D39

N85-16976

THERMAL DESIGN OF THE SPACE SHUTTLE SOLID ROCKET BOOSTER

Robert R. Fisher, Jerold L. Vaniman, and William J. Patterson
NASA/Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ABSTRACT

The challenge of designing reusable space transportation systems has resulted in defining new and unique requirements. These requirements led to development of new Thermal Protection Systems (TPS) to meet the quick turnaround and low cost required for reuse of the SRB hardware. The TPS development had to take into account the ease of application, changing ascent/reentry environments, and the problem of cleaning the residual insulation upon recovery. This development led to a sprayable ablator TPS material which was developed at the Marshall Space Flight Center (MSFC). This paper discusses the challenges that were involved in designing and development of this unique thermal system.

INTRODUCTION

During the early stage of the Solid Rocket Booster (SRB) design, thermal design environment data were not well developed. The initial low heating rates predicted indicated that a "heat sink" design approach would be feasible and that no thermal protection material would be required. The structural design approach of the external skin line was primarily to simplify manufacture. Examples of the structural design approach are shown in Figure 1 by the attach ring and kick ring protuberances, the protruding bolts in the nose cap, frustum, and aft skirt, and the externally milled-out forward skirt.

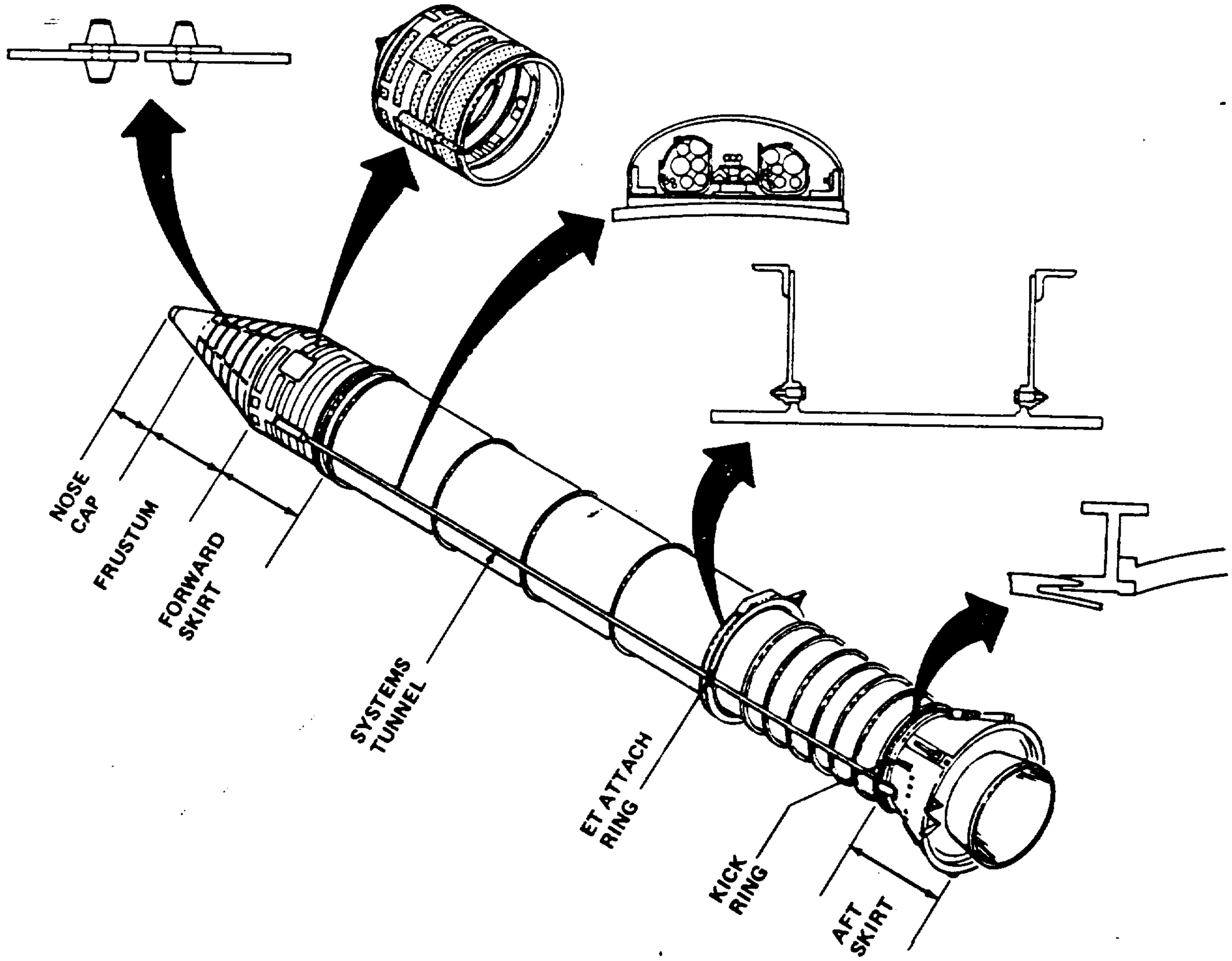

Figure 1. Sketch of SRB Showing Structural Elements.

As design trajectories changed and aerodynamic heating data from wind tunnel tests became available, the thermal design environment became much more severe, significantly increasing the predicted structural temperature levels. Maximum structural temperatures predicted for an uninsulated SRB are shown in Table 1. The allowable maximum temperatures for all SRB elements with the exception of the steel Solid Rocket Motor (SRM) case were exceeded, as shown by comparison to Table 2. Therefore, it was concluded that the "heat sink" approach was no longer feasible and that an external TPS would be required to maintain acceptable temperatures.

TABLE 1. MAXIMUM STRUCTURAL TEMPERATURES PREDICTED FOR AN UNINSULATED SRB

SRB Element	Maximum Temperature Range
Aluminum Structure	
o Nose Cap	310°F to 820°F
o Frustum	310°F to 460°F
o Forward Skirt	240°F to 500°F
o Systems Tunnel	410°F to 590°F
o Aft Skirt	295°F to 530°F
Steel Structure	
o ET/SRB Attach Ring	380°F to 700°F
o Kick Ring	425°F to 600°F
o SRM Case	140°F to 480°F

TABLE 2. SELECTED SRB THERMAL DESIGN LIMITS

Component	Maximum Allowable Temperature
o Reuseable Structure	
- Aluminum	300°F
- Steel	500°F
o Parachutes	200°F
o Electrical Wiring	200°F to 250°F
o Pyrotechnic Components	120°F to 250°F
o Sealant Material (Fastener and faying surfaces corrosion protection)	300°F
o Electronic Components	122°F to 185°F

TPS DEVELOPMENT CHALLENGE

The initial material under consideration was bonded cork, due to its availability and extensive prior use as an ablative insulation. However, it was recognized early in this program that the cork presented serious drawbacks from initial application time/cost and refurbishment for multi-flight use. The cork bonding process on major flight hardware structures is extremely labor intensive, resulting in significant cost penalties over a large number of vehicles. Also, the high density cork with its discreet layer of adhesive on the metallic substrate proved to be extremely difficult to remove during refurbishment studies.

Therefore, the initial challenge to the SRB project was the development/qualification of a primary TPS system for large acreage application (nose cap, frustum, and forward skirt). The drivers for this development were as follows:

a. Thermal performance in 10 to 15 Btu/ft^2-sec range.

b. Low material density/high thermal efficiency.

c. Low material cost.

d. Applicable to spray processing utilizing robot technology.

e. Compatible with the Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), and Kennedy Space Center (KSC) facility restrictions.

f. Spray/cure process relatively insensitive to environment variables.

g. High material strength/damage tolerance.

h. Ease of removal for refurbishment.

This rather formidable set of requirements was the focus of a large scale development activity by Materials and Processes Laboratory within MSFC. Following an intensive formulation screening and spray development phase, a system was chosen which utilized an aromatic, amine-cured, urethane-modified epoxy binder (or matrix resin) filled with glass and phenolic microballoons as well as glass reinforcing fibers. The system was demonstrated to be routinely sprayed in 1/4-in. thickness using chlorinated solvents as the spray carrier. The ablator composition, designated as Marshall Sprayable Ablator (MSA-1) is shown in Table 3.

The ablator is routinely sprayed in a spiral-wrap, continuous mode by robot manipulator and requires an elevated temperature cure of 150°F to 160°F for a 6-hr period. The cured MSA-1 material is characterized by properties as shown in Table 4.

TABLE 3. MSA-1 FORMULATION

Component	% By Weight
Phenolic Microballoons	37.7
Glass Microballoons	12.6
Chopped Glass Fibers (1/4 in.)	1.3
Milled Glass Fibers (1/16 in.)	3.1
Crest 7344 (Resin)	36.8
Crest 7119 (Catalyst)	5.1
Bentone 27 Clay	3.5
Ethanol (Bentone Activator)	-

Spray Solvents: 60/40 volume percent of methylene choloride to perchloroethylene

TABLE 4. MSA-1 CURED MATERIAL PROPERTIES

Flatwide tensile strength	80 to 100 psi at 75°F
Density	15 to 17 lbs/ft^3
Strain compatibility	1.6% at 75°F
Thermal conductivity	0.48 to 0.6 Btu-in/ft^2-hr-°F
Heat rate limit	10 to 15 Btu/ft^2-sec
Flammability	Self extinguishing on 1/8-in. Al substrate (NHB 8060.1)

THERMAL CHARACTERIZATION

Once the MSA-1 met the material requirements, thermal characterization was required for development of computer thermal models which could size the SRB TPS. The MSA-1 material performs as a charring ablator and, therefore, requires that the material ablation properties be determined, as well as the usual thermal properties of specific heat and thermal conductivity, etc. Thermal test facilities utilized for the MSA-1 thermal characterization were selected on their ability to simulate design thermal environment parameters such as heat rate, enthalpy levels, and aerodynamic shear forces. A Hot Gas Facility (HGF) was designed and built at MSFC for the purpose of screening candidate TPS and verifying design configurations. The von Karman Gas Dynamic Facility wind tunnel "C" at the Arnold Engineering and Development Center (AEDC), Tullahoma, Tennessee, was used extensively to obtain TPS thermal characterization data.

Flat panel specimens were prepared with the MSA-1 material sprayed on an aluminum substrate with the same surface finish as the SRB structure as shown on Figure 2. The panels were subjected to known heating rates for specific periods of time. The aluminum substrate temperature was monitored during the test and the MSA-1 material remaining after the test was measured. A typical post-test MSA-1 panel is shown in Figure 3. An ablation rate was determined by dividing the amount of material lost by the total test time. This type of data was obtained over the applicable heat range for the MSA-1, plotted and a nominal curve fit determined as shown on Figure 4. Thermal computer models were developed using the ablation rate curve. Effective MSA-1 material properties, such as ablation temperatures, heat capacitance, and thermal conduction values were adjusted in the computer models until the best correlation was obtained. With the thermal characteristics for the MSA-1 determined (Table 5), thermal models were developed to predict inflight structural temperatures with a specified thickness of MSA-1 material.

Figure 2. Pretest Photo of 1/4-in. Thick MSA-1 Panel to be Tested in Hot Gas Facility.

ORIGINAL PAGE IS
OF POOR QUALITY

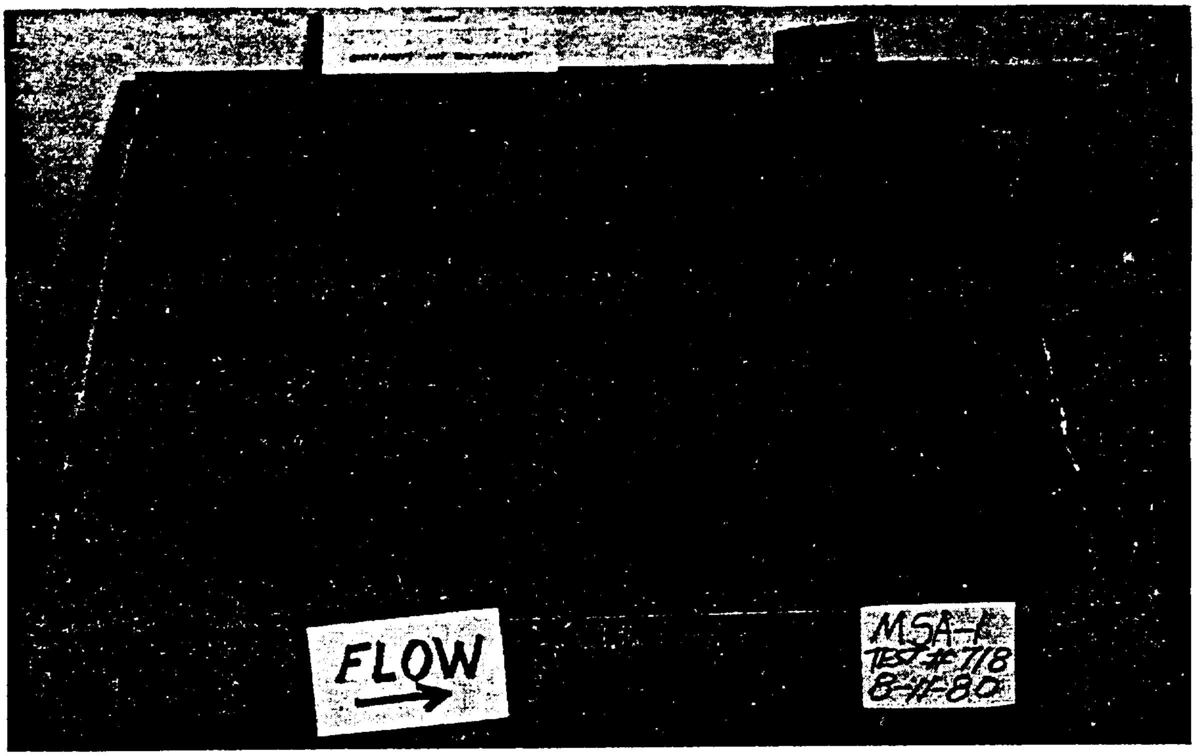

Figure 3. Post-Test Photo of 1/4-in. MSA-1 Panel Tested in Hot Gas Facility. Test Duration: 60 sec; Average Heating Rate: 13.5 Btu/ft²-sec (12 to 39 Btu/ft²-sec)

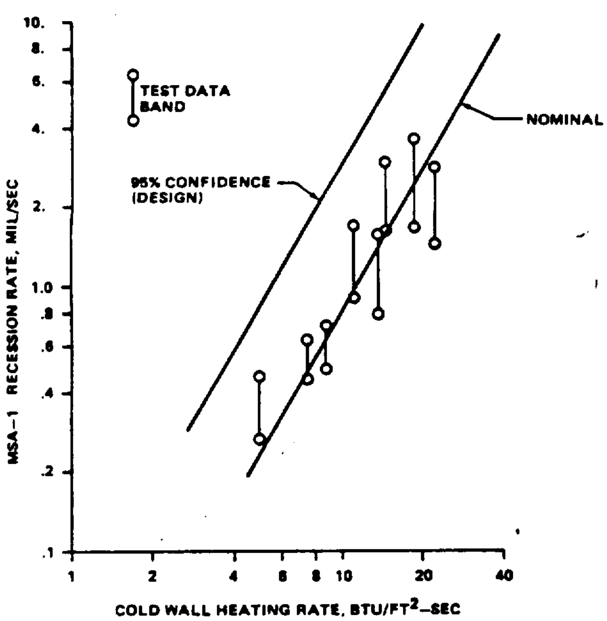

Figure 4. Recession Rate Versus Heating Rate for MSA-1 Panels Run at AEDC in Tunnel C.

TABLE 5. MSA-1 THERMAL CHARACTERISTICS USED IN COMPUTER MODEL

Parameter	Value
Density, lb/ft^3	16
Thermal Conductivity, Btu-in/ft^2-hr-°F	70°F to 600°F; 0.32 to 0.46
Specific Heat, Btu/lbm-°F	70°F to 600°F; 0.17 to 0.35
Recession Rate, mil/sec	$0.0501\ Q_{cw}^{1.754}$
Ablation Temperature, °F	620

Note: Q_{cw} = Cold Wall Heat Rate

TPS SIZING

After thermal computer models were developed, the next challenge was to size the TPS to the SRB. A 95 percentile deviation of the nominal ablation rate curve (Fig. 4) was used to size the MSA-1 thicknesses for the SRB structure. This conservative design approach ensures adequate thermal protection without undue weight penalty. A "design" heating environment, developed by perturbating trajectory parameters such as air density, vehicle angle of attack, wind direction, etc., was also utilized for sizing the TPS to cover "worst case" conditions. Aerodynamic heating rates vary at different locations on the SRB due to boundary layer growth, SRB configuration, influence of adjacent protuberances and influence of the adjacent External Tank (ET) and Orbiter. The aft areas of the SRBs are heated by radiation from its own SRM plume and from the Orbiter engine plumes. Thermal computer models were constructed for each SRB structural configuration requiring TPS and the appropriate heating environments for the ascent and descent portions of the flight imposed. Various MSA-1 thicknesses were then analysed at each location until one was found that would maintain the structure within the design temperature limits. Results of these analyses indicated MSA-1 material could furnish adequate thermal protection on the SRB nose cap, frustum, forward skirt, and a significant portion of the systems tunnel, as shown on Figure 5. However, the maximum sprayable thickness of MSA-1 was found to be limited to 1/4 in. to ensure consistent material characteristics. High heating rates on the aft attach ring, kick ring, aft portion of the systems tunnel and the aft skirt precluded utilization of MSA-1 on these structures due to thickness limitation, and/or low tolerance to airstream shear forces. Consequently, cork insulation was utilized on the aft skirt and local areas on the systems tunnel. However, phenolic glass fairings were selected to protect the aft attach ring and kick ring areas. This design was driven by the requirement for easy refurbishment, the ring structural configurations and the high (130 Btu/ft^2-sec) Space Shuttle Main Engine (SSME) plume impingement heating during SRB separation. The SRB TPS is shown on Figure 6.

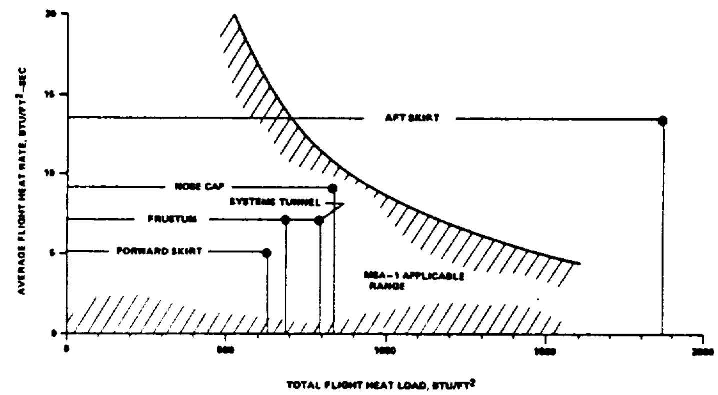

Figure 5. SRB Elements TPS Thermal Requirements Compared with the Thermal Capability of MSA-1.

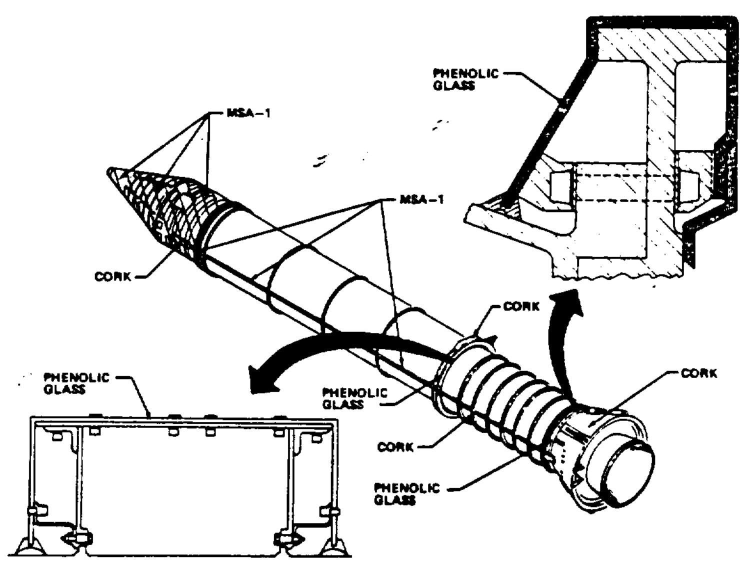

Figure 6. Sketch of SRB Showing TPS Utilized.

TPS VERIFICATION

After the MSA-1 had been analytically sized, verification tests were performed to verify the thermal and structural integrity of the baselined TPS to physically survive simulated flight pressure and thermal loads.

The philosophy used in planning the verification test conditions was:

a. Utilize a heating rate representative of the average expected during ascent, staging, and descent.

b. Select a test time adequate to produce the maximum predicted integrated flight heat load.

c. Orientate the TPS test panel in the test facility such that the flight aerodynamic pressure loads can be simulated without compromising the average heating rate determined in (a) above.

d. Provide a combined environments test to simulate heating simultaneously with structural and acoustic loads.

The success criteria established for the TPS verification tests were as follows:

a. The predicted integrated flight heat load must be applied.

b. The measured TPS recession rate must not exceed the 95 percentile design value.

c. The substrate temperature must not exceed the maximum predicted flight temperature.

d. The TPS must physically survive the combined imposed environments of thermal, shear, acoustic, and pressure loads.

After the TPS successfully completed the verification test phase, it was certified as flight-worthy, and requirements for the minimum thicknesses were specified to the designers. Actual TPS coverage on an SRB may be greater than analytically determined patterns because of the economics involved in TPS application.

The MSA-1 spray development optimization, accomplished at MSFC, allowed a technology transfer to KSC where the SRB prime contractor, United Space Boosters, Inc. (USBI), currently applies MSA-1 to all forward elements of SRB flight hardware (as well as to systems tunnel cover segments). Application of MSA-1 on the frustum is shown on Figure 7. This material has proven to be totally compatible with the

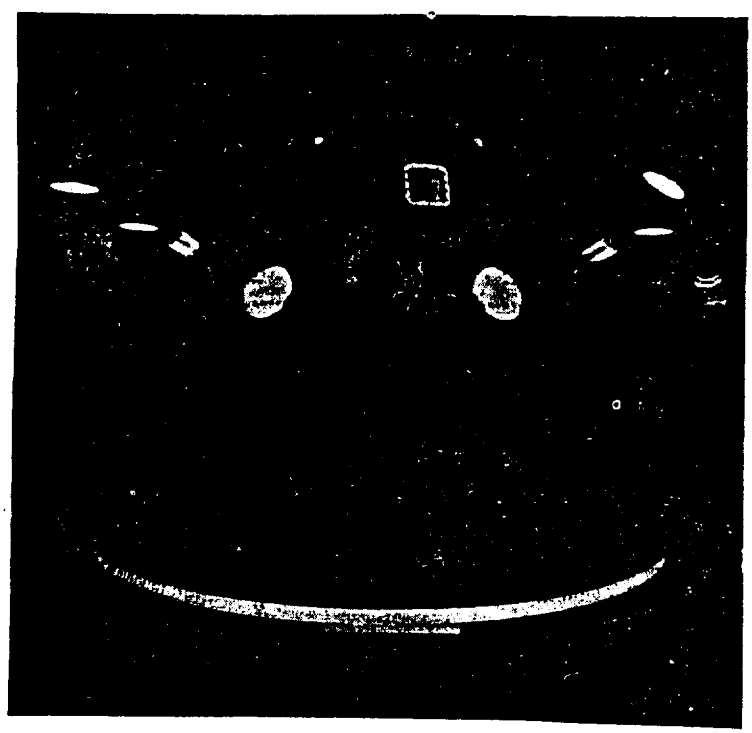

Figure 7. SRB Frustum with MSA-1 Applied.

ORIGINAL PAGE IS
OF POOR QUALITY

rigorous Florida EPA requirements and is applied in the vertical assembly building (VAB) low bay area with only modest temperature/humidity controls. The nonflammable spray solvents are compatible with the stringent VAB flammability requirements. The ease of removal of MSA-1 by high pressure water impingement (hydrolaser) has proven to be exceptionally valuable, since it allows rapid removal of material from a recovered structure and results in a residue-free surface without damaging the protective Bostik paint system on the aluminum. The cured MSA-1 is typically sprayed with a white hypalon-based topcoat (Fig. 8) to minimize moisture absorption.

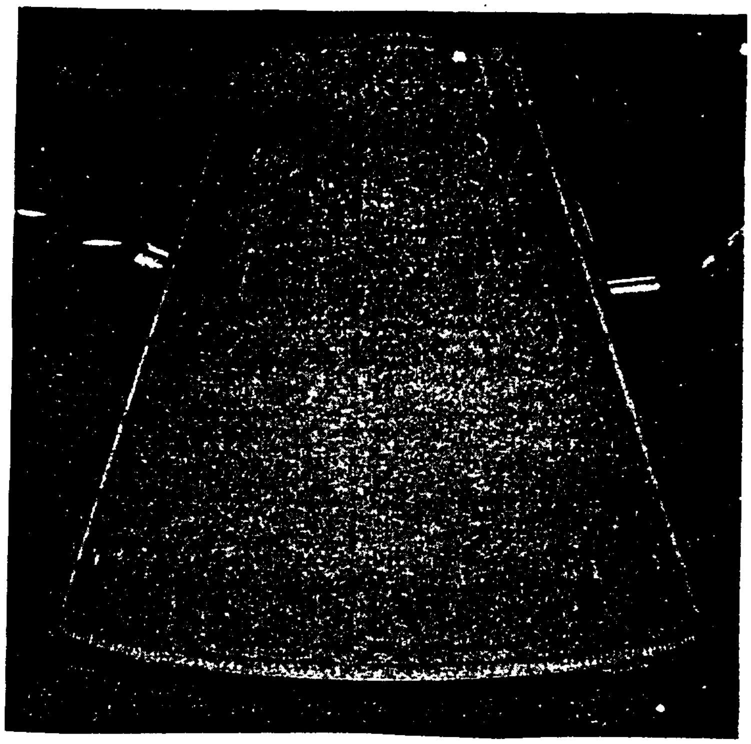

Figure 8. SRB Frustum with MSA-1 and Hypalon Paint Applied.

Replacement of the labor-intensive cork bonding operation by robotic spray application of MSA-1 results in a cost reduction of at least $100,000 per shipset (based on two nose caps, two frustums, and two forward skirts). This estimate includes the significant savings realized in removal of MSA-1 versus cork on the forward skirts and frustums.

CONTINUING TPS CHALLENGES

Although MSA-1 has effectively met the challenges of cost and refurbishment for the nose cap, frustum, and forward skirt, the aft skirt still requires cork insulation. The thermal environments for this structure were predicted to be considerably above the performance range for MSA-1, considering its thickness limitation (1/4 in.). Considering the undesirable features of cork mentioned earlier, a second challenge was presented in the form of an improved ablation system which could accommodate greater application thicknesses to provide more thermal protection.

Thus, as soon as the MSA-1 optimization/qualification was completed, the development of a second generation sprayable ablator was undertaken to provide a system that could be sprayed in thicknesses up to 1/2 in. to replace cork on the clean-skin areas of the aft skirt. The MSA-2 development philosophy was based on minimizing the modification of MSA-1 formulation/processing to allow carryover of the maximum amount of MSA-1 experience and technology, as well as maintaining its favorable chemical and thermal properties. While the specific target for MSA-2 was to replace bonded cork on the aft skirt, it is currently planned to utilize MSA-2 as a single system for all SRB sprayed ablator requirements.

The original MSA-2 formulation development work involved screening several epoxy and modified epoxy resin binders, including conventional Epon 828 resin, rubber-modified 828, and phenolic-modified 828. As these formulations were screened by spraying 1/2 in. thick test panels, it became evident that curing stresses and shrinkage considerations would be the overriding factors in defining the formulation. A substantial effort was carried out to minimize cure stress, both from formulation ingredient selection and application/cure parameters. As a result of this effort, the flexible epoxy resin EC-2216 (3M Company) was chosen as the binder, together with replacement of 15 percent by volume of phenolic microballoons (from the MSA-1 formulation) with ground cork. The cork particles provided additional stress relief in the matrix resin to minimize cracking/delamination. The final MSA-2 formulation is represented in Table 6. The sprayed formulation is typically applied to the substrate in two 1/4-in. layers, with up to 1 hr delay between applications. The current elevated temperature cure utilized for test panels is 150°F to 160°F for a 6-hr period.

TABLE 6. MSA-2 FORMULATION

Component	% By Weight
EC-2216 Resin/Catalyst	43.04
Ground Cork	3.12
Phenolic Microballoons	32.88
Glass Microballoons	12.89
Chopped Glass Fibers (1/4 in.)	1.29
Milled Glass Fibers (1/16 in.)	3.22
Bentone 27 Clay	3.55

(A small amount of ethyl alcohol is added to activate the Bentone for viscosity control.)

SPRAY SOLVENTS: 1/1 mixture of perchloroethylene and methylene chloride.

The cured ablator, MSA-2, is characterized by the properties as shown in Table 7. Recession rates for MSA-2 as a function of cold wall heating rate derived from TPS panels tested at AEDC are shown on Figure 9. The thermal evaluation performed to date on 1/2-in. thick MSA-2 panels has been quite successful, and this system potentially provides the means for replacing cork on the aft skirt as shown on Figure 10. The MSA-2 system appears, at this point in its development, to meet all the design challenges. The development/qualification schedule for MSA-2 calls for qualification testing and all-up spray verification to occur in late 1983 with implementation on SRB hardware by early 1984.

TABLE 7. MSA-2 CURED MATERIAL PROPERTIES

Flatwise tensile strength	60 to 80 psi at 75°F
Density	16 to 18 lbs/ft^3
Strain compatibility	1.4 to 1.6%
Thermal conductivity	0.4 to 0.5 Btu-in/ft^2-hr-°F
Heat rate limit	10 to 15 Btu/ft^2-sec
Flammability	Self extinguishing on 1/8-in. Al substrate (NHB 8060.1)

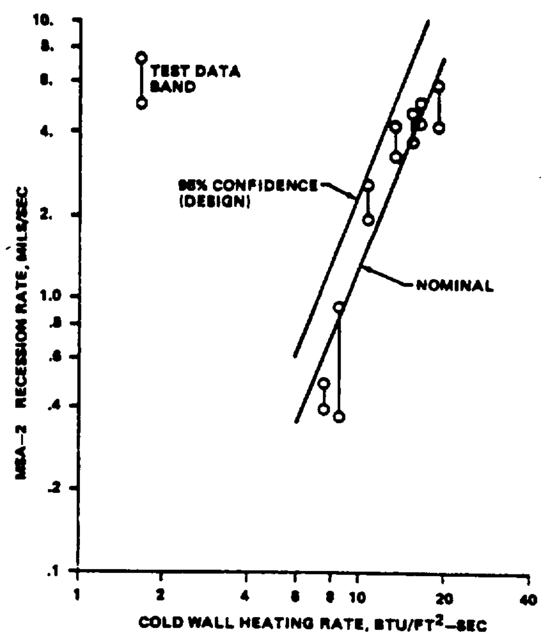

Figure 9. Recession rate versus heating rate for MSA-2 Panels Run at AEDC in Tunnel C.

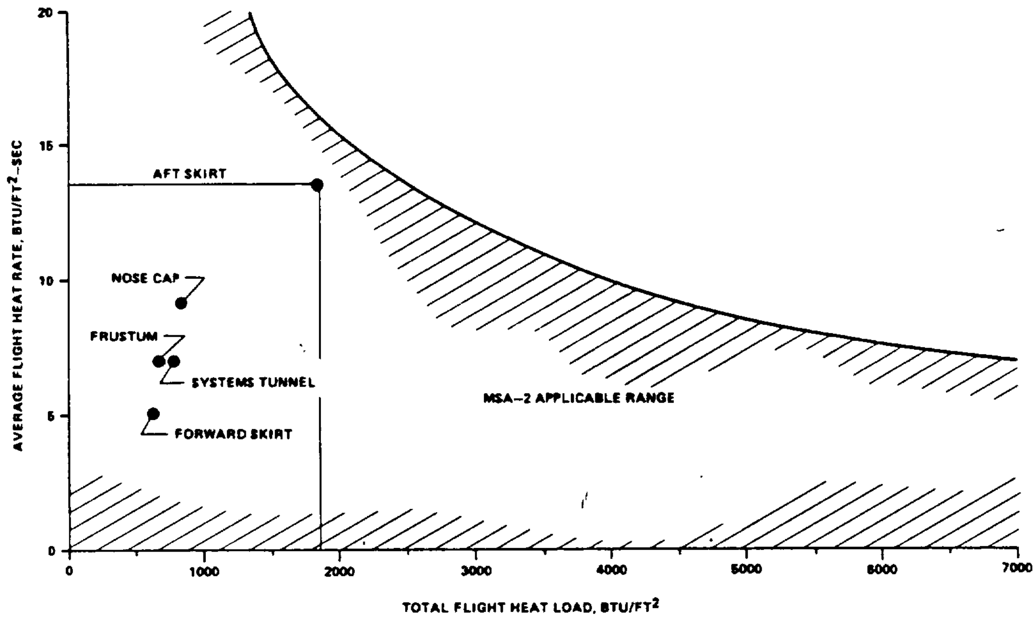

Figure 10. SRB Elements TPS Thermal Requirements Compared with the Thermal Capability of MSA-2.

The estimated cost reduction in replacing cork with MSA-2 on the aft skirt is at least $50,000 per shipset (2 aft skirts). This estimate includes the significant cost savings in refurbishment for MSA-2 versus cork.

FLIGHT RESULTS AND FUTURE IMPROVEMENTS

The MSA-1 thermal protection material has been successfully flown on six Space Shuttle flights and has performed as expected. Temperature sensors were installed at selected locations on the SRB structure covered by MSA-1 and were recorded throughout flight. These temperature measurements correlated well with the predicted temperatures as shown on Figure 11. However, the flight trajectories flown to date have resulted in aerodynamic heating environments that are significantly less severe (>50%) than the design heating environment used to size the SRB TPS. Consequently, only limited MSA-1 ablation has occurred on the Space Shuttle flights to date. This has instigated a SRB TPS optimization study at MSFC with the goal to minimize SRB TPS requirements. It is believed that the current thermal design environments can be made more commensurate with planned flight thermal environments by revising the current methodology applied, and by incorporating new data obtained from flight and wind tunnel tests.

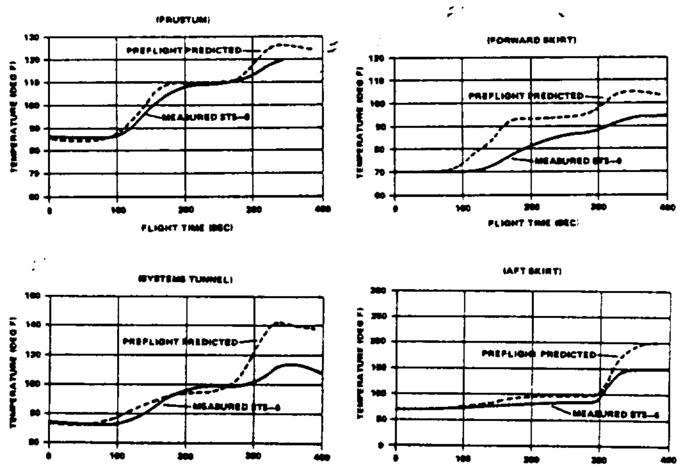

Figure 11. Typical SRB Structural Temperature Responses when Protected with MSA-1.

Changes in the ground rules for establishing SRB TPS are also being contemplated. The SRB TPS requirements were determined based on a design heating environment with the structural constraint being reusability. However, the design environment would seldom be encountered during an actual flight. Therefore, TPS reductions on the SRB should be possible if the TPS requirements for reusability were based on a "nominal" heating environment and the design thermal environment considered only for the ascent portion of flight to assure SRB structural integrity. If a design heating level was encountered, Space Shuttle safety would not be compromised, but the SRB reusability would have to be evaluated.

Studies are also in progress to simplify TPS closeout and installation on the SRB systems tunnel and the aft attach ring areas. The attach ring structural configuration modification being pursued is to change the angle stiffener at the edge of the ring to a flat ring stiffener. This change will significantly reduce aerodynamic heating effects as it will eliminate the small radius angle edge projecting into the airstream. Flight experience has also enabled a significant reduction in the design SSME plume impingement heating rates that occur during SRB separation. However, the sealant material on the ring fasteners will still have to be thermally protected or a new sealant material selected that will survive temperatures in the neighborhood of 500°F to 600°F. The systems tunnel configuration currently used requires a significant amount of time to close out the gap between the systems tunnel fairing and the tunnel floor plate. This precludes hot gas (high temperature boundary layer air) intrusion which would damage electrical wiring and could auto-ignite the range safety linear shaped charge housed within the fairing. This closeout is required after the SRB's are stacked on the Mobile Launch Platform (MLP), and has a direct impact on the launch turnaround time. An entirely new systems tunnel design is being evaluated that would significantly reduce the TPS closeout time on the MLP.

SUMMARY

The challenge of effectively providing thermal protection for the SRB has been accomplished. A TPS material, MSA-1, has been developed at MSFC and flown successfully on six Space Shuttle flights. However, cork insulation is currently being flown on the aft skirt because the thermal environments are considerably above the performance range for MSA-1, considering its thickness limitation of 1/4 in. Application/refurbishment costs of this cork is not cost effective. Consequently, development of a second generation sprayable ablator, MSA-2, is underway at MSFC to furnish an economical replacement for the cork. Results of thermal tests performed to date on 1/2-in. thick MSA-2 panels have met all expectations. The development/qualification schedule for MSA-2 calls for qualification testing and all-up spray verification to occur in late 1983 with implementation on SRB hardware by early 1984.

Flight experience, wind tunnel thermal data, and thermal protection material improvements are continuing to be utilized at MSFC to make the SRB TPS more efficient and economical. Structural configuration changes for the aft attach ring and systems tunnel are also being pursued to further simplify/eliminate SRB TPS requirements. Consequently, challenges still exist to establish a thermal protection system for the SRB that can truly be considered as operational.

REFERENCES

1. "Space Shuttle Aerodynamic Heating Data Book," Shuttle Vehicle Booster-Ascent - Volume III, SD73-SH-0180-3A, September 1978.

2. "Preliminary Shuttle Operational Flight Environments - SSME Plume Impingement to SRB's During Staging," ED33-83-2, January 12, 1983.

3. "SRB Reentry Thermal Environment Data Book," SE-019-053-2H, Rev. C, August 1981. Part 1 of 3, Part 3 of 3 and Appendix C.

4. "Space Shuttle Program Thermal Interfaces Design Data Book." SD74-SH-0144D, December 1977.

5. "Natural Environments for the Space Shuttle Solid Rocket Motor Booster," SE-019-043-2H, May 1975.

6. "SRB Thermal Design Data Book," SE-019-068-2H, April 1976.

7. "Tests to Evaluate an Expediting Technique for Postflight Refurbishment of SRB TPS," EP44(82-71), July 1982.

8. "Data Report for MSA-2 Development Tests," EP44(82-72), July 1982.

9. "SRB TPS Aeroheating Test Data Assessment," EP44(83-77), May 1983.

10. "SRB Materials Test and Evaluate in NASA-MSFC Hot Gas Facility, NASA-Ames 36 Foot HWT and AEDC Tunnel C," LMSC-HREC TMD 497497, November 1977.

11. "SRB TPS Verification Test Report," SE-019-186-2H, January 1981.

12. Vaniman, J., Fisher, R., Wojciechowski, and Dean, W.: "Ablative Thermal Protection System," presented at the International Conference on High Temperature Corrosion, March 2-6, 1981.

13. Solid Rocket Moto.. Thermal Protection System Materials Processing and Refurbishment Data Transfer Document, NASA IN-EH-77-01, 1977.

14. Patterson, W. J.: Strain Compatibility Assessment for SRB Sprayable Ablator MSA-1, NASA TM-78228, 1979.