Ablative Thermal Protection for Space Tug Multipass, Aerobraking Entry

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Analytical studies had found the employment of an aerobraking trajectory for return of a reusable Space Tug from geosynchronous missions to be feasible and practical. To establish the minimum weight ablative dome heat shield, trajectories involving 2 and 30 perigee passes were investigated, both analytically and by plasma arc testing. Silicone-base ablators with densities of 15, 30, and 55 lb/ft^3 were selected for evaluation. All models withstood the multipass exposures without deleterious surface recession or char erosion. Dome heat shield weights based on optimum ablative compositions indicated that ablators are a highly efficient thermal protection system for these missions.

Nomenclature

H = enthalpy
p = pressure
$\dot{q}$ = heating rate
Q = total heat
t = time
V = velocity
ρ = density

I. Introduction

IN a study conducted by The Boeing Company,[1] utilization of aerodynamic drag for braking a reusable space tug from the geosynchronous orbit back to a low earth orbit was investigated. Figure 1 shows typical trajectory profiles for a space tug conventional return and for an aerobraking return. The potential advantage of aerobraking stems from the reduced propellant requirement for the return portion of the mission.

Boeing studied the conversion of its baseline (retrorocket-braked) tug configuration (Fig. 2) to one with aerobraking capability by retrofitting with an aerobraking kit. This kit incorporated the additional structures, materials, and subsystems required by the aerobraking mission for thermal protection, increased drag, aerodynamic stability, guidance, control, and payload protection. Round trip payload capabilities were established as a function of number of aerobraking passes; then, vehicle and payload weights were extrapolated to a 65,000-lb tug.

Based on these data, the Boeing study reached five conclusions. 1) Employment of an aerobraking trajectory for return of a space tug from a geosynchronous orbit to the Space Shuttle orbit is both feasible and practical. 2) Payload capability of an aerobraked tug is maximized by missions having 25-30 atmospheric passages (duration of return mission is 4-7 days). 3) A one-day return mission (2-5 atmospheric passages) generates a more severe thermal and pressure environment, necessitating higher structures and thermal protection weights at the expense of payload. 4) Longer mission durations necessitate increased weights for the electrical power system, for reaction control system fuel, and for astrionic systems redundancy. 5) A geosynchronous round-trip mission with 3000 lb of payload requires a conventional tug with a specific impulse of 470 sec and a mass fraction of approximately 0.895. However, aerobraking makes it possible to accomplish this mission with state-of-the-art technology, using a specific impulse of 460 sec and a mass fraction of 0.862. If the higher specific impulse and mass fraction are achievable and used in conjunction with aerobraking, then approximately 6500 lb of payload could be roundtripped in a geosynchronous mission.

The entry attitude of the aerobraked tug was with the propulsion end down. Therefore, a dome structure and side walls had to be provided to protect the engine components and fuel tanks from the entry heating environment. The dome must be swung outward to facilitate engine firing for deorbit. For a 30-pass entry mode, peak dome temperatures were calculated to be on the order of 2000-2500°F and the dome was designed as a radiative heat shield. Superalloy or coated columbium were recommended as the dome materials. For a 2-pass entry, dome equilibrium temperatures would exceed 3000°F and a titanium dome structure with an ablative heat shield was selected as the thermal protection approach. In sizing the ablative heat shield for the dome of the aerobraked tug, Boeing selected a 55 lb/ft^3 density ablator and assumed that all charred ablator material would be lost or rendered ineffective between entry passes. These assumptions were highly conservative and yielded high heat shield weights for the 2-pass entry mode for which ablative thermal protection had been selected. This, in part, accounted for the greater payload capability of the 30-pass aerobraking mission.

The feasibility of utilizing lightweight ablative dome heat shields for aerobraking thermal protection was studied by Martin Marietta Corporation in a NASA/MSFC program. (Contract NAS8-27161). The objectives of this study were to experimentally establish the char retention capabilities of ablators during multipass entry heating and to ascertain realistic ablative heat shield weights for an aerobraked space tug.

II. Ablative Heat Shield Requirements

The Martin Marietta Corporation study of ablative heat shielding for aerobraking entry was based on Boeing's 14-ft diam cylindrical tug with a 2:1 elliptical aluminum dome. A high drag version of this configuration containing a 60° flare at the payload end was also investigated (Fig. 3). Trajectories involving 2 and 30 perigee passes were considered. Peak heating rates for the low drag configuration were 127 Btu/ft^2 sec for a 2-pass entry and 35 Btu/ft^2-sec for a 30-pass entry. For the high drag configuration, peak heating rates were 85 Btu/ft^2-sec for the 2-pass entry and 21.6 Btu/ft^2-sec for the 30-pass entry. Stagnation point heating rate histories for two-

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Index categories: Material Ablation; Thermal Modeling and Experimental Thermal Simulation.

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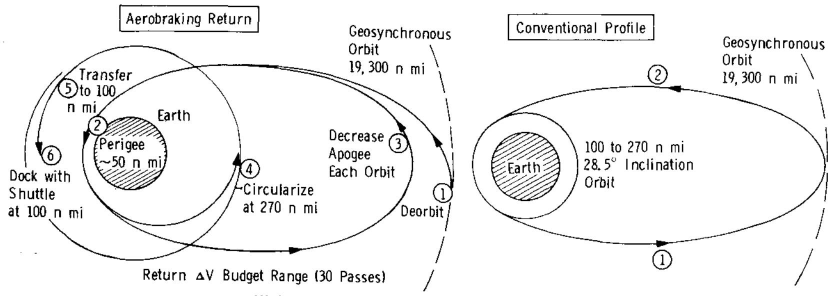


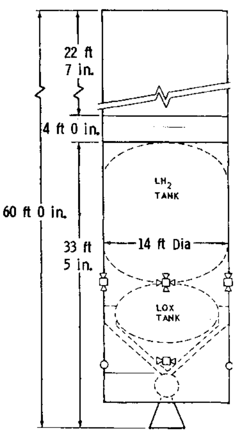
Return ΔV Budget Range (30 Passes)

	Minimum	Maximum
① Deorbit	5993 ft/sec	5993 ft/sec
④ Circularize	133 at 100 n mi	380 at 270 n mi
⑤ Transfer to 100 n mi	--	656
⑥ Docking Reserves	324	1371
Total	6450 ft/sec	8800 ft/sec

ΔV Budget

① Ascent	14,500 fps
② Descent	14,500 fps

Fig. 1 Tug trajectory profiles.



Weight Estimate (lb)

Payload Adapter			200
Astrionics Module			1,960
Electrical	515		
Avionics	842		
Structure	300		
Thermal	303		
Propulsion Module			50,868
Propellant		45,000	
Inerts		5,868	
Engine	639		
Prop/Mech	801		
Thermo/Micro	573		
Structure	2912		
Cont & Residual	943		
Total Space Tug Weight			53,028
Mass Fraction			0.849

Fig. 2 Conventional Tug (starting point).

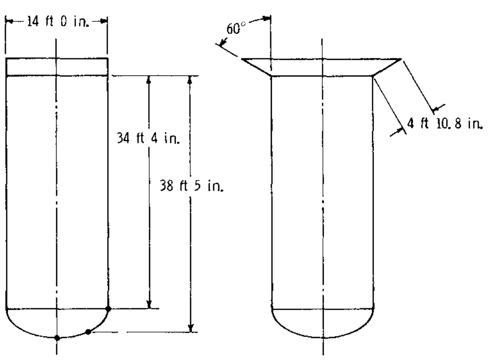


Fig. 3 Aerobraking configuration concepts.

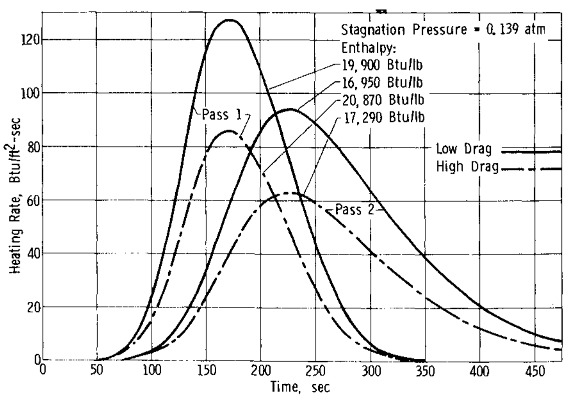


Fig. 4 Stagnation heating rate history for 2-pass aerobraking entry.

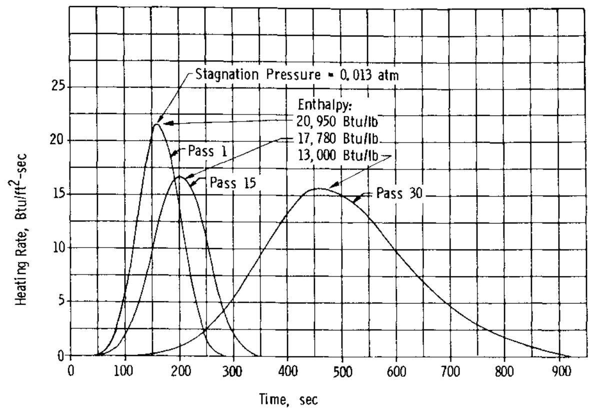


Fig. 5 Stagnation heating rate history for high-drag configuration, 30-pass aerobraking entry.

pass entry modes are shown in Fig. 4. Stagnation point heating rate histories for a 30-pass entry are shown in Fig. 5. Peak stagnation pressures and recovery enthalpies are also listed on these figures.

Three Martin Marietta silicone-base ablators contained in a fiberglass honeycomb core were considered for these missions: ESA-5500, $\rho = 55$ lb/ft^3; ESA-3560, $\rho = 30$ lb/ft^3; and SLA-561, $\rho = 15$ lb/ft^3. The materials were selected for their low temperature flexibility, ease of application, and proven performance in flight and ground simulation testing of vehicles such as PRIME, PAET, Viking, and Space Shuttle. The ablators are fully characterized. Pertinent thermal and mechanical properties are listed in Table 1.

Ablator thicknesses were calculated for the dome stagnation point and for two other locations on the dome (50 and 10% of stagnation point heating). The ablators were backed up by the aluminum dome with an effective thickness of 0.156 in. at the stagnation point and 0.083 in. at the other locations. Maximum allowable aluminum temperature was 300°F. Temperature at start of entry was 100°F for the first entry pass and 175°F for all subsequent entries. The 175°F temperature was based on the equilibrium temperature reached between entry passes with one-half solar constant (0.061 Btu/ft^2-sec) applied to the exterior of the heat shield. The required stagnation point ablator thicknesses are listed in Table 2. The higher density ablators were selected for the high heating rate mission and the lower density ablators for the lower heating rate missions in order to avert surface recession or mechanical erosion of the ablator char.

III. Aerobraking Heating Simulation

Twelve flat-faced, cylindrical ablator models were fabricated for plasma arc tests. Specimens were 2½-in. diam for 2-pass entry simulation and 8-in. diam for 30-pass entry

Table 1 Properties of silicone ablators

	ESA-3560F	ESA-5500	SLA-561
Ablator density, lb/ft^3	30	55	15
Char density, lb/ft^3	10.5	30.9	8.3
Ablator specific heat, Btu/lb-°F	0.26(70°F)	0.19(70°F)	0.30(70°F)
Char/specific heat, Btu/lb-°F	0.37(1000°F)	0.29(1000°F)	0.37(1000°F)
Ablator thermal conductivity, Btu/in.-sec-°R	1.3×10^{-6} (300°F)	3.0×10^{-6} (300°F)	0.7×10^{-6} (300°F)
Char thermal conductivity, Btu/in.-sec°R	5.0×10^{-6} (2500°F)	9.5×10^{-6} (2500°F)	$0.95\text{x}10^{-6}$ (2500°F)
Char Emissivity	0.80(2500°F)	0.85(2500°F)	0.92(2500°F)
Specific heat of gaseous products, Btu/lb-°F	0.6	0.6	0.6
Heat of depolymerization, Btu/lb	0	0	0
Order of decomposition reaction	2	2	2
Fraction of ablator that vaporizes	0.65	0.44	0.44
Tensile strength, psi	150(70°F) 350(−125°F)	140(70°F) 400(−125°F)	60(70°F) 150(−125°F)
Tensile elongation, %	9.5(70°F) 17.0(−125°F)	36.0(70°F) 60.0(−125°F)	2.5(70°F) 3.1(−125°F)

Table 2 Stagnation point ablator requirements

Entry configuration	Ablator	Thickness, in.	Weight lb/ft^2
2-pass low drag	ESA-5500	2.08	9.53
	ESA-3560	1.43	3.58
2-pass high drag	ESA-3560	1.36	3.40
	SLA-561	1.68	2.06
30-pass high drag	ESA-3560	2.13	5.35
	SLA-561	1.92	2.35

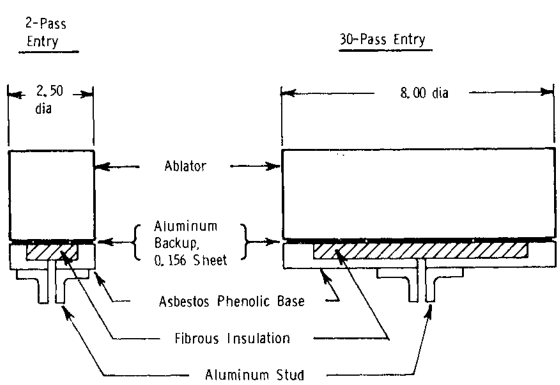


Fig. 6 Model configuration.

simulation (see Fig. 6). They were instrumented with thermocouples and were bonded to a 0.156-in. aluminum backup representative of the thermal mass of the dome structure. Ablator thicknesses were those calculated at the stagnation point for a peak aluminum temperature of 300°F.

Table 3 Comparison of flight and test heating

	Peak heating rate, Btu/ft^2-sec		Total heat, Btu/ft^2	
Entry mode	Entry heating	Test pulse	Entry heating	Test pulse
2-pass low-drag				
Pulse 1	127	120	11,590	11,250
Pulse 2	94	80	16,950	17,100
2-pass high drag				
Pulse 1	86	80	9950	9500
Pulse 2	63	55	11,740	12,650
30-pass high drag				
Pulse 1	20	20	2320	2290
Pulse 30	16	14	5600	5100

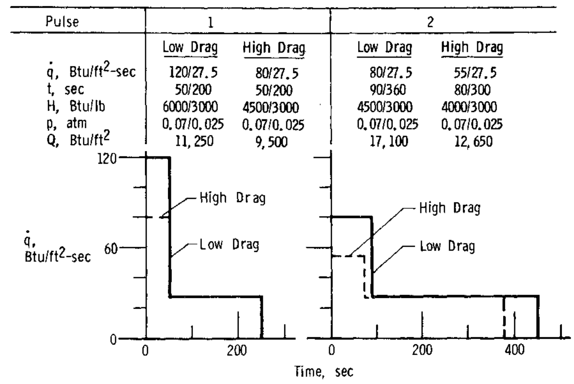


Fig. 7 Test pulses for 2-pass simulation.

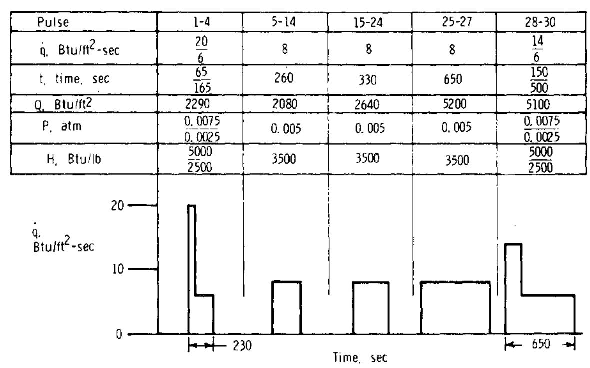


Fig. 8 Test pulses for 30-pass, high-drag simulation.

The models were exposed in the Martin Marietta plasma arc to two-step heat pulses representative of stagnation point heating. The 2½-in. diam models were tested in a 3-in. diam air stream; 8-in. diam models in a 10-in. diam air stream. The test pulses are shown in Figs. 7 and 8. The test conditions simulated the peak heating rates, heating times, and total heat of the multipass entries (Table 3). Stagnation pressures attained in the plasma arc were approximately one-half those associated with flight. Models were allowed to cool in a low pressure environment between successive exposures.

All models withstood the plasma arc tests without detrimental char erosion. In some models, minor char loss occurred at the model periphery where the honeycomb cells were open and provide only partial support for the ablator char. Typical model appearance after test is illustrated in Fig. 9. The sectioned view reveals the char cleavage planes characteristic of silicone-base ablators. In addition, a series of vertical fissures are evident, which result from the shrinkage process that accompanies char formation. These fissures were larger and more widespread in the low-density ESA-3560 and SLA-561 ablators than in the higher density ESA-5500 and were less pronounced in the 30-pass models because the lower

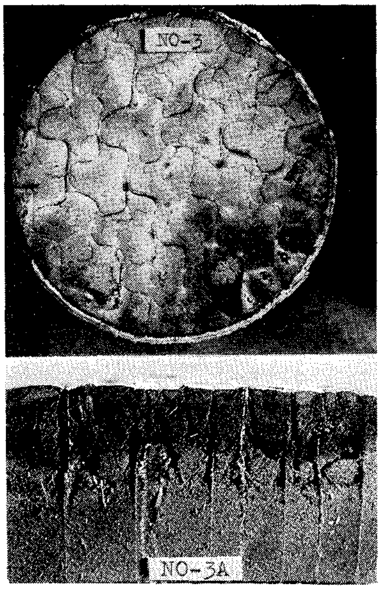


Fig. 9 Post-test appearance of EAS-3560 after simulated 2-pass, high-drag heating.

Table 4 Correlation of plasma arc test response

Test condition	Ablator	Internal temperature rise after final test pulse, °F Calculated	Measured	Final char thickness, in. Calculated	Measured
2-pass low-drag	ESA-5500	985	1015	0.595	0.702
2-pass high-drag	ESA-3560	450	550	0.633	0.745
30-pass high drag	ESA-3560	895	940	0.832	0.797

heat flux experienced by these specimens caused reduced char shrinkage.

Ablative heat transfer analyses were conducted for several test pulse conditions. Good agreement of calculated temperatures and char thicknesses with measured values were obtained as illustrated in Table 4.

IV. Heat Shield Design Concepts

Dome heat shield weights applicable to 2-pass and 30-pass aerobraking trajectories were determined for different ablators and ablator combinations. The surface area of the elliptical dome is 213.5 ft^2 and heating across the dome varies as shown in Fig. 10. To facilitate the weight assessment, ablator design curves for multipass entry heating (300°F peak aluminum backup temperature) were constructed as illustrated in Fig. 11 and the variations of ablator thickness over the dome semiarc length were derived as illustrated in Fig. 12. Calculated dome ablator weights are listed in Table 5.

Because the ratio of local heating rate-to-stagnation point heating rate varies from 1.00 at the stagnation point to 0.08 at the dome-cylinder tangency point, the use of a single ablation material over the entire dome constitutes a nonoptimum design from the weight standpoint. The three ablation materials ESA-5500, ESA-3560, and SLA-561 use the same silicone resin system and are supported by the same honeycomb core. Therefore, they are mutually compatible and can be used in combination. Criteria for selection of ablators in composite heat shields were based on limit heating rates for char stability: ESA-5500, $\dot{q} > 100$ Btu/ft^2-sec; ESA 3560, $25 < \dot{q} < 100$ Btu/ft^2-sec; and SLA-561, $\dot{q} < 25$ Btu/ft^2 sec.

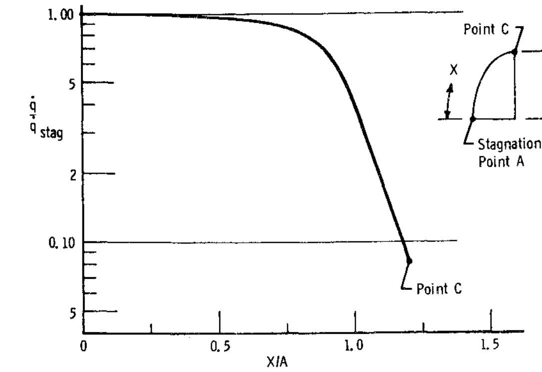


Fig. 10 Heating rate distribution for 2:1 ellipse.

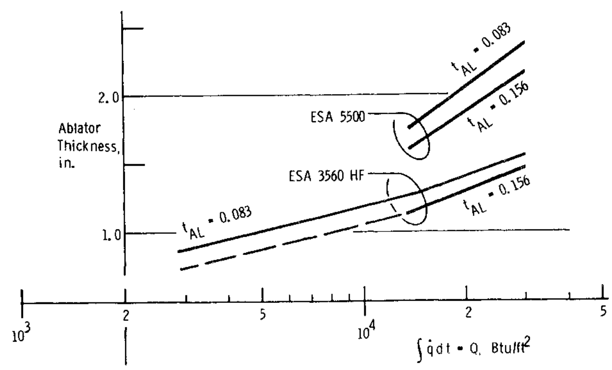


Fig. 11 Ablator design curve for 2-pass low-drag configuration.

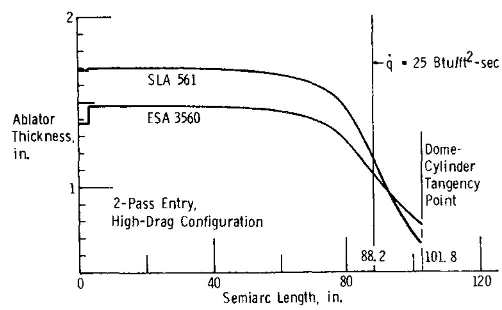


Fig. 12 Ablator thickness across elliptical dome.

For the 2-pass entry low drag environment, an ESA-3560 heat shield weighing 713 lb is the recommended design. Heating rates at the stagnation point exceed 100 Btu/ft^2-sec for approximately 60 sec during the first entry pass. Testing had shown that ESA-3560 can withstand the 125 Btu/ft^2-sec peak heating rate and an all ESA-3560 heat shield weighs only half as much as a composite ESA-5500/ESA-3560 heat shield. For 2-pass high-drag heating, a composite ESA-3560/SLA-561 heat shield weighing 622 lb is the recommended design. The weight of an all ESA-3560 heat shield would be 9% higher.

A composite ESA-3560/SLA-561 heat shield weighing 859 lb is also the recommended design for the 30-pass low-drag mission. An all SLA-561 heat shield would weigh only 500 lb and holds promise of meeting flight requirements. However, further testing and qualification of SLA-561 for this mission would be necessary. For the 30-pass high drag heating environment, an all SLA-561 heat shield weighing 437 lb is the recommended design.

Boeing's dome heat shield designs for 2-pass heating are compared with the recommended Martin Marietta designs in Table 6. For the low drag (no flare) configuration, Boeing established an ablator thickness of 3.32 in. at the stagnation point, 1.00 in. at the dome tangency point, and a total ablator weight of 2380 lb. The Martin Marietta design comprises 1.43 in. of ablator at the stagnation point and 0.82 in. at the

Table 5 Dome ablator weights

Entry trajectory	Vehicle configuration	Ablator material	Total ablator weight, lb	Comments
2-Pass	Low drag	ESA-5500	1840	Not recommended, too heavy
2-Pass	Low drag	ESA-3560	713[a]	Recommended design
2-Pass	Low drag	ESA-5500 to arc length = 71.4 in. Then ESA-3560	1395	Conservative design
2-Pass	High drag	ESA-3560	678	Conservative design
2-Pass	High drag	SLA-561	370	Potential minimum weight design
2-Pass	High drag	ESA-3560 to arc length = 88.2 in. Then SLA-561	622[a]	Recommended design
30-Pass	Low drag	ESA-3560	1056	Conservative design
30-Pass	Low drag	SLA-561	500	Potential minimum weight design
30-Pass	Low drag	ESA-3560 to arc length = 77.3 in. Then SLA-561	859[a]	Recommended design
30-Pass	High drag	ESA-3560	972	Conservative design
30-Pass	High drag	SLA-561	437[a]	Recommended design

[a] Weights of recommended designs.

Table 6 Two-pass thermal protection comparison

	Boeing (NAS8-27501)	Martin Marietta (NAS8-27161)
Low drag configuration		
Dome structure	Titanium, 405 lb	Alunimum, 255 lb
Ablation material	ESA-3560IIA (56 lb/ft^3)	ESA-3560 (30 lb/ft^3)
Thickness—stagnation point	3.32 in.	1.43 in.
Thickness—tangency point	1.00 in.	0.82 in.
Total heat shield weight	2380 lb	713 lb
High drag configuration		
Dome structure	Titanium, 395 lb	Aluminum, 255 lb
Ablation material	ESA-3560IIA (56 lb/ft^3)	ESA-3560 (30 lb/ft^3) and SLA-561 (15 lb/ft^3)
Thickness—stagnation point	3.20 in.	1.36 in.
Thickness—tangency point	1.00 in.	0.66 in.
Total ablator weight	2305 lb	622 lb

tangency point, with a total ablator weight of 713 lb. For the high drag (60° flare) configuration, ablator thicknesses are slightly lower than for the low drag configuration. The Boeing design weighed 2305 lb as compared to 622 lb for the Martin Marietta design.

For a 30-pass high-drag mission, the total dome weight, including the 437-lb SLA-561 ablator and 255-lb aluminum structure, is 692 lb. Boeing's comparative weight estimate for a radiative heat shield structure is 480 lb. Total dome weight for a 30-pass low-drag entry is 1154 lb for the Martin Marietta ablator design and 610 lb for the Boeing hot radiative structure design. Considering the greater reliability of a cool aluminum structure compared with a hot metallic structure operating above 2000°F, the weight penalty carried by the ablative design does not appear to be excessive.

The lower mission time of 2-pass entry (8.9 hr) as compared to a 30-pass entry (131 hr) makes the shorter mission more attractive. Short duration missions are desired because they will minimize the Shuttle's on-orbit stay time and the associated monitoring and/or tracking operations of ground stations. In addition, for the low drag configuration, the 2-pass entry mode requires less ablator weight than the 30-pass entry mode. The high drag configuration is more stable aerodynamically than the unstable low drag configuration which requires a reaction control system. Furthermore, the heat shield weight of the high drag configuration is lower. However, these advantages of the high drag tug are offset by the weight and complexity of the flare, which must be foldable to fit into the 15-ft diam cargo bay of the Shuttle Orbiter.

V. Summary and Conclusions

Ablative heat shields were designed for Space Tug aerobraking trajectories involving 2 and 30 perigee passes. The tug configuration was a 14-ft-diam cylinder with a 2:1 elliptical dome. Both a low drag and a high drag configuration were studied. High drag would be achieved by attaching a 60° retractable flare at the aft end of the cylindrical body. Silicone-base ablators ranging in density from 15-55 lb/ft^3 were selected for evaluation. Flat-face ablator models were tested in a plasma arc under conditions simulating stagnation point heating for 2-pass and 30-pass entry modes.

The tests and supporting analyses established that the use of ablatives as thermal protection for multipass aerobraking re-entry is feasible; silicone-base ablators were found to be suitable for this application. Char loss only occurred at the periphery of the models where the cells of the honeycomb are cut. For the trajectories investigated, ablators with densities higher than 30 lb/ft^3 are not required.

The silicone ablator chars contained fissures that were oriented both parallel and perpendicular to the ablator surface. These fissures are characteristic of state-of-the-art silicone ablators and the char is retained primarily by its adhesion to the honeycomb cell walls. Optimizing the ablator compositions for multipass heating can minimize the potentially detrimental effects of char fissures.

Ablator thicknesses for aerobraking entry heating are calculable with a high degree of confidence. Stagnation point ablator thicknesses were on the order of 1.35-1.70 in. for 2-pass entry heating and 1.90-2.15 in. for 30-pass entry heating. Ablative dome heat shields were designed to weigh less than 715 lb for 2-pass entry heating. This is 30% of the ablator weight estimated by Boeing for such missions. For 30-pass entry heating, ablative dome heat shields would weigh less than 860 lb. While heavier than a metallic radiative dome structure, ablators are more reliable, are capable of withstanding a heat flux overload, and provide a cool dome structure free of thermal stress.

The high drag entry configuration experiences a less severe heating environment than the low drag configuration and, consequently, requires less heat shielding. However, this weight advantage is offset by the weight and complexity of the aft flare. Dome ablator weights for 2-pass missions and 30-pass missions differ by less than 200 lb. Thus, 2-pass entries would be preferred because of the shorter mission duration.

References

[1] Corso, C.J. and Eyer, L.L., *Space Tug Aerobraking Study,* Doc. No. D5-17142, (prepared under Contract NAS8-27501), April 1972, Boeing Co., Huntsville, Ala.