SPACE SHUTTLE ORBITER AFT HEAT SHIELD SEAL

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ABSTRACT

An intriguing assignment in the design of the orbiter has been the development of the aft heat shield seal (AHSS). It is a structure and mechanism at the three main propulsion system (MPS) engine interfaces to the aft compartment structure. Access to each MPS engine requires disassembly and removal of the AHSS. Each AHSS accommodates the engine movement, is exposed to an extremely high temperature environment, and is part of the venting control for the aft compartment. This paper discusses the baseline design, various improvements for engine access, and technical problem solutions.

INTRODUCTION

The Space Shuttle system orbiter vehicle is being developed as a "space truck" to deliver large and heavy payloads to space. This paper discusses the evolution of the orbiter AHSS design, which involved advancing mechanical seal technology in a severe thermal environment.

The orbiter structure is divided into separate compartments. The three MPS engines are located at the orbiter aft end; they are installed partly in and form part of the aft compartment enclosure. The three AHSS's are a major factor in the structural integrity of the aft compartment. Compartmentation is used to minimize compartment pressures and loads generated during ascent venting and descent repressurization. Excessive seal leakage or failure could cause increased pressures and possible failure of other aft fuselage structures, i.e., the X_O 1307 bulkhead.

Each AHSS is both a structure and mechanism at the three MPS engines interfaces to the aft compartment structure (Figure 1). Each AHSS consists of a stationary conical dome heat shield fastened to the base structure, a hemispherical engine heat shield mounted on and moving with the engine, and a seal mounted to the dome heat shield. The seal bears against the engine heat shield and accommodates the relative movement between the two heat shields (Figure 2). The seal mechanism, whose mean diameter is 210 centimeters (7 feet), is basically two assemblies–the sliding and flexible seals. The sliding seal accommodates the engine gimbaling, and the flexible seal accommodates the forward motion between the engine and compartment structure. For the baseline design, access to an MPS engine for maintenance or line replaceable unit (LRU) removal requires the disassembly and removal of the seal components, removal of the dome heat shield halves, and removal of the engine heat shield halves. The remaining base structure opening, 265 centimeters (106 inches) in diameter, is adequate for engine installation clearance.

As the AHSS baseline design was developed, the MPS maintainability requests matured and became more definitive. In addition, the thermal environments and the dynamic loads were

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increased. Concern was expressed with respect to engine turnaround time. The thermal, structural, and turnaround time concerns became the basis for AHSS improvement studies, which were to include baseline redesigns as well as new design concepts. This paper discusses the baseline design, the various improvement studies, and the technical problems that were overcome.

BASELINE REQUIREMENTS

The AHSS was designed according to the requirements listed below. Orbiter control requires the large engine gimbal angles. The thrust structure reacts the engine thrust and compresses under loading. The engine, therefore, moves forward relative to the base structure. Structure fabrication tolerances, structure deflection, engine and dome heat shields installation tolerances—all require additional seal design compensation. The reversible pressures limit design solutions. The seal venting area must be controlled to the limits shown. The upper and lower temperature limits decree the use of high-temperature materials for the engine heat shield and the seal. The engine access is to be as readily accessible as possible. A multiuse request of 100 flights is the goal.

- MPS engine gimbal angles
  - $\pm 11^{\circ}$ pitch, $\pm 9^{\circ}$ yaw — $\pm 14^{\circ}$ corner
- Movement, deflection, and tolerances
  - Engine forward movement = 5.5 cm (2.2 in.)
  - Structural deflection, Installation tolerances — As defined
- Delta pressure
  - +7.75 kg/cm^2 (+2.65 psi) burst
  - -3.86 kg/cm^2 (-1.32 psi) crush
- Allowable venting area
  - 58.5 cm^2 (9 in.^{2}) per engine
  - 175.5 cm^2 (27 in.^{2}) total (per orbiter)
- Temperature
  - 871°C (1600°F) design–external
  - 177°C (350°F) design–internal
- Acoustics
  - 164 dB
- MPS engine access
  - As readily as possible
- Multiuse
  - 100 flights (goal)
- Minimum weight/cost

BASELINE DESIGN

The AHSS baseline design (Figure 3) was developed in accordance with the baseline requirements. The seal design was limited by the space that could be made available between the dome and engine heat shields as defined by the engine movements. The baseline design was utilized only on the main propulsion test article (MPTA) vehicle.

As noted, the seal is the mechanism between the two heat shields. It consists of the sliding and flexible seals. The sliding seal is a series of graphite blocks held in a retainer ring with 48 spring cans that are uniformly spaced about the periphery and exert pressure on the graphite blocks to slide and seal against the engine heat shield spherical surface. The dome heat shield provides support and reaction to the spring cans. The sliding seal/retainer ring is held in posittion by three articulated links anchored to the dome heat shield. The links allow the sliding seal to follow the engine heat shield's forward translation as the engine thrust builds up. The ring stiffness is tailored so that it can distort momentarily to a noncircular, nonplanar shape as the links pass over center at the midpoint of the forward motion.

The flexible seal materials must be capable of operating in a high-temperature environment. The materials, especially the silica fabric, cannot tolerate excessive wrinkles. The silica fabric encloses the thermal insulation, the glass fabric pressure seal/structure, the polyimide film for the pressure seal backup, and Inconel mesh for lightning protection. The entire assembly is sewn together by quartz thread (Figure 4).

The flexible seal has a unique design to cope with the reversible pressures (Figure 5). Under positive or burst pressure, the flexible seal cross section is radial to provide hoop tension forces between the load reaction pivot attachments at the dome and engine heat shields. Under negative or crush pressure, flexible seal circumferential elements are circular and provide complete hoop tension forces. The design has a controlled shape, is properly supported at the edges, and requires only slight flexures—which results in minimum wrinkling and no shape reversals.

Seal disassembly requires a lacing disengagement at the flexible seal vertical meridian splices, structural disconnection of the retainer ring, and a folding back of the flexible seal to unbolt it from the dome heat shield's circumferential joint. The individual spring cans are then removed as opposite pairs to balance out the spring forces. After all the spring cans are removed, and the stabilizing links are disengaged, the flexible seal and the retainer ring/graphite blocks are removed as two individual assemblies.

The dome heat shield is bonded aluminum honeycomb with reusable surface insulation (RSI) tiles on the outside and thermal insulation blankets on the inside. It consists of two half-cones structurally joined by bolts at the vertical meridian splices. A row of outer peripheral bolts attaches the dome heat shield to the base structure. Additional bolts are used to attach the RSI tiles at both the meridian and peripheral joints.

The engine heat shield is a spot-welded, Rene 41 honeycomb assembly protected by a thermal coating (Pyromark) on the outside and thermal insulation blankets on the inside. It consists of two spherical segments that are structurally joined by dual rows of bolts at the vertical meridian and by a row of bolts at the heat-shield-to-engine-nozzle inner peripheral joint.

IMPROVEMENT STUDIES

Various studies were undertaken to improve both the structural and maintenance aspects of the AHSS design. The studies included new concepts as well as revisions of the baseline design.

Design

A "roman tunic" design with overlapping steel plates or sheaves was attached to a dome heat shield and slid on the hemispherical engine heat shield, but the large positive and negative differential pressures and the engine's forward movement during firing made the design impossible. Utilizing a "quarter segments" design instead of half segments to remove specific LRU's did not improve maintenance and added weight.

The "flexible curtain" concept consisted of a high-temperature flexible material (similar to the baseline flexible seal) attached to both the base structure and the engine nozzle. Its conical length allowed engine gimbal action, and the design was extremely appealing because it was visualized as two half panels fastened together at the meridian splices and at the base structure and engine nozzle peripheral joints. However, it was dropped because the shape could not be controlled and the excess material required in the conical length created wrinkles and folds that the material could not tolerate.

The "conical bellows" was another appealing design that did not work. It was a steel, cone-shaped bellows attached to both the base structure and the engine nozzle. The design was visualized as either a two-part or a single assembly. It did not work because the cone configuration was too short for the bellows' angular motion. Also, there was no known way to design a meridian split in the bellows to allow installation on the engine. Preassembling the bellows on the engine nozzle before the nozzle was attached to the engine was impractical.

Several designs of "cylindrical bellows" were investigated but the size required—inner diameter of 265 centimeters (106 inches)—to slip over the engine nozzle and the length required to allow angular motion made them too heavy.

The "external engine-mounted heat shield" reversed the baseline engine heat shield and dome heat shield locations. The engine heat shield was aft of the dome heat shield for easier removal—especially advantageous for specific LRU removal. But it would not work because there was not enough room for the engine heat shield gimbal action relative to the back end of the orbiter.

A ground support equipment (GSE) "restraint device" for locking each baseline spring can to the dome heat shield was designed but not used. The advantage was that the spring cans did not have to be dismantled from the seal. The disadvantage was that the flexible seal still had to be folded over and disconnected from the dome heat shield to allow insertion of the restraint device on the spring can.

The "lock-out device" is a design improvement that was incorporated (Figure 6). The lock-out device is a GSE tool that is inserted through the RSI tile and the spring can to lock the spring can to the dome heat shield. Its advantage is that the seal does not have to be dismantled. The disadvantages were minor. The revised access procedure is to lock the seal to the dome heat shield, disengage the lacing and disconnect the retainer ring at the seal meridian splices, disconnect and remove the dome heat shield (plus seal) in two major assemblies, and disconnect and remove the engine heat shield in two halves.

Engine Accessibility

Access requirements for each engine were incrementally defined by Rocketdyne and Kennedy Spacecraft Center (KSC) throughout the later portion of the design phase. The engine power head is to be inspected and the turbopumps are to be internally inspected and torqued after each MPTA firing and after each research and development (R&D) flight. The sequence thereafter occurs after every 12th operational flight. There are planned replacements for the major engine components (fuel and oxidizer pumps, nozzle, and total engine replacement) during the MPTA firings, but none is planned through R&D and operational flights. An exception is the replacement of the total engine after every 55th operational flight.

Further maintenance studies disclosed that the engine power head could be inspected from within the aft compartment without removing the AHSS. However, the KSC maintenance studies for pump access indicated advantages for a local hole with a removable cover (access port) in the engine heat shield for pump internal inspection and torquing. KSC could also accept the planned (every 12th operational flight per engine) pump torquing and inspection by removal of the AHSS, since it would not impact the turnaround time line. Unplanned contingency pump torquing and inspection could be a time line problem.

The access port design improvement was not initially utilized because there was no strong KSC requirement. Also, the access ports could not be designed into the baseline engine heat shield, which was made of Rene 41 material. The access port design required an edge member whose heat sink problem, when combined with the other engine heat shield thermal problems, could not be solved for the thermal gradients in and across the structure.

Joint Attachments

Joint attachment improvement studies were done on joints whose disassembly was required for removal of the AHSS. The improvements were to decrease the number of bolts, combine structural and thermal protection system (TPS) bolts, and utilize quick-action Milson fasteners. These fasteners were dropped in favor of power-driven tools for bolts. There were 14 studies in all whose joint improvements, if utilized, would decrease maintenance time (Figure 7).

The use of lock-outs halted the single improvement study for the flexible seal attachment to the dome heat shield. Two dome-heat-shield-to-base-structure studies were stopped when the base structure was installed on Orbiter 102 because changes to the base structure or RSI tiles on the base structure would severely impact tooling, manufacturing, and the tile subcontractor. Four dome heat shield meridian splices were studied. One concept was incorporated into the dome heat shield being redesigned for the improved spring-can angular offset problem. Three engine-heat-shield-to-engine peripheral joints were studied. No improvement could be made because of a thermal problem in this area. Four engine heat shield meridian joints were studied. The design improvement was a fallout of the solution to a thermal problem. These three problems and others are discussed below.

PROBLEMS AND SOLUTIONS

The engine heat shield, the seal designs, and the maintenance improvement studies were repeatedly interrupted by the need to solve various design problems (Figure 7).

Seal Loading

Thermal distortions, structural deflections, and manufacturing tolerances (outer shell, thrust structure, dome heat shield, engine heat shield, and engine installation) were greater than originally anticipated and resulted in inadequate seal loading. The angular offset of the seal cans (Figure 3) could not provide adequate sealing forces, nor could the major assembly tooling control the problem.

Figure 8 is the spring geometry and force diagram for the spring can installation. It indicates the problem that arises if the engine heat shield is located too far aft relative to the dome heat shield. Dimension (B) must always be reasonably positive to guarantee that the spring cans impose a positive sealing force (C) by never being on or near center.

Table I summarizes all tolerances and deflections for the baseline design and the design fix. The nominal spring offset (A) (Figure 8 and Table I) was increased from 2.11 to 4.000 centimeters (0.833 to 1.600 inches). All manufacturing tolerances for the aft fuselage assembly and dome heat shield were literally tooled out at the seal detail installation. Nothing could be done about the engine heat shield and engine installation tolerances and the various deflections. The result was that dimension (B) minimum (Figure 8 and Table I) was increased from +0.273 to +2.998 centimeters (+0.109 to +1.199 inches).

The increased spring-can angular offset required revision of the dome heat shield aft end to allow the spring can's outer pivot point to be relocated further aft without being moved inboard (Figure 6). The redesign of the dome heat shield and spring cans was combined with two improvements previously described: lock-out device and dome heat shield meridian splice. The manufacturing tolerances were minimized by a special tool that duplicated the engine centerline at null position. It also defined the location of the dome heat shield structure trim lines and seal components—all in the correct position relative to the engine. In effect, the seal installation was customized for each actual engine location. This tool is used by both manufacturing and field operations to define the null position of the engine centerline for rigging purposes, and by manufacturing for seal component assembly.

Thermal Considerations

MPS engine plume heating is the largest heating source of the adverse thermal environment. The latest thermal data update indicated increased heating rates (Figure 9) with the maximum heat load at 420 seconds. The temperatures are as high as 882°C (1620°F) in local areas between the engines. The problem is now the high temperature, the temperature gradients both in plane, through the thickness gradient, and in the circumferential gradient. In addition, engine dynamic loads on the engine heat shield became a problem at the engine-heat-shield-to-engine peripheral joint.

Design fixes were required for the engine heat shield meridian joints to increase joint capability for thermal stresses. A joint improvement fall-out was the reduction in the number of bolts. A design fix of the engine-heat-shield-to-engine peripheral joint was required by the increased thermal stresses and dynamic loads. This problem nullified any joint attachment improvement.

The incompatibility (high temperature, gradients too severe across the seal area) of the graphite sliding seal with the Rene 41 honeycomb engine heat shield was solved by changing the engine heat shield material and the sliding seal design to decrease the graphite seal thermal mass (Figure 10).

The engine heat shield was redesigned to be made of Inco 625, which does not exhibit the brittle failure characteristics of Rene 41. Instead, it yields at relatively low stress levels with good elongation, so that the thermal stresses that are above yield and in the plastic range are self-relieving. Since there is no known thermoplastic analysis method for spherical shapes like the engine heat shield, certification must be accomplished by test. Inco 625 at the 882°C (1620°F) maximum operating temperature yields and retains some permanent strain. Repeated exposures result in accumulated strain, which appears as intracell wrinkling of the heat shield face sheets during each flight and a gradually increasing wrinkle amplitude as the flights are repeated. To obtain the maximum wrinkle/life capability, the gauge of the face sheets was increased from 0.043 to 0.063 centimeter (0.017- to 0.025-inch) skins. The final face-sheet thickness will be determined by thermal data obtained from the first orbital flights. The final thickness is estimated to be 0.040 centimeter (0.016 inch) for acceptable wrinkle/life capability. The use of Inco 625 also allowed the porthole improvement when the requirement for turbopump torque/inspection was changed to after every operational flight.

The sliding seal was redesigned (Figure 6) to reduce seal thermal mass by using a wiper and slider blocks. The thermal mass reduction also reduced the gradient to approach the desired value shown in Figure 10, which in turn decreased the wrinkling tendency in the Inco 625 engine heat shield. The wiper is Teflon-coated silicone rubber. The slider blocks are individual electro-deposited nickel units. The wiper and slider block seal are also more compatible with the engine heat shield wrinkled face sheet for pressure sealing. The wiper will deteriorate under high-temperature repeated usage. Thermal coatings were added to the inside of the sliding seal. The three articulated links were increased to four. The engine heat shield surface coating was changed to Linde L103 to increase its life. The flexible seal outer material was changed from Irish Refrasil silica fabric to AB312 for improved handling characteristics.

Small, spherical, gore-component thermal cyclic tests were conducted to provide data and confidence that the full-up AHSS design and the forthcoming certification test will be successful. The tests are designed to produce representative flight thermal strains to check the behavior of the honeycomb face sheets and the seal wiper. The Inco 625 engine heat shield and the seal wiper should have a repeated usage of at least 20 flights. The maximum usage will be determined by later test data. All efforts will be made to improve the engine heat shield and wiper life to reduce orbiter maintenance operation. Replacement of the wiper requires removal of the dome heat shield and seal. Replacement of the engine heat shield requires removal of the total AHSS.

SUMMARY

In summary, the structural deflections, the assembly and installation tolerances, and high-temperature, high-gradient requirements were the drivers that led to the present design. The lock-out device and portholes were the major maintenance improvements. The dome and heat shield meridian joints were structural and maintenance improvements.

TABLE I – TOLERANCE/DEFLECTION SUMMATION (INCHES)

	Item	Baseline Design			Design Fix		
(A)	Nominal Spring Offset	0.833 √			1.600 √		
	Mfg Tolerances		√			√	
	Dome and seal details	±0.211	±0.488		Tooled	±0.030	
	Engine mount/dome	±0.277					
	SSME	±0.050	±0.250		±0.050	±0.250	
	SSME heat shield	±0.200			±0.200		
	Deflections						
	Structural defl	+1.487 -0.170	+1.744 -0.290		+1.487 -0.170	+1.744 -0.290	
	Thermal distortions	+0.157 -0.020			+0.157 -0.020		
	Vibration (acoustic)	±0.100		Rms Values	±0.100		Rms Values
	Subtotal			↓			↓
	Tolerances and deflections		+2.482 -1.028	+1.752 -0.724		+2.024 -0.570	+1.429 -0.401
(B)	NET OFFSET (nom + Σ tol and defl)	Max Min	+3.315 -0.195	+2.585 +0.109 √	Max Min	+3.624 +1.030	+3.029 +1.199 √

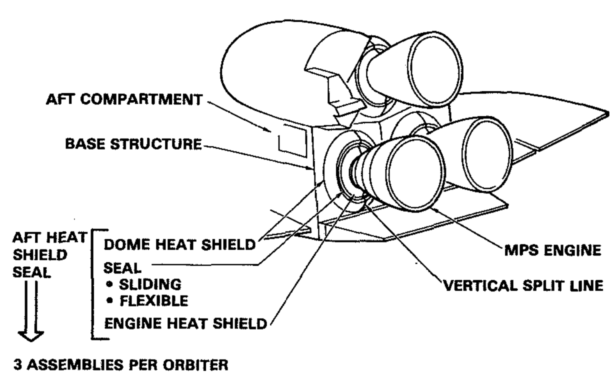

Figure 1 – Aft Heat Shield Seal

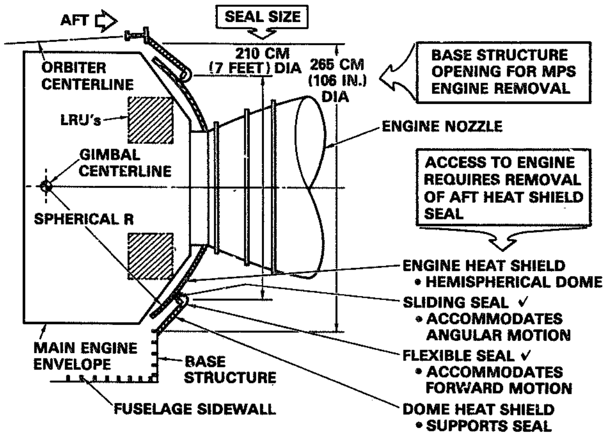

Figure 2 – Operation and Access

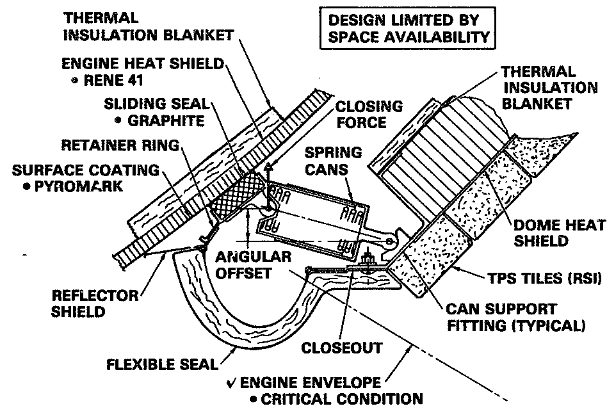

Figure 3 – Seal Installation Baseline Design

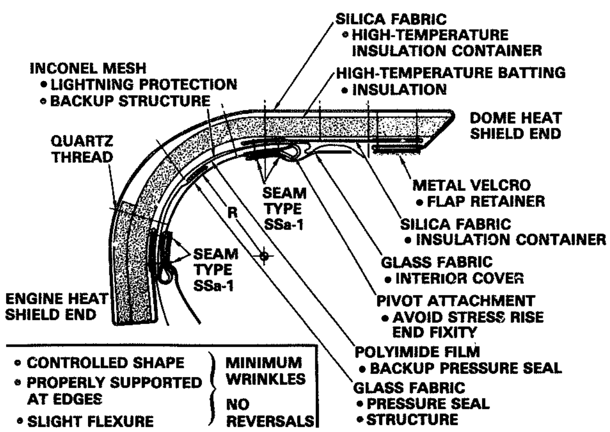

Figure 4 – Flexible Seal Baseline Design

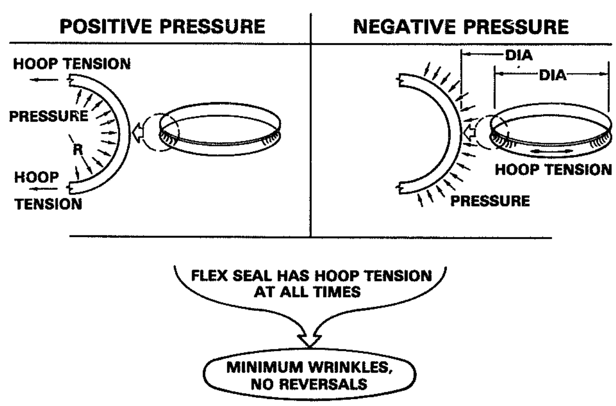

Figure 5 – Flexible Seal Pressure Capability

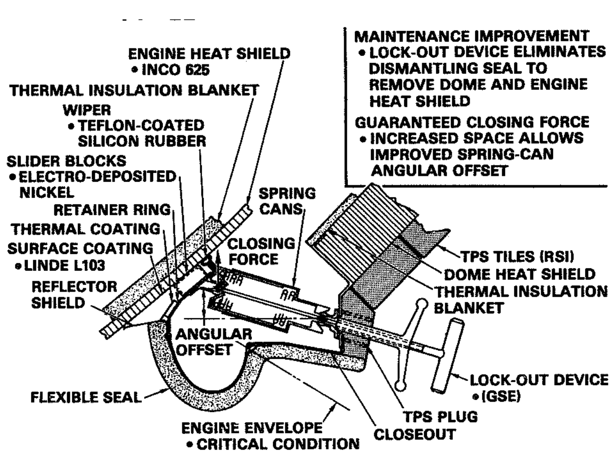

Figure 6 – Seal Installation With Lock-out Device

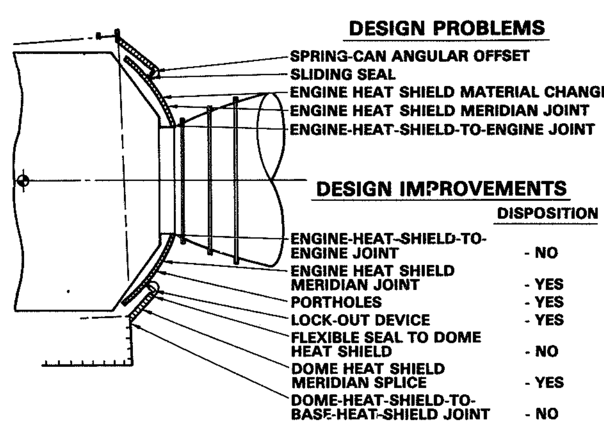

Figure 7 – Problems and Improvements

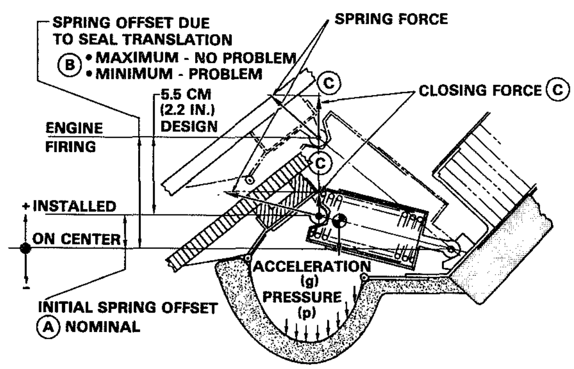

Figure 8 – Spring Geometry/Force Diagram

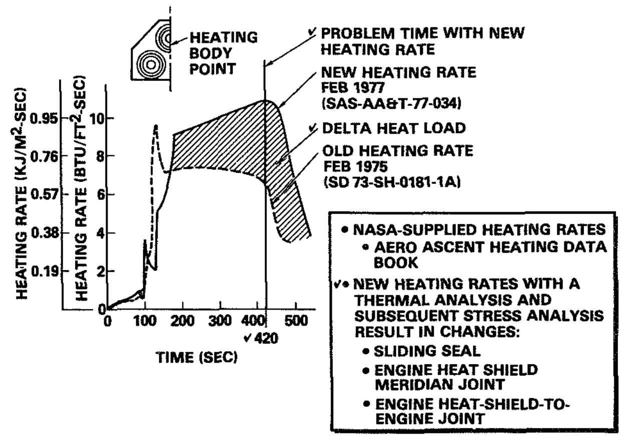

Figure 9 – Aft Heat Shield Seal Heating Rates

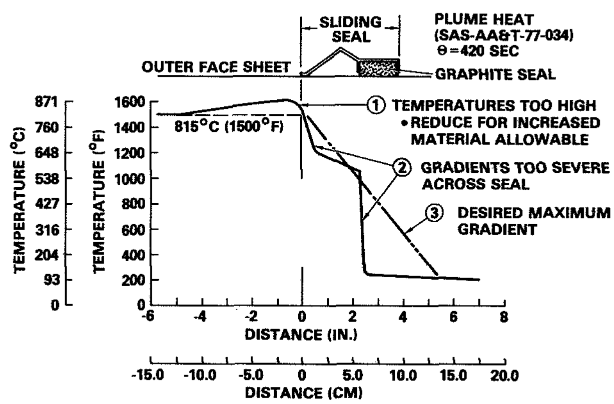

Figure 10 – Engine Heat Shield Baseline Temperature Gradient