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Deployable Heatshields for Future Multistage Missiles

Alan C. Goetz* and Duane L. Jensen†
Lockheed Missile Systems Division, Sunnyvale, Calif.

On a multistage ballistic missile, extensive insulation is usually required on the aft side of powered upper stages to protect the components and structure from excessive heat generated by the upper main stage motor. The objective of this program is the development of a lightweight, inexpensive, reliable heatshield to protect the aft end components and structure of a powered upper stage from the thermal environment generated by direct plume impingement and radiation from the upper-stage motor. Presented in this paper are two deployable heatshield concepts—inflatable torus and flex-rib—which offer a potential range performance improvement and cost advantage when compared to a current approach of individually insulating each component and structure as is effected on the Trident I fleet ballistic missile.

Introduction

On a multistage ballistic missile, one of the significant technical problems is that extensive insulation is usually required on the aft side of powered upper stages to protect the components from heat generated by the upper-stage motor. This insulation protects not only primary structure, but also brackets, electronic components, cables, connectors—in short, almost everything.

Individually insulating each component and the supporting structure is very costly from a fabrication and maintainability point of view. The current method of insulation (used on Trident I and other large boost vehicles) requires many sheets of cork with a multitude of cutouts around the structure and components to provide the basic thermal protection. But this alone is not adequate. For any gaps between the cork sheets of 0.060 in. or more, a hand-trimmed strip must be bonded in place. All gaps less than 0.060 in. must be filled by hand using a chopped cork/resin compound; a detailed, time-consuming, and costly process.

The complicated nature of the aft side of the Trident I upper-stage structure (equipment section and third stage) required complex analytical procedures to define the minimum weight insulation requirements. During the Poseidon and Trident I programs, several iterations in insulation requirements resulting from analytical re-evaluations and unexpected flight test data occurred, causing costly redesign and tooling rework. Use of a general heatshield could significantly simplify both the design and analysis resulting in reduced development costs.

Another significant problem with the current insulating methods is damage to the cork. Polaris and Poseidon missile practice is that most gouges or scratches in insulation must be repaired. The Trident I program is permitting minor damage without repair, although a sealer is still required to prevent fungus growth. With the extensive amount of insulation in the missile and with the frequency of access required for general maintenance, the susceptibility of the cork to damage could become a costly repair problem. With total life cycle costs (which includes maintenance) becoming increasingly important, the cork repair problem takes on greater significance.

The unique approach of deploying a heatshield after the staging pressure pulse has decayed makes the deployable heatshield concept an attractive alternative applicable for use on future multistage ballistic missiles which can result in lower development and maintenance costs. Two deployable heatshield concepts—inflatable torus and flex-rib—were investigated and compared with the Trident I approach to determine if improvements over the current method of insulation were obtained.

Technical Objective

The objective was the development of a lightweight, inexpensive, reliable system of protecting aft end components and the structure of a powered upper stage from the thermal environment generated by direct plume impingement and radiation from the main stage motor. The goal is a system which is competitive in cost and range performance with the present methods of insulating missile structure and components.

Approach

Design Criteria and Groundrules

The basic missile configuration chosen for study is shown in Fig. 1. It was chosen because of its applicability to a large variety of future mobile, land-based, or underwater launched multistage vehicles. The primary structure uses graphite/epoxy as the basic structural material. Although higher service temperature materials are in development, they may not be technically mature in time for advanced missile developments in the early 1980's, and protecting a graphite/epoxy structure poses the "worst case" for a heatshield. If successful, this concept also provides the option of using current materials such as low-cost uninsulated aluminum or graphite/epoxy for future multistage missile systems.

The basic missile configuration used in this study employs a stage separation technique which causes high pressures in the area of the heatshield. Designing a heatshield to sustain the high loads caused by this separation technique is one of the reasons heatshields have not been competitive in the past. Trident I design limit loads were used for the concepts developed during this program since it is anticipated that these loads will be similar to those determined for future missile programs.

The thermal environments used in this study originate from data assuming that the propellant for the upper-stage motor is the same as used on Trident I. This was selected because it is a new technology high-energy propellant which may be used on

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*Supervisor, Equipment Section Design—Missile Body Mechanical Engineering.

‡Senior Design Engineer, Missile Body Mechanical Engineering.

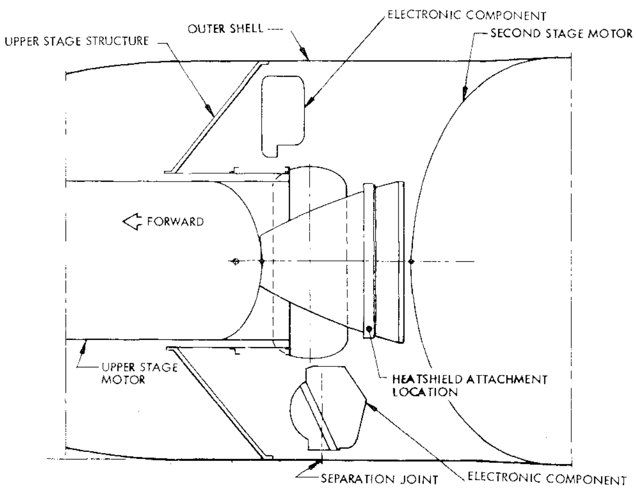

Fig. 1 Baseline configuration for study.

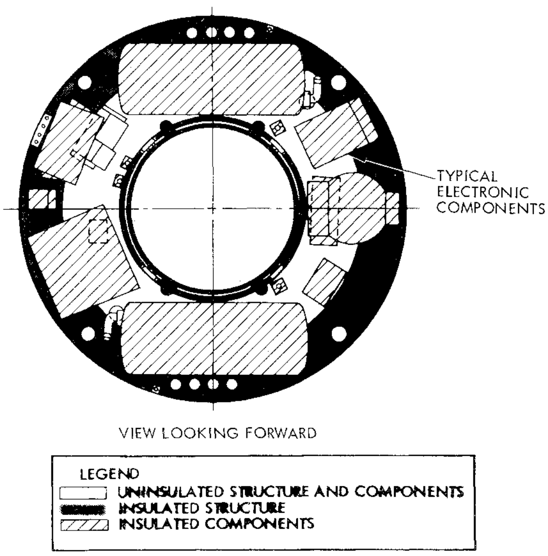

Fig. 2 Trident I insulation requirements.

future missiles and because Trident I flight data provides reliable thermal environments for this study. Flight heating consists of convection and radiation heating. Flight cold-wall convection heating is 11 Btu/ft^2-s with a 3960°R gas temperature. Radiation heating is 6 Btu/ft^2-s originating from 4000°R alumina particles in the rocket exhaust plume.

Basis for Evaluation

The insulation weights and costs for the Trident I third stage and equipment section were used to provide a basis of comparison to determine if these heatshield concepts represented an improvement over current insulation methods. On the Trident I, the graphite/epoxy structure and electronic components are individually insulated. Figure 2 shows the insulation requirements of the upper-stage structure and components. Note that major portions of the structure and components require insulation. Table 1 lists the weight

Table 1 Weight of Trident I insulation scaled to larger diameter advanced technology missile

Equipment section aft structure and components	21.9 lb
Third-stage aft structure and components	2.4 lb
Total	24.3 lb

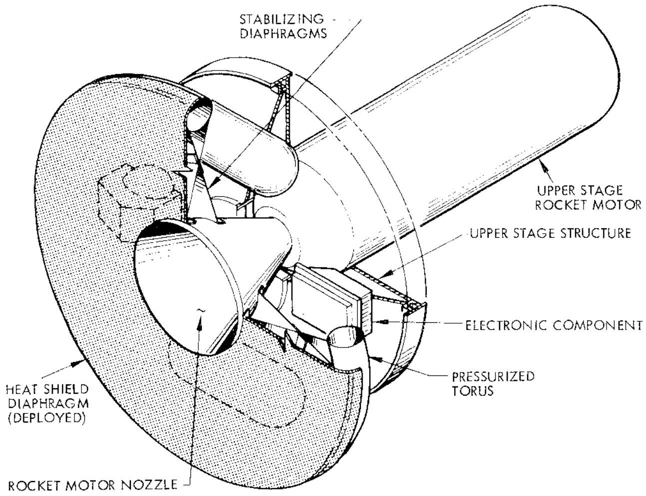

Fig. 3 Inflatable torus heatshield.

associated with individually insulating electronic components and the structure. The 24.3 lb of insulation provided a basis to compare with the heatshield concepts. The Trident I insulation weight was scaled up proportionally to account for the larger baseline missile configuration chosen for this study.

Inflatable Torus Heatshield

The inflatable torus heatshield is shown deployed in Fig. 3. Prior to deployment, it is stored in a protective housing which is bolted to the structure of the upper-stage motor nozzle. After second-stage separation and upper-stage ignition, when the ignition pressure has decayed, the heatshield is deployed by inflating the torus in much the same manner as inflating an inner tube. As the torus pressurizes it expands radially outward, deploying the cloth heatshield with it. This occurs at an altitude in excess of 400,000 ft.

Figure 4 is a cross section through the heatshield. A two-piece mylar bag is used to contain the heatshield in the stowed position. The top half of the bag is attached to the forward flange of the housing and the lower half of the bag to the aft end of the housing wall. Once the heatshield is stowed, the two pieces of mylar are joined together at the ziplock joint. At deployment, the torus pressurizes, separates the ziplock joint, and deploys. The torus consists of one ply of quratz cloth with 0.5 mil mylar on the inside to form a pressure seal. Gaseous nitrogen is contained in a 2000 psi tank which inflates the torus to 40 psi by means of two hoses. A pyrotechnic initiator begins the inflation sequence. The thermal barrier consists of one ply of carbon cloth. The continuous stabilizing diaphragms, which also act as thermal barriers, consist of low thermal conductive quartz cloth with aluminized Kapton on the aft surfaces to reflect the heat away from the upper-stage structure and components.

Having designed the the heatshield for 0.1 psi pressure load, it is not deployed until the motor ignition pressure decays to this value. This would occur in about 200-300 ms. This delay also allows enough time for the second stage to separate from the upper-stage structure and clear the heatshield. Deployment of the heatshield is between one and two seconds. Testing is required to obtain the optimum deployment time.

The thermal response of this design is shown in Fig. 5. The carbon cloth reaches a temperature of 1800°F. The heated carbon cloth radiates heat to the metallized Kapton/quartz cloth diaphragms which heat up to 600°F. The diaphragms radiate heat to the aft surfaces of some electronic components, which reach a maximum temperature of 170°F at the end of upper-stage flight. The Trident I criteria for most electronic components is the surface temperature of the component case shall not exceed 200°F, with a few components limited to 160°F. Therefore, some local thermal

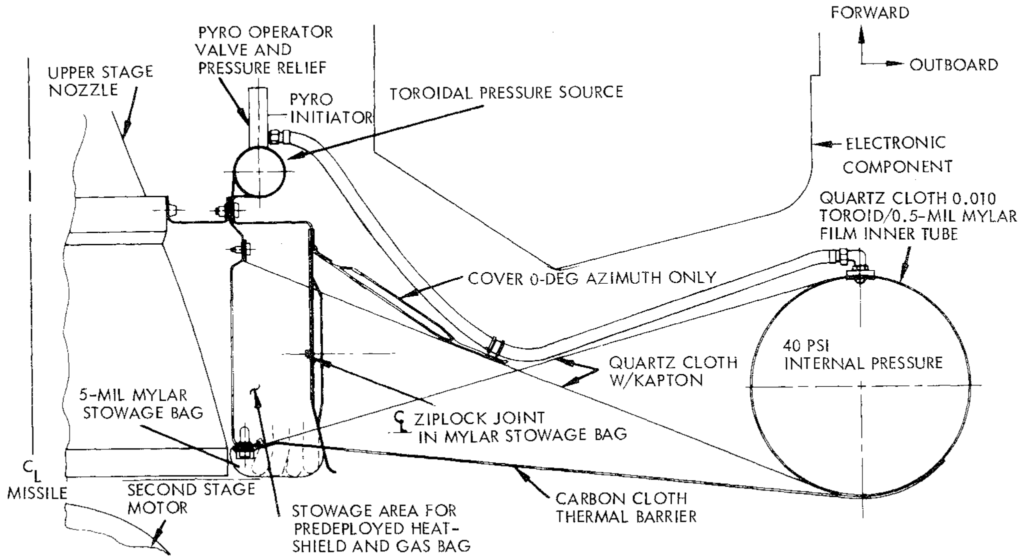

Fig. 4 Inflatable torus heatshield design.

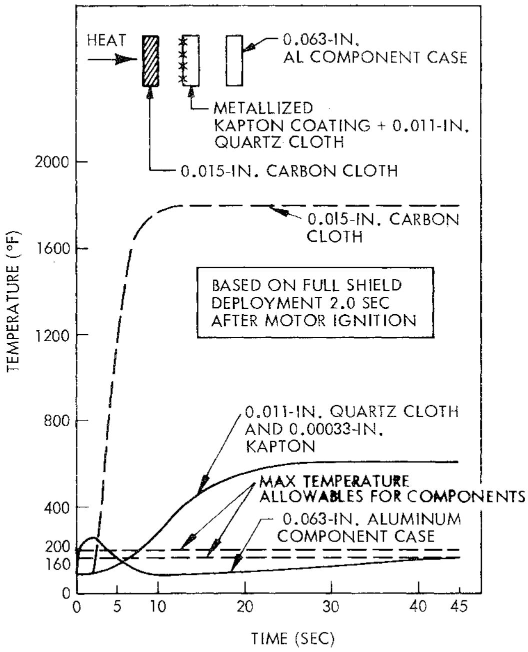

Fig. 5 Thermal response of inflatable torus materials.

Table 2 Inflatable torus heatshield system weight

Heatshield	8.2 lb
Protective housing	6.5 lb
Initiation system	8.9 lb
Nozzle attachment structure	1.2 lb
Insulation/sacrificial plies on missile structure	1.6 lb
Total	26.4 lb

Table 3 Advantages/disadvantages of inflatable torus heatshield

Advantages	Disadvantages
Stowed in protective housing	Attached to upper-stage nozzle
Unobstructed access to equipment section during maintenance operations	Heating at second-stage separation and at upper-stage separation absorbed by packages
Protects entire aft end of upper-stage and equipment section	Moderate developmental risk
Separates with upper stage—no equipment section weight penalty	Requires energy source for deployment
	ΔP staging absorbed by packages

protection or reorientation of some components would be required to stay within the 160°F criteria which is a minor problem. Prior to heatshield deployment, the aft surfaces of the components are exposed to the plume and reach a temperature of 250°F. Once the heatshield is deployed, the component surface temperature quickly decreases. Present criteria would require insulating the components for this short-term thermal spike.

This unnecessarily adds a range performance penalty to the missile. Instead, a revised design criteria, which allows short-time external case temperatures above the present criteria, may be required. Internal components would not have enough time to reach the 160 or 200°F limit if the case is subjected to 250°F for a short time. The analysis of electronic component thermal responses assumes the heatshield will not be fully deployed until 2.0 s after staging.

The weight of the inflatable torus heatshield system is listed in Table 2. The nozzle structure on the upper-stage motor must be increased in size to allow attachment of the heatshield. This adds 1.2 lb to the nozzle. 1.6 lb is also allowed for sacrificial plies of graphite/epoxy on the structure to protect it for the separation heating. This will be addressed in greater detail when the flex-rib heatshield is discussed.

The advantages and disadvantages of the inflatable torus heatshield are summarized in Table 3. The primary advantage is that fleet maintainability problems, as previously discussed, are virtually eliminated without any loss in range performance since the heatshield is stored in a protective housing. (A relative range performance comparison of each concept is listed in Table 6.)

Flex-Rib Heatshield

Another deployable concept is the flex-rib heatshield as shown in Fig. 6. It is stored in a protective housing attached to the upper-stage nozzle and deployed using flexible ribs to provide a thermal umbrella over the upper-stage structure and components.

Several space satellite antennas, which are deployed by flexible semilenticular (C-shaped) ribs, have been built, tested, and flown.[1] The ribs are attached to a central hub

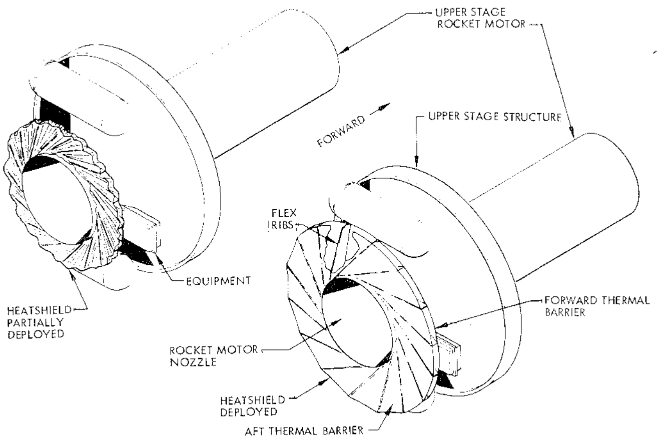

Fig. 6 Flex-rib heatshield.

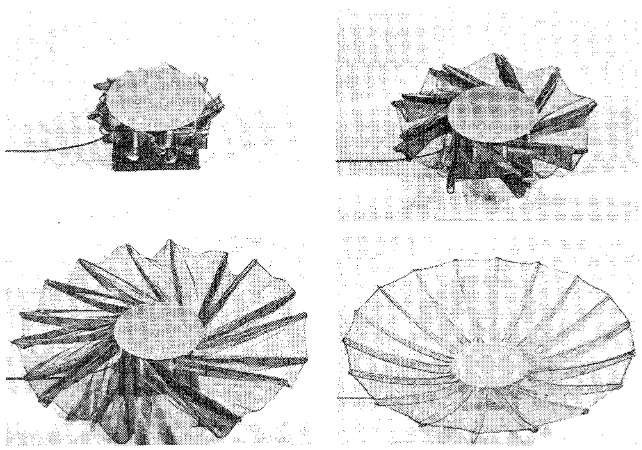

Fig. 7 Deployable antenna deployment sequence.

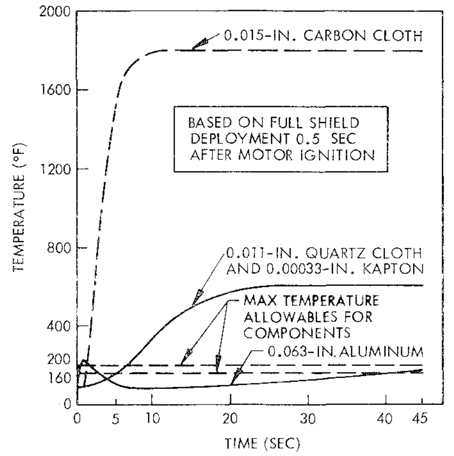

Fig. 9 Thermal response of flex-rib heatshield materials.

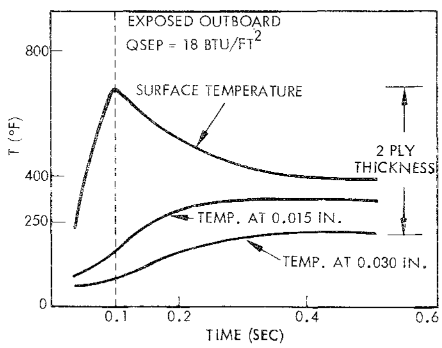

Fig. 10 Equipment section structure thermal response.

through spring-loaded hinges. For stowage, the ribs are rotated on the hinge pin to a hub tangent position, then elastically buckled and wrapped against the hub. Hinged doors encapsulate the ribs and are, in turn, restrained by a 1/6-in. diameter cable wrapped around the outside of the doors. For deployment, a pin puller is pyrotechnically fired which releases the cable. The stored energy in the ribs pushes the doors open and the ribs unwrap to a full radial position. Figure 7 illustrates the deployment sequence of an antenna.

Figures 6 and 8 show the design of a flex-rib heatshield using the antenna principle. Thermal barrier materials closely parallel the inflatable torus heatshield with the aft thermal barrier consisting of one ply of carbon cloth and the forward thermal barrier consisting of quartz cloth and the metallized Kapton. The 0.016-in. thick titanium ribs are bolted directly to the housing, as shown in Fig. 8, and are fully deployed tangentially to the housing. Twelve 1-in wide doors restrain the ends of each of the twelve ribs in the stowed position. Mylar is used in much the same way as in the inflatable torus heatshield to enclose the remainder of the housing. At deployment, the cable is cut, the ribs break the ziplock joint and deploy. The protective housing completely encloses the heatshield to insure that the aluminized Kapton's shiny surface is not contaminated. If the aluminized surface is dirty, the emissivity value increases, resulting in more heat energy absorbed by the quartz cloth and reradiated to the equipment and structure.

Like the inflatable torus heatshield, the flex-rib heatshield is designed to sustain a 0.1 psi pressure load and thus must

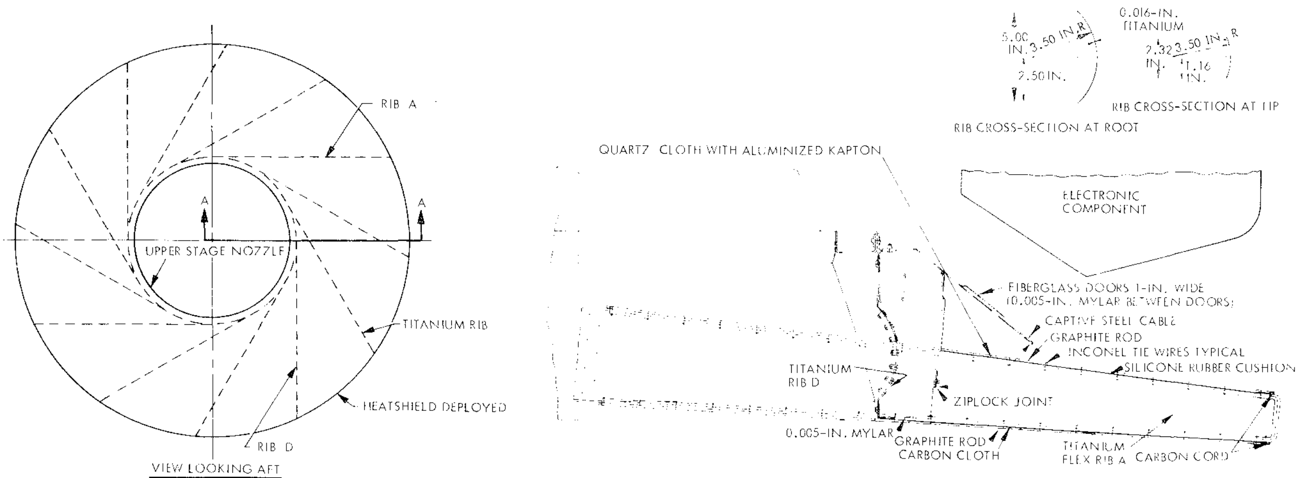

Fig. 8 Flex-rib heatshield cross-section.

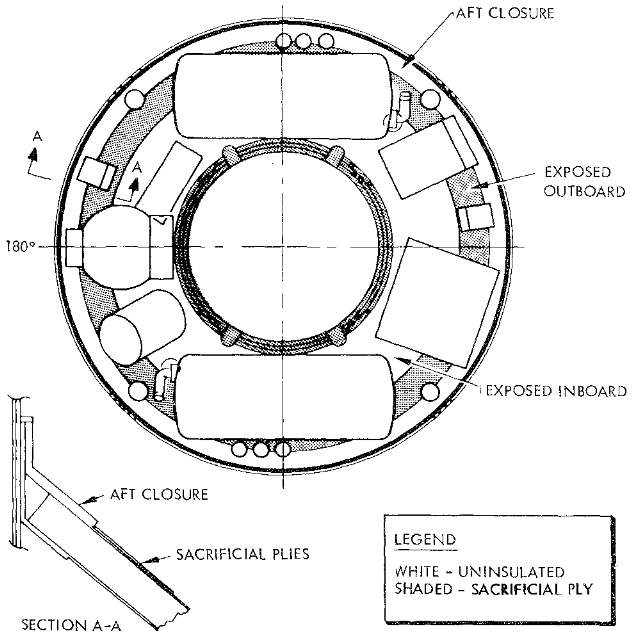

Fig. 11 Insulation requirements prior to heatshield deployment.

wait the 200 ms before deployment. Analysis indicates the heatshield will be fully deployed in 300 ms. Therefore, the components and structure are exposed to the plume for only 500 ms. The thermal response of the heatshield materials and their effect on a typical electronic component case is shown in Fig. 9.

Figure 10 is the structure thermal response due to separation heating, and Fig. 11 illustrates the areas of the upper-stage structure which require insulation for the half-second plume exposure. The exposed outboard portion of the structure reaches a surface temperature of over 700°F and then decreases asymptotically to 400°F. The Trident I design criteria is to prevent the graphite/epoxy structure from exceeding 250°F. To protect the structure, two sacrificial graphite/epoxy plies are added, as illustrated in Fig. 11. If

Table 4 Flex-rib heatshield system weight

Heatshield	10.8 lb
Protective housing	10.4 lb
Initiation system	0.5 lb
Nozzle attach structure	1.2 lb
Insulation/sacrificial plies on missile structure	1.6 lb
Total	24.5 lb

Table 5 Advantages/disadvantages of flex-rib heatshield

Advantages	Disadvantages
Stowed in protective housing	Attached to upper-stage nozzle
Unobstructed access to equipment section during maintenance operations	Small reduction in access to upper stage during operations
Deployed by energy stored in flex ribs in stowed position	Heating at second-stage separation and upper-stage separation absorbed by packages
Protects entire aft end of equipment section and upper stage	ΔP at staging absorbed by packages
Separates with upper-stage motor—no equipment section weight penalty	
State of the art—minimal development risk	

Table 6 Weight and range comparison of various concepts

Concept	Weight, lb	Range, n. mi.[a]
Trident I approach	24.3	Basis
Flex-rib heatshield	24.6	+5.8
Inflatable torus heatshield	26.4	+3.6

[a] Range shown relative to Trident I method of individual component insulation; + equals improved range performance.

Table 7 Cost comparisons of various concepts

Inflatable torus heatshield		
Labor	$ 4,850	$ 9,800/missile
Material	4,950	
Flex-rib heatshield		
Labor	12,200	14,400/missile
Material	2,200	
Trident I insulation cost		
Equipment section aft structure		
Labor	6,500	16,000/missile
Material	750	
Third-stage aft structure		
Labor	250	
Material	250	
Components	8,200	

cork is used, it must be bonded to the cone, a varnish sealer added (which takes 6 h to dry), and then a second varnish sealer added (12 h to dry)—an expensive, time-consuming process.

Table 4 summarizes the weight of the flex-rib heatshield. The half-pound for the initiation system includes the cable cutter, pyrotechnics, and the initiator block. As with the inflatable torus, the nozzle structure of the upper-stage motor must be increased in size and weight to allow the heatshield to be inserted past the nozzle exit plane and bolted to the nozzle.

Table 5 summarizes the advantages and disadvantages of the flex-rib heatshield. As with the inflatable torus heatshield, the major advantage is the substantial reduction of fleet maintenance problems concerning insulation. Another advantage is the minimal number of mechanisms required, with only the cable cutter and the hinges on the doors required for the entire system. The concept is therefore judged to be highly reliable. The disadvantages are negligible when compared to the advantages.

Conclusions

Table 6 presents the weights and relative range performance of each concept using range partials of −1.5 miles per pound for equipment section weight and −1.2 miles per pound for upper-stage motor weight. Although the heatshields weigh slightly more than the Trident I approach, they are ejected along with the upper-stage motor. Therefore, they incur the smaller negative range partial, resulting in a range increase over the Trident I approach.

Table 7 lists the manufacturing costs for the concepts based on a first production run of 52 missiles. The inflatable torus heatsheld was the least expensive, while the remaining concepts were essentially equivalent. However, when total life cycle costs are evaluated, the deployable concepts indicate lower life cycle costs because of reduced development program costs and reduced maintainability costs since heatshields are stored in a protective housing.

References

[1] Woods, A.A., Jr. and Wade, W.D., "An Approach Toward the Design of Large Diameter Offset-Fed Antennas," AIAA/NASA Conference on Advanced Technology for Future Space Systems, Langley Research Center, Hampton Va., May 1979.