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Thermal Protection System Materials and Costs for Future Reusable Launch Vehicles

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Nomenclature

$A(i, n)$	=	$i(1+i)^n/[(1+i)^n - 1]$, amortization function
C_{fab}	=	$C_{purch} + C_{pers}h_{inst}$, installed cost of material, \$/ft^2
$C_{i/r}$	=	$C_{pers}\ h_{i/r}$, cost for inspection and repair, \$/ft^2
C_{payl}	=	payload cost to orbit, \$/(lbm payload)
C_{pers}	=	personnel cost, including both direct and indirect costs, \$/hr
C_{purch}	=	purchase cost, \$/ft^2
F_{rate}	=	flight rate, #/yr
F_{sp}	=	$(N_{limit} - 1) f_{damage}$, TPS spares fraction (minimum)
f_{amort}	=	$N_{limit} A(f_i/F_{rate}, N_{limit})$, amortization factor
f_{damage}	=	damage replacement fraction, %/flt
f_i	=	yearly interest rate, %
f_{payl}	=	payload conversion factor, (lbm payload)/(lbm TPS)
h_{inst}	=	installation time, hr/ft^2
$h_{i/r}$	=	inspection and repair time, hr/ft^2
N_f	=	total number of flights, #
N_{life}	=	TPS reuse flight limit, #
N_{limit}	=	$\min(N_f, N_{life})$, #
T_{max}	=	maximum reuse temperature, °F
W_{area}	=	areal weight, (lbm TPS)/ft^2
$\bar{\$}$	=	life-cycle cost parameter, \$/ft^2-flt

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Introduction

THERE is considerable interest in developing new reusable launch vehicles (RLVs) for reducing the cost of transporting payload to and from orbit.[1–3] This work reviews 13 candidate thermal protection system (TPS) options currently available for RLVs. It is useful to begin with the current Space Shuttle TPS layout as a reference.[4] The nose cap and wing leading edge, which reach the highest temperatures, are made of reinforced carbon-carbon (RCC) that is protected from oxidation by an external coating (~0.020 in. thick) of silicon-carbide. Most of the windward surface consists of 9 lb/ft^3 ceramic tiles (LI-900) with a thin (~0.012 in.) coating of reaction cured glass (RCG). The leeward side of the vehicle is covered largely by advanced flexible reusable surface insulation (AFRSI), a quilted ceramic blanket, and FRSI, a polyamide felt. These four materials can be considered to be first generation reusable TPS. Since the time of the Space Shuttle design, considerable progress has been made advancing TPS technologies in terms of thermal performance, robustness, and cost. For each of the major systems a second generation ceramic TPS has been developed, tested, and characterized. Metallic-based systems have also been developed.[5,6]

For applications requiring RCC in the past, advanced carbon-carbon (ACC) is now available.[7] This material has better mechanical properties, somewhat higher temperature capability to 2900°F, and greatly increased oxidation resistance. New carbon fiber-reinforced silicon-carbide matrix composites (C/SiCs) have shown additional improvement in properties over ACC with use temperatures to 3000°F and above.[8] For rigid tiles NASA Ames Research Center has made two significant advancements. The first is a tile substrate called alumina enhanced thermal barrier (AETB),[9] which incorporates alumina fibers for improved dimensional stability at high temperatures, to 2600°F and above. This material can be made to densities as low as 8 lb/ft^3. The second is a coating preparation called toughened uni-piece fibrous insulation (TUFI),[10] which penetrates about 0.1 in. into the tile substrate. The resulting composite, with a density gradient near the surface, provides orders of magnitude increased damage resistance compared with RCG-coated LI-900, with only a small weight increase. The TPS that combines these two developments is called AETB-8/TUFI and has been adopted for high damage areas on the Space Shuttle Orbiters.

Two notable developments have occurred in flexible ceramic blanket technology. The first is aluminoborosilicate-based fibers with use temperatures of 2000°F and above,[11] in comparison to quartz and silica fiber used in AFRSI, which have multiuse temperature limits of 1200–1400°F. Blankets incorporating these new high-temperature fibers are referred to as AFRSI-HT.[12] The second is an integral weaving technique that produces a fluted core blanket with a smoother surface and greater resistance to aeroacoustic noise, to levels as high as 170 dB.[13] This NASA Ames Research Center innovation is called tailorable advanced blanket insulation (TABI). Finally, for felt-based TPS Boeing is developing polybenzimidazole blanket insulation (PBI), with a multiuse temperature limit of 1000°F and above, in contrast to shuttle FRSI, which has a multiuse temperature limit of about 700°F.

NASA Langley Research Center and BF Goodrich (formerly Rohr Corp.) have led the development of metallic-based TPS.[5,6] This activity uses essentially three approaches: metallic tiles, which encase a fibrous ceramic batting in a box fabricated largely from metallic honeycombs, typically nickel-based alloys; metallic honeycomb sheets, made of nickel-based alloys, incorporating a fibrous back-side insulation encapsulated in a metallic foil bag, providing reduced weight; and metallic multiwall, which is comprised of dimpled titanium metal sheets, which are stacked and then diffusion bonded at contact points to form the TPS. The nickel-based systems can be used up to temperatures of about 1800°F and the titanium system to about 1100°F.

These 13 TPS materials have various benefits and limits in terms of temperature capability, weight, initial cost, and maintenance. Carbon-carbon and C/SiC systems have the highest temperature capability but are relatively expensive and heavy, requiring significant

Table 1 TPS material and cost data[a]

Material	T_{max}, °F	N_{life}, # flt	C_{purch}, \$/ft^2	h_{inst}, hr/ft^2	$h_{i/r}$, hr/ft^2	f_{damage}, %/flt	W_{area}, lb/ft^2	$\bar{\$}$ components, \$/ft^2-flt: Fabrication	i/r	Payload displacement	$\bar{\$}$, total \$/ft^2-flt
Carbon fiber CMC (C/SiC)[b]	3,000	100	15,000	96.0	0.08	0.11	1.70	479	8	850	1,337
Advanced C-C (ACC)[b]	2,900	100	12,000	96.0	0.11	0.13	1.70	428	11	850	1,289
Shuttle coated C-C (RCC)[c]	2,700	40	12,000	96.0	0.14	0.13	1.70	724	14	850	1,588
AETB-8/TUFI[b]	2,600	100	800	45.0	0.64	0.14	1.19	106	63	594	763
LI-900/RCG[c]	2,300	100	1,160	91.0	2.10	0.25	1.10	225	208	550	983
TABI (PCC coating)[b]	2,000	100	1,030	4.90	0.49	0.96	1.00	52	49	500	601
AFRSI-HT (PCC coating)[b]	2,200	100	500	6.10	0.96	1.80	0.94	54	95	470	619
AFRSI (C-9 coating)[c]	1,200	100	330	6.10	0.96	1.80	0.94	46	95	470	611
PBI felt (VHT coating)[b]	1,000	100	240	0.48	0.09	2.40	0.62	17	9	310	336
FRSI (DC92 coating)[c]	700	100	160	0.55	0.09	2.80	0.62	14	9	310	333
Nickel super-alloy tile[d]	1,900	100	4,450	74.0	0.53	0.12	2.00	233	52	1,000	1,285
Nickel super-alloy sheet[d]	1,800	100	4,450	74.0	0.53	0.12	1.32	233	52	660	945
Titanium multiwall[d]	1,100	100	6,035	43.0	0.26	0.11	2.16	201	26	1,080	1,307

[a]Assumptions: $C_{pers} = \$100/\text{hr}$, $C_{payl} = \$1000/\text{lbm}$, $f_i = 10\%$, $f_{payl} = 0.50$, $N_f = 100$, $F_{rate} = 8$. TPS change-outs for blankets are included in i/r cost that assumes usage on leeward surfaces only. Weights are determined for a heat load of 2000 BTU/ft^2.
[b]Second-generation shuttle TPS. [c]First generation. [d]Metallic concept.

time and expertise and costly facilities and tools for design and fabrication. Second generation ceramic tiles are relatively light, durable, simple to fabricate and easy to install; however, waterproofing is a concern. Blankets and felts are light, simple, inexpensive, and easy to install over curved vehicle surfaces, but durability and waterproofing are concerns. Metallics are robust and appear to have eliminated waterproofing, but they tend to be heavy and relatively expensive, requiring costly facilities and tools. If thin metal sheets are used to reduce weights, then issues arise from possible metal fatigue and corrosion caused by thermal cycling, pressure oscillations, and environmental exposure.

System analyses[14,15] have shown that a significant component of future RLV life cycle cost is the TPS; however, it is difficult to quantify and compare the potential savings of advanced systems without performing full vehicle designs using each of the different options. Because these design studies involve a considerable effort and also tend to submerge TPS cost impacts under unrelated vehicle design assumptions, there is a clear need for a simpler quantitative method to evaluate the cost impact of different TPS options. To this end, this work introduces a TPS life-cycle cost parameter, which is easily computed and applicable to generic RLVs.

Results and Discussion

The three major components of TPS life-cycle costs are fabrication, inspection/repair (i/r), and payload displacement. Fabrication is the cost for purchase and installation of the TPS on the vehicle, amortized over the vehicle lifetime. Inspection/repair is the cost to prepare and certify the TPS for reflight. Payload displacement accounts for the fact that the purpose of the vehicle is to put payload (not TPS or any other vehicle system) into orbit, and that for every pound of TPS some fraction of a pound of potential payload is displaced. A simple development leads to the following analytic expression for the life-cycle cost parameter, or dollar-bar:

$$\bar{\$} = \frac{C_{fab}(1 + F_{sp}) f_{amort}}{N_{limit}} + \frac{C_{i/r}(N_{limit} - 1)}{N_{limit}} + C_{payl} W_{area} f_{payl} \quad (1)$$

The three major terms on the right-hand side of Eq. (1) are the fabrication, i/r, and payload-displacement cost components, respectively. In developing this formula, constant year dollars were assumed. This assumption allows all effects of the time value of money to be incorporated into the amortization factor f_{amort}, which is unity if the interest rate is zero. The quantity C_{pers} embedded in C_{fab} and $C_{i/r}$ accounts for both direct (e.g., salaries, benefits) and indirect (e.g., tools, facilities, consumables) costs for TPS installation and i/r. We also assume that spares for damage replacement are purchased up front (otherwise, $C_{fab}\,f_{damage}$ is included but not amortized in the fabrication cost component), that post-flight i/r costs are not incurred at TPS change-outs, and that TPS processing is not the pacing item in preparation of the vehicle for reflight.

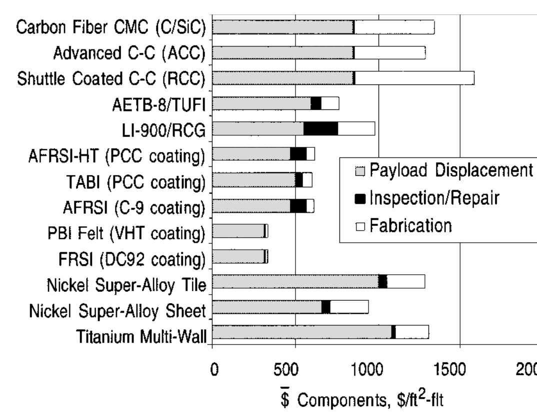

Fig. 1 Life-cycle cost components.

Table 1 lists input data and computed values for $\bar{\$}$ components for 13 TPS options. The data were compiled largely from Ref. 15, a system analysis study performed by Boeing (formerly Rockwell International) for NASA Langley Research Center as part of the Advanced Manned Launch System Program. This reference provides an excellent comprehensive analysis with detailed breakout of costs, weights, tasks, and personnel hours for a number of TPS configurations, with data based on actual Space Shuttle Orbiter program experience.

Figure 1 plots $\bar{\$}$ cost components for the 13 TPS options listed in Table 1. The first notable feature is the dominance of the payload displacement component. Although this may be surprising at first, it is easily explained. The payload displacement cost reflects all of the other systems (e.g., structure, propulsion, avionics, cryo-tanks, etc.) that are necessary for the vehicle to operate. A weight savings in the TPS leads to corresponding savings in many of the other systems. The second notable feature is that second generation systems have lower $\bar{\$}$ and/or higher use temperatures than the first generation systems, but the ordering between the systems remains the same. The ranking from lowest to highest life-cycle cost is 1) felt blankets, 2) ceramic blankets, 3) ceramic tiles, 4) metallics, and 5) carbon-carbons or C/SiC. This ordering remains the same even disregarding the payload-displacement component of $\bar{\$}$, except for first generation Shuttle LI-900/RCG tiles, which have high i/r cost.

This simple analysis strongly suggests that to minimize RLV life-cycle costs a designer should select the TPS with the lowest $\bar{\$}$ and use it up to its temperature limit, then switch to the TPS with next smallest $\bar{\$}$, and so on. Given that current RLV designs typically generate maximum temperatures between 2000–3000°F, the data and results from Table 1 indicate that new RLVs incorporating a combination of advanced felts, ceramic blankets, ceramic tiles, and possibly advanced carbon-carbon or C/SiC would be expected to provide the lowest vehicle life-cycle costs. In addition, given the predominance of the payload-displacement cost, minimum areal weight should be the dominant TPS selection factor.

Summary

A simple method to quantify and compare life-cycle costs of different TPS options for RLVs is proposed. This method includes relevant fabrication, inspection/repair, and payload displacement costs. Data and results for shuttle first generation TPS, second generation counterparts, and metallic concepts are presented. The computed ranking from lowest to highest life-cycle cost is 1) felt blankets, 2) ceramic blankets, 3) ceramic tiles, 4) metallics, and 5) carbon-carbon and C/SiC. The dominant life-cycle cost component is directly related to the TPS areal weight; fabrication and inspection/repair costs are smaller. Based on these results, future TPS research and technology development should strive to reduce weights and to improve temperature capabilities, with lower fabrication and inspection/repair costs as important but secondary objectives.

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