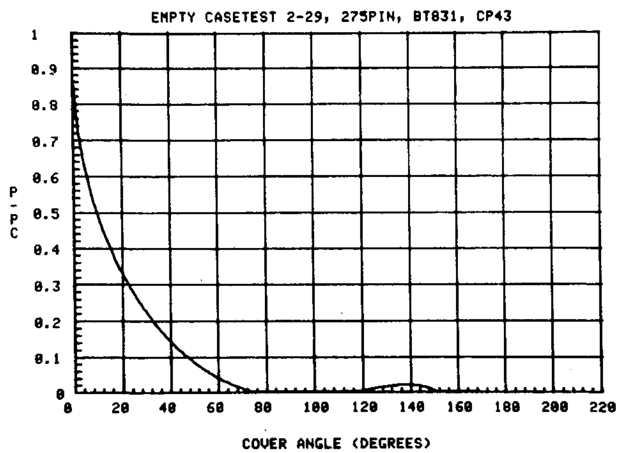

Fig. 14 Dimensionless pressure calculation for test 2-29 (empty-case test 2-29).

without the frangible link. Before firing, a gap of approximately 0.2 in. was observed between the cover and the seal; nevertheless, the final opening angle was 160 deg.

Additional vibration tests[2] on a loaded BSM motor assembly resulted in a frangible link failure when vibrated in the longitudinal mode. Investigations identified a fixture resonance which accounted for the failure. Subsequent corrections to the fixture in addition to a reduction in the NASA specification have precluded failures on subsequent tests.

Structural and Leakage Tests (*See Ref. 1, pp. 3-51 through 3-56.*)

A series of structural tests were performed to verify large margins of safety during ascent and cover operation. Analysis has indicated, however, that during reentry, under worst-case aerodynamic loading, the ring will experience bending; however, this would not result in ejection of the cover, and was therefore deemed acceptable.

Leakage tests with GN_2 verified the integrity of the environmental seal to ± 4 psi. Typical pressure at which leakage occurs is $+11$ psi.

Conclusions

Two BSM aeroheating shield approaches were successfully demonstrated. The hinged cover approach, being the final selection for advanced development, met all design and test objectives and has demonstrated large margins of safety during ascent and operation. A comprehensive series of tests clearly demonstrated that the aeroheating shield will:

1) Survive the ascent aeroheating and vibration environments.

2) Function repeatably under extreme operating conditions and produce no debris under any operating condition including those with induced single-point failures.

3) Meet or exceed all program objectives.

Based on the above, it is concluded that the hinged cover aeroheating shield will provide the required aeroheating protection to the space shuttle's forward BSM's without adding any significant hazards to any given mission.

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[1] Dettling, J.R., "Space Shuttle BSM Program Aeroheating Shield Development Test Evaluation Report," Chemical Systems Division, United Technologies Corporation, Sunnyvale, Calif., CSD 5180-78-69, Jan. 1979.

[2] Higgs, R.N., "Space Shuttle BSM Program Problems and Resolution Report," Chemical Systems Division, United Technologies Corporation, Sunnyvale, Calif., CSD 5180-78-20, Nov. 1978.