Metallic Thermal Protection Concept for Hypersonic Vehicles

H. Grallert*
Messerschmitt-Bölkow-Blohm GmbH, Munich, Germany
and
K. Keller†
European Space Research and Technology Centre, Noordwijk, The Netherlands

Since the first development and operation of reusable hypersonic vehicles, metallic and ceramic reradiative thermal protection systems (TPS) have been emphasized and investigated. Due to temporary advantages of rigid ceramic tiles with respect to specific weight, this protection concept has been applied primarily in the U.S. Space Shuttle Program. Meanwhile, some inherent disadvantages have led to increased development activities in the area of metallic and advanced ceramic composite TPS. Newer metallic TPS developments show competitive specific weight, and, in addition, they indicate advantages such as simpler and safer attachment and higher durability. In this paper, TPS application conditions in future European space transporter systems like SÄNGER (first stage: launcher vehicle, and second stage: reentry vehicle) are discussed. The predicted surface heating rate is lower for both stages than that for the HERMES reentry glider. The various load impacts on the design are outlined. Several TPS concepts have been studied and the concept selection criteria are specified. Metallic multiwall panels optionally combined with ultralight multiscreen insulations seem to be favorably applicable in the temperature range of 200–1300°C. For higher temperatures, advanced ceramic composites are preferable, if basic ceramic material problems have been solved. For temperatures ranging from 200–1300°C, a comparison of metallic and ceramic TPS design characteristics will be presented.

Introduction

THE feasibility of hypersonic space transportation systems mainly depends on available key technologies. As a consequence of high thermal loads onto the upper stage during re-entry and descent, as well as aerothermal loads onto the winged lower stage during an extended cruise phase, thermally resistant airframe structures and thermal protection systems are required. These components need specific hardware development. Aerodynamically guided space transport vehicles can be operated economically only by applying frequently reusable components and elements. Therefore, hot structures and thermal protection systems have to be designed with respect to low maintenance and repair effort.

The aerothermodynamic load characteristics of the vehicle surface are defined above all by the vehicle class concerned. The upper stage of SÄNGER to be designed for re-entry and named HORUS 3 is a pressure-dominated vehicle like the U.S. Shuttle, HERMES, and HOPE. The size of HORUS is comparable to the size of the Shuttle, whereas HERMES and HOPE[9] are much smaller.

The winged first stage of SÄNGER belongs to a different vehicle class similar to the Mach 5 airliner or the TAV and, thus, poses different problems with respect to thermal control.

This paper is concerned with passive thermal surface protection systems (TPS) for post-HERMES space transportation systems, emphasizing appropriate concepts for the SÄNGER stages.

Future reusable space transportation systems like SÄNGER are more critical to weight than the Shuttle. Mass budgets of related concepts have shown that the TPS mass fraction is usually 15–20% of overall net mass. Therefore, its mass reduction is as sensitive as that of substructure and propulsion system masses.

Furthermore, advanced launcher systems promise a reduction in operational cost. This requires, among other things, a reduction in TPS cost, which apart from low mainteance/refurbishment cost implies the use of a basic construction principle, which is easy to adapt to specific local requirements.

Thermal Loads

Vehicles moving with high speed in the Earth's atmosphere are heated by friction and compression of air. The surface temperature is determined by the heat balance between aerothermal load, heat reradiated from the surface, and heat conducted into and stored in the vehicle structure.

Surface temperature predictions for future hypersonic vehicles have been performed with software verified with data from the Shuttle-Orbiter flights (Fig. 1).

Excellent agreement between simulation[6] and flight data[1] was found for the medium bottom section. In the front section, the simulation presents moderate overestimation (nonequilibrium real gas), and in the rear section higher overestimation (turbulent heating). However, nonequilibrium real gas flow causes additional heat at surfaces with higher catalycity than the one of the Shuttle surface. Further, earlier transition

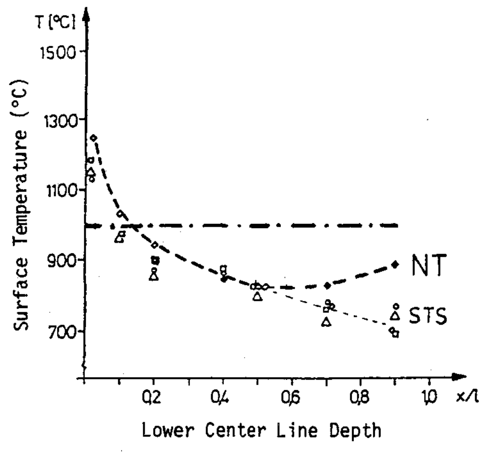

Fig. 1 Shuttle surface temperatures (NT: simulated nominal temperature; STS: flight data).

Received Oct. 22, 1988; revision received May 11, 1989; accepted for publication Aug. 11, 1989.

*Project Manager, Hypersonic Space Systems and Technology.
†Senior Thermal Engineer.

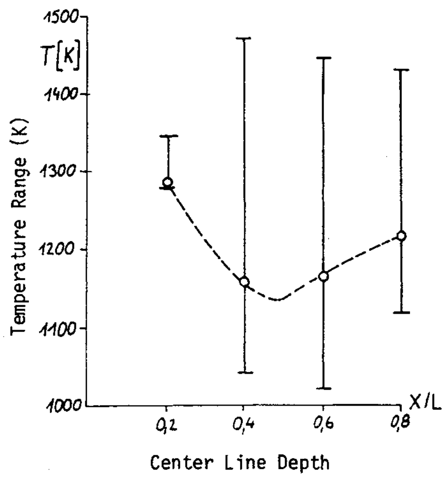

Fig. 2 Transition model uncertainties.

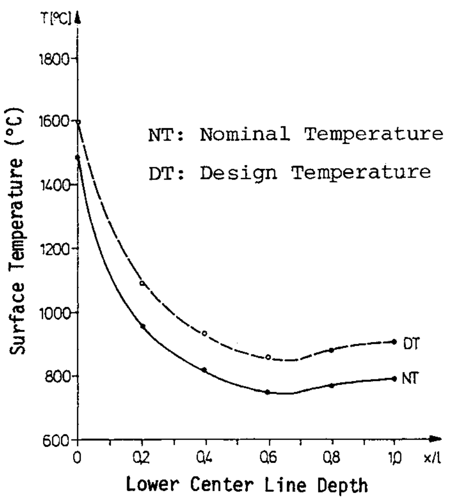

Fig. 3 SÄNGER upper stage temperatures.

to turbulence is expected for surfaces rougher than the Shuttle surface.

Turbulent heating is quite sensitive to the transition model assumptions (e.g., surface roughness, etc.) and the gas model of the flow (earlier transition for real gas). Figure 2 presents a sensitivity analysis for a typical re-entry vehicle. The dashed line corresponds to the model parameters, as used in the Shuttle simulation.

For a re-entry vehicle that is similar to the Shuttle in terms of size and surface characteristics, quite accurate and reliable predictions can be expected from the computation tool used.

The size of HORUS 3 is similar to that of the Shuttle. Consideration of moderately higher atomic recombination and surface roughness yields the curve marked DT in Fig. 3, whereas the curve NT is based on surface properties close to the Shuttle.

Evaluating the windward surface and the leeward surface temperatures computed for HORUS 3, a heating up of about 80% of the surface to temperatures below 1000°C is expected.

At the SÄNGER first stage, the flow is in a state of real gas equilibrium, but fully turbulent. Hence, catalycity and surface roughness are of less importance compared to that of the re-entry stage.

Even the difference between equilibrium real gas and perfect gas model predictions is quite low in this case. A difference of only 30–40°C in surface temperature has been found for all areas, except at stagnation points.

The actual trajectory selected and the surface materials envisaged with an emissivity higher than the one of polished titanium are of primary importance for the surface temperatures of the lower stage.

Calculations performed for the winged launcher stage of SÄNGER show that about 95% of the total surface region can be expected with temperatures below 900°C.

Summarizing these results, thermal protection systems for the temperature range of 500–1000°C are required for large surface areas of both stages of SÄNGER.

The critical design load cases of SÄNGER are as follows:

1) Second stage: high-temperature load with relatively short duration during re-entry (in the order of 20 min.).

2) First stage: moderate temperature load with longer duration during an extended cruise phase.

Representative temperature ranges are shown in Figs. 3 and 4.

Thermal Protection System Candidates

Reusable thermal protection systems are divided into two classes: 1) hot structures carrying mechanical loads, and 2) thermal protection of cold and load carrying structures.

Hot structure elements are relevant for stagnation areas like nose cones, leading edges, and control surfaces, but they will not be discussed in detail in this paper.

Fiber reinforced ceramics (e.g., C/SiC) or carbon-carbon elements (C/C) with a coating resistant against oxidation seem to be the best solution for hot structures.

For temperatures below 500°C, two candidate solutions are in competition: metallic multiwall panels[4,7] and flexible surface insulation.[1,2]

It should be noted that advanced flexibile surface insulation might be extended to application temperatures of approximately 650°C. Metallic multiwall panels have been successfully verified by tests[8] up to some 550°C, and they were found to be weight competitive.

As mentioned in the second section, TPS for the temperature regime between 500°C and 1000°C are emphasized in this paper. In principle, four basic candidate TPS have been characterized that are also applicable at higher temperatures (cf., Table 1):

1) rigid ceramic tiles (Fig. 5),

2) ceramic shingles combined with internal insulation (Fig. 6),

3) metallic corrugated heat shields combined with internal insulation, and

4) metallic multiwall panels optionally combined with internal insulation (Fig. 7).

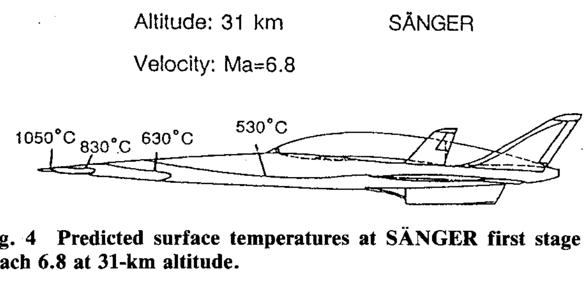

Fig. 4 Predicted surface temperatures at SÄNGER first stage for Mach 6.8 at 31-km altitude.

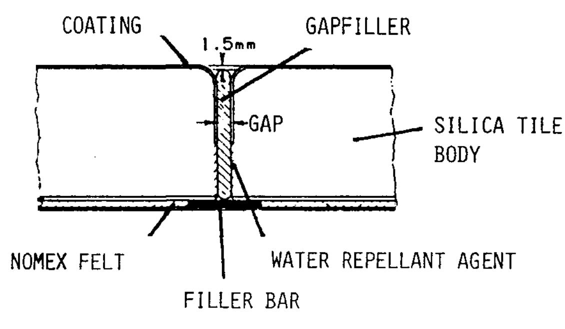

Fig. 5 Rigid ceramic tile TPS concept.

Rigid ceramic tiles are applicable up to approximately 1250 °C. Their density is above 150 kg/m^3. They are manufactured from SiO_2 fibers[1] and adhesively bonded to a strain isolator pad that itself is bonded to the cold structure. Although the thermal performance of the tiles is excellent, their disadvantages are brittleness, rain erosion, and humidity sensitivity. To improve these characteristics, a borosilicate glass coating was applied.

The adhesive is sensitive to overheating, such as that which led to the loss of tiles in the STS flight program.[1] The adhesive used in the Shuttle is limited to about 290°C maximum service temperature. Therefore, depending on the thickness of the Nomex felt required, the maximum temperature of the primary load carrying substructure is limited.

A further drawback is the scattering in mechanical characteristics of the tiles.

Ceramic shingles will be applied for HERMES. These shingles are constructed as a dual strap panel, targeting approximately 0.6-mm material thickness, and an internal multiscreen insulation that is integrated in small compartments or bags.[2] Pressure loads from the environment are transferred by each shingle via four supports onto the cold structure. For that purpose, screws and shear pins located in the gaps of adjacent panels will be used. The rigid ceramic shingle will be manufactured either from carbon fibers in silicone carbide matrix (C/SiC) or from silicone carbide fibers in silicone carbide matrix (SiC/SiC). The latter composite material will be applicable up to some 1250°C and will not need any additional coating.

Standoff metallic reradiative heat shields have been investigated in the predesign phase of the U.S. Space Shuttle Orbiter as well as in the German ART program[3] and in the French VERAS program. The stiffened metallic heat shield is constructed from corrugated sheet material. Its attachment and intermediate insulation is similar to the ones of the standoff ceramic shield. This concept is applicable up to the temperature limit of refractory metals (approximately 1300°C) and requires a reliable coating against oxidation beyond 1000°C. Adjacent panels are shifted and overlap to reduce gap penetration. This concept has been successfully tested up to 1000°C, and technological improvements concerning standoff elements and sealing against subsurface flows (cf. Fig. 8) have subsequently been made.[3]

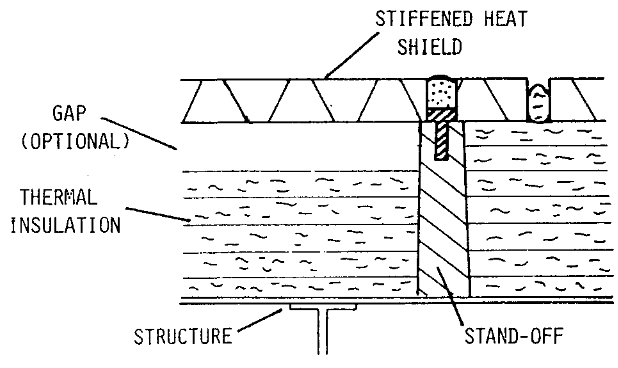

Fig. 6 Standoff shingle TPS concept.

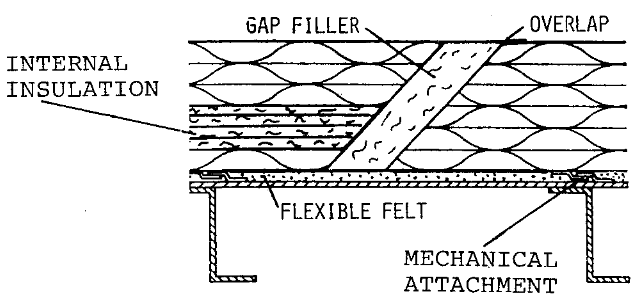

Fig. 7 Metallic multiwell TPS concept.

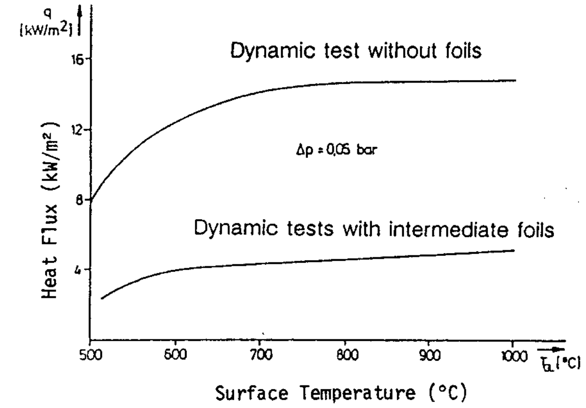

Fig. 8 Limitation of subsurface flows by internal metallic foils.

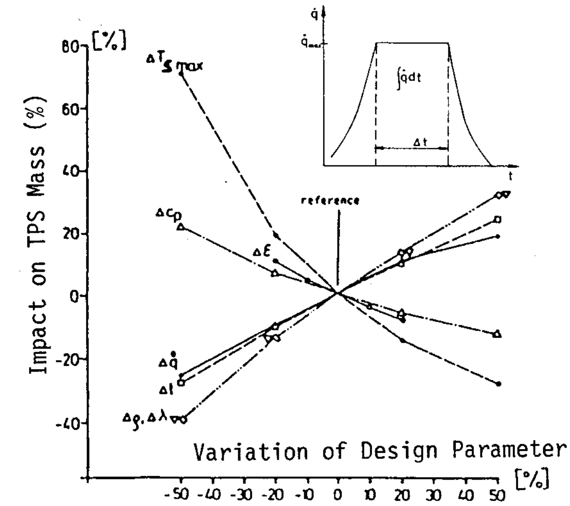

Fig. 9 Sensitivity of TPS mass against different design paramter variations.

Last but not least, the metallic multiwall TPS concept represents a synthesis of earlier TPS concepts. Thin metallic foils (50–100 μm) are dimpled and diffusion-bonded at the dimples to form multiwall layers. Several layers, optionally combined with a layer of internal multiscreen insulation, build up a multiwall panel. Together with variations in dimple pattern and layer thickness, this allows a flexible system applicable even at spherically curved surface areas. The upper temperature limit is defined by the materials applied, e.g., about 1000°C for nickel- or cobalt-based alloys and about 1300°C for molybdenum-based alloys.[5] The latter need an oxidation resistant coating anyway. The multiwall panels will be mechanically attached to the cold structure by clips.[4,7]

This attachment allows an increase of the primary substructure temperature limit and enables application of other substructure materials with further weight-saving potential (TPS and substructure).

In Table 1, some technological characteristics of the main TPS candidates are summarized.

Concept Selection

The design criteria for the HORUS/SÄNGER thermal protection concepts are divided into basic design criteria, requirements for materials, criteria for surface characteristics, and construction criteria.

Basic Design Criteria

The basic criteria are comprised of the following.

1) Reusability: This basic requirement excludes the use of ablative solutions. All solutions discussed in the previous section are reusable.

Table 1 Summary of TPS candidates characteristics

Criteria	TPS					
	Flexible surface insulation	Rigid ceramic tiles	Ceramic shingle	Metallic shingles	Multiwall TPS panels	C/C hot structure
Upper temperature limit	≃650°C	≃1260°C	≃1300°C	≃1300°C	≃1300°C	≃1600°C
Local application	Leeward fuselage/wings	Fuselage/wings	Fuselage/wings	Fuselage/wings	Fuselage/wings	Nose cap, leading edge, control surfaces
Attachment	Adhesive bonding	Adhesive bonding	Screws and shear pins	Screws and bolts	Clips or studs	Screws and bolts
Sealing	Buit joint	Ceramic fabrics	Ceramic fabrics	Sealing plates	Sliding joint + ceramic fabrics	Ceramic fabrics and rings
Manufacturing tools effort	Low	High	High	Moderate	Moderate	High
Maintenance/repair effort	Low	Moderate	Low	Moderate	Low	High
Scattering of material characteristics	Moderate	High	High	Low	Low	High
Mechanical strength	Low	Moderate	High	High	High	High
Coating reasoning	Surface sealing	Erosion, humidity	Not relevant for Sic/SiC	Oxidation[a]	Oxidation[a]	Oxidation
Thickness at comparable conditions	Not applicable	Moderate	High	Moderate	Low	Not applicable
Thermal expansion	Low	Low	Low	High	High	Low

[a]above 1000°C.

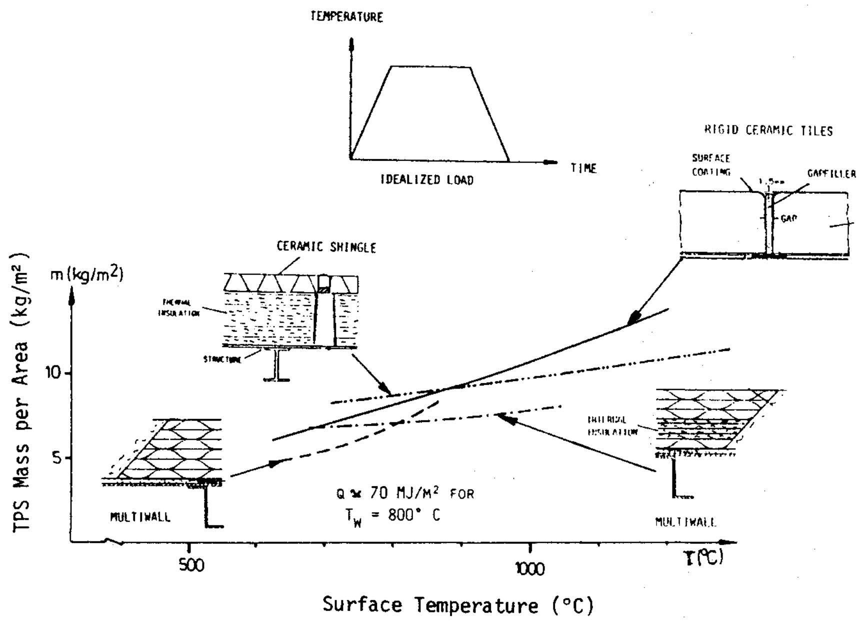

Fig. 10 Trend of TPS mass per area vs temperature for representative TPS candidates.

2) Safety: The safety requirements are higher for a manned spacecraft. One of the critical tasks is the reliable attachment, which consequently favors mechanically attached systems compared to adhesively bonded systems.

3) Low maintenance: A thermal protection system with low maintenance will save cost. Favorable concepts (cf. Table 1) are flexible surface insulations, ceramic shingles, and multiwall panels.

4) Minimum weight: In the Shuttle, the weight of the thermal protection systems was about 30% of the total payload capability. Advanced vehicles are even more critical with respect to weight, since their payload fraction is rather low (less than 4% gross liftoff mass) and the TPS mass proportion of completely reusable upper stages exceeds 30% of the payload mass.

To identify TPS weight-saving potential, several TPS parameters have been varied independently for typical heat loads and for a representative location on the windward surface. The reference TPS mass per unit area is based on the related Shuttle solution for a representative location and the associated heat load. The primary substructure was assumed to be adiabatic, with temperature limited during re-entry, including an appropriate waiting period after landing.

The sensitivity analysis (cf. Fig. 9) indicated that the highest weight-saving potential as calculated for a representative re-entry trajectory is given by a reduction of thermal conductivity or density of the TPS, closely followed by an increase in the admissible cold structure temperature. For example, a reduction in thermal conductivity of 50% yields a TPS weight reduction of about 30%, and an increase in admissible cold

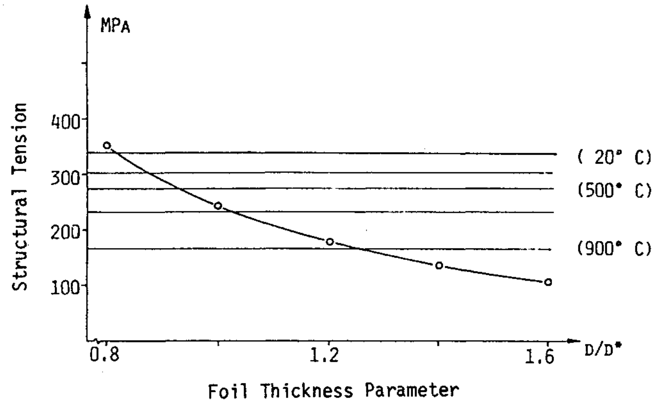

Fig. 11 Structural tension as a function of the foil thickness ratio for multiwall TPS.

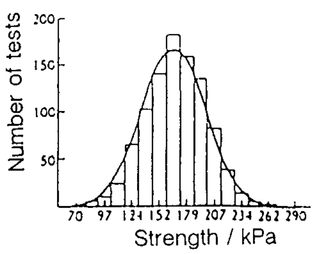

Fig. 12 Scattering of strength for rigid ceramic tiles (Space Shuttle).

structure temperature by 50% yields a weight reduction of about 25%.

Future reinforced plastics and aluminum-based alloys (e.g., lithium-aluminum alloys) promise a possible increase in admissible cold structure temperature from 130°C to more than 200°C.

The current ceramic tiles of the Shuttle can neither be essentially reduced in density nor in thermal conductivity, and they provide a quite excellent thermal solution. Progress is achievable only by alternative concepts. Figure 10 presents a trend analysis for representative transient thermal loads and design assumptions that are not too pessimistic.

This trend analysis indicates that ceramic shingles combined with multiscreen internal insulation are superior above around 900°C in weight per area to rigid ceramic tiles. For lower temperatures, the weight of shingles and attachment is disadvantageous because the shingles alone provide almost no thermal insulation capability.

Further weight reduction is promised by metallic multiwall systems combined with internal multiscreen insulation, at least in the temperature range of 700–1050°C. This is due to the thermal insulation capability of the multiwall layer.

Considering the actual history of thermal and pressure loads during a representative re-entry, an optimization of metallic foil thickness is possible (cf. Fig. 11). Consequently, optimized homogeneous multiwall panels might be superior in the range of 500–800°C.

However, it should be noted that metallic multiwall panels as well as ceramic shingles, both combined with internal insulations, have the lowest sensitivity with respect to variations of re-entry time.

In summary, the trend analysis indicates some weight advantages of advanced multiwall systems.

Requirements for Materials

The material selections criteria are comprised of the following.

1) Temperature resistance: The materials selected should provide sufficient mechanical strength up to the related maximum use temperature.

2) Chemical resistance: This mainly implies that no significant material degradation in an oxidizing environment should occur. For an upper stage entering the atmosphere and performing a hypersonic flare maneuver, the aggressiveness of atomic oxygen is far more severe than for the winged launcher stage flying in the lower hypersonic regime.

3) Damage tolerance: Failure mechanism for metals is quite well-understood, whereas on reinforced ceramics little knowledge is available today.

4) Low scattering of material characteristics: This is usually warranted for metals, but not for ceramics. Figure 12 shows the scattering in strength for ceramic tiles of the Shuttle. For reinforced ceramics, the data show large scattering, as described by several manufacturers.

Criteria for Surface Characteristics

The surface criteria are comprised of the following.

1) Low catalycity: High catalycity, i.e., high atomic recombination, implies higher heat loads. A 50% increase in the heat load level yields a nearly 20% increase in TPS mass. The borosilicate glass coating provides quite low catalycity, whereas SiC/SiC ceramics and metal oxides have proven higher catalycities.

2) High emissivity: This makes possible the reradiation of a large amount of aerothermal heat to space and, thus, yields reduced surface temperatures.

3) Smoothness: Rough surfaces, particularly with concentrated roughness at the front section of the vehicle, will induce early transition to turbulent flow and accordingly higher heat loads on re-entry vehicles. Early transition has a strong impact on the material selection but a smaller effect on total TPS mass.

4) Reduced leakage: Gap flow yields locally higher heat loads and should be minimized by space qualified gap fillers. Additional improvement is provided by metallic multiwall

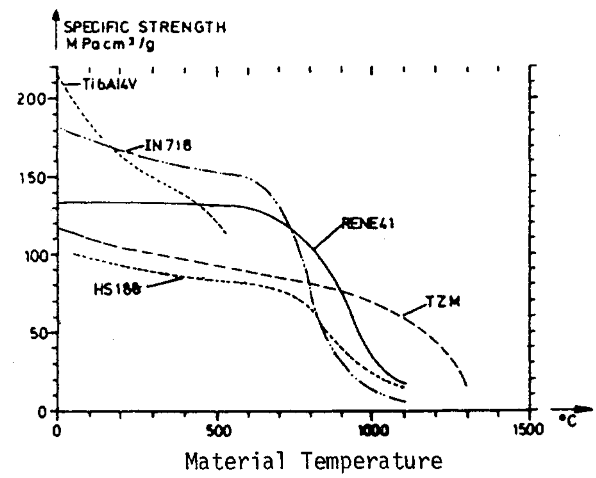

Fig. 13 Tensile strength vs temperature for different metallic high-temperature TPS materials.

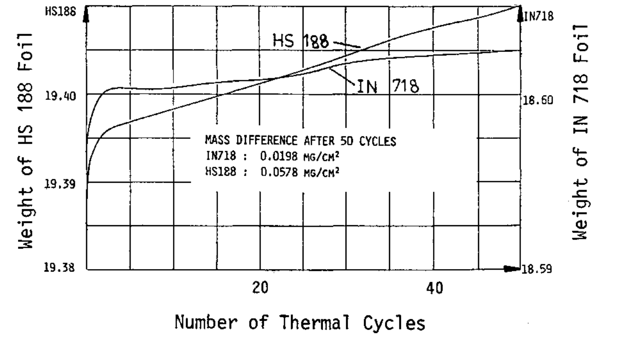

Fig. 14 Oxidation rates of foils from IN718 and HS188 measured after simulation of 50 re-entry cycles (temperature load up to 900°C).

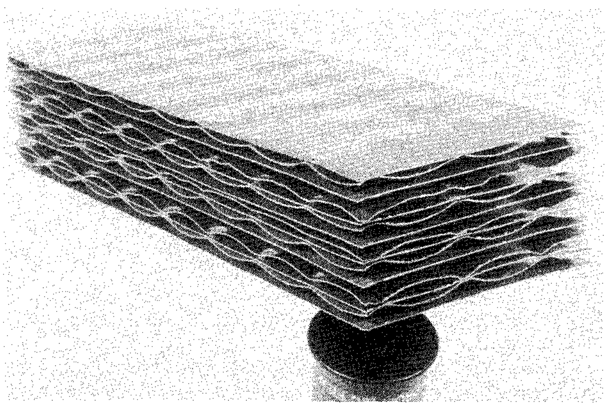

Fig. 15 Laboratory multiwall package sample from IN718.

Table 2 Emissivities of foils from IN718 and HS188 measured at room temperature prior to and after 50 thermal cycles (temperature load up to 900°C, cf. Fig. 14)

Foils	As supplied	Oxidized
IN718	0.136	0.188
HS188	0.149	0.291

systems by means of the overlapping edges of adjacent panels.[8]

Construction Criteria

The construction criteria are comprised of the following.

1) Reduced thickness of TPS elements: Saving in panel thickness means a volume gain, e.g., for a re-entry vehicle with about 740 m^2 external surface, each centimeter in thickness reduction yields a volume gain of about 7.4 m^3. This criterion is even more important for vehicles and airframe parts of small size due to the unfavorable surface to volume ratio.

2) Limitation of subsurface flows: In the course of combined thermal/mechanical tests performed by Messerschmitt-Bölkow-Blohm (MBB) in the past,[3] subsurface flows in fibrous insulations have been identified to deteriorate the thermal performance. However, the introduction of impermeable extremely thin metallic foils strongly limited subsurface flows (cf. Fig. 8).

3) Compensation of thermal expansion: Thermal expansion requires expansion gaps. The mandatory gap can be smaller for ceramic TPS solutions than for metallic solutions with constant panel size. To avoid large gaps, the size of TPS panels is accordingly limited.

Considering the load environment and the preceding design criteria, metallic multiwall panels promise to be a viable solution for the SÄNGER concept.

Metallic Multiwall Systems

For the multiwall solution proposed (for the design principle, see Fig. 7), some basic technological problems will be discussed. The selection of materials is based on evaluation of thermal and mechanical characteristics. Figure 13 gives the temperature dependence of the tensile strength for some metallic candidate materials.

The following alloys have been chosen from all of the materials investigated: titanium alloys (up to 500°C), cobalt/nickel-base alloys (up to 1000°C), NiCrSi steel (up to 1150°C), and coated refractory alloys (up to 1300°C).

Oxidation tests have been performed for several alloys; results for two of them are shown in Fig. 14 for 50 simulated reentry cycles and up to 900°C.[5]

IN718 showed a lower oxidation rate than HS188; however, both values are rather small and the impact on foil strength is negligible.

Besides this criterion, the impact of oxidation on thermooptical properties is evident. Table 2 gives measured emissivities after the preceding thermal cycle tests. The emissivities are measured at room temperature (RT). No catastrophic degradation was observed.

Accurate forming and heat resistant joining of thin metallic foils requires adequate tooling and manufacturing methods. To identify and to verify the optimum and cost-efficient processing, various laboratory samples have been manufactured using different processing tools and parameters. Figure 15 shows one laboratory sample made from IN718 that has been manufactured by cold plastic forming. Titanium-based foils require hot plastic forming (e.g., SPF).

The joining of single dimpled foils to a complete multiwall package has been performed by diffusion bonding (DB). The same joining process is applicable when combining planar and dimpled foils for shear strength reinforcement. The total process is proper for the manufacture of curved panels as well.

From the structural analysis performed, the following major parameters have been identified (providing an optimization potential): foil thickness, dimple pattern, and dimple form.

Figures 16 and 17 show the distribution of different thermal regions—typical of upper and lower stage surfaces and requiring appropriate TPS solutions.

In region 4 of Fig. 16, the homogenous multiwall solution based on titanium alloys is preferred. Alternatively, flexible surface insulations may be applied. In region 3, multiwall panels combined with internal multiscreen insulation are preferred. As a backup solution, ceramic shingles with multiscreen insulation are envisaged.

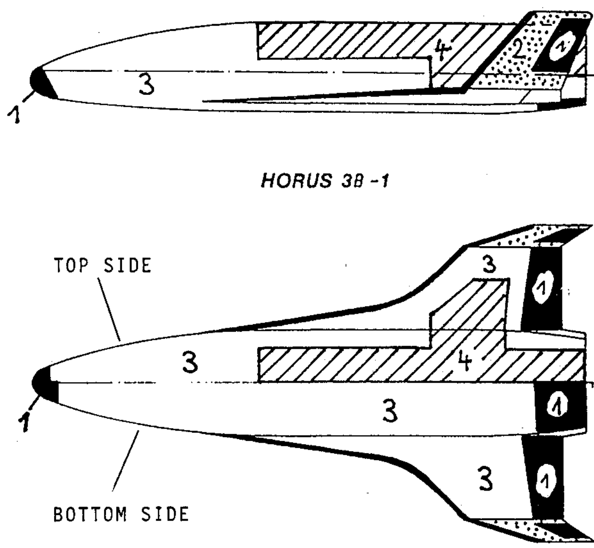

Fig. 16 Nominal SÄNGER upper stage surface regions for specific TPS application (regions 3 and 4 are relevant for metallic multiwall TPS).

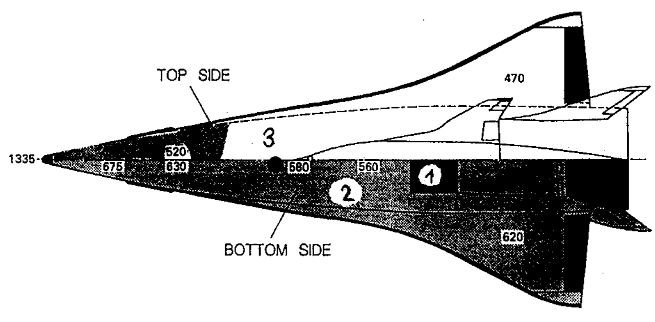

Fig. 17 Nominal SÄNGER first stage surface regions for specific TPS application (region 2 is relevant for metallic multiwall TPS).

In particular, in region 2 of Fig. 17, multiwall solutions are preferable for the SÄNGER first stage.

Conclusions

Based on the thermal and mechanical load assessment for the two-staged and winged launcher concept (SÄNGER), a number of appropriate thermal protection system concepts have been identified. The metallic multiwall concept promises to be a viable and flexible solution for application to both stages in largely extended surface regions.

No major technological impediment has been found during recent MBB development activities, so far performed up to 1000°C. The advanced multiwall concept promises the following advantages:

1) low mass per area,
2) simple and safe attachment,
3) low scattering of metallic characteristics,
4) high durability and material toughness,
5) application temperature up to 1300°C, if the related coating problem can be solved,
6) commonalized design concept flexibility adaptable to the specific load requirements, and
7) potentially low manufacturing and maintenance cost.

Therefore, the related multiwall development effort will be continued by MBB.

References

[1]Arrington, J. P., and Jones, J. J., "Shuttle Performance Lessons Learned," NASA-CP-2283, March 1983.

[2]Chaumette, D., and Cretenet, J. C., "HERMES Thermal Protection System Overview," IAF, Innsbruck, Oct. 4–11, 1986.

[3]Grallert, H., "Wärmeschutzsysteme für aerodynamisch gesteuerte Wiedereintrittskörper," *J. Raumfahrtforschung* Vol. 19, No. 4, 1974, pp. 188–209.

[4]Grallert, H., Keinath, W., and Keller, K., "Metallische Wärmeschutzentwicklung," Messerschmitt-Bölkow-Blohm GmbH, Munich, Germany, MBB-TN-RA403-372/87, 1987.

[5]Grallert, H., and Keller, K., "Investigations for Advanced Thermal Protection Systems," Second European Space Congress, EGEE, Munich, Germany, Nov. 1987.

[6]Keller, K., "Bewertung semiempirischer Hyperschall-Aufheizrechnungen," Messerschmitt-Bölkow-Blohm GmbH, Munich, Germany, MBB-TN-RR33-53, 1986.

[7]Kelly, H. N., and Webb, G. L., "Assessment of Alternate Thermal Protection Systems for the Space Shuttle Orbiter," AIAA Paper 82-0833, June 1982.

[8]Shideler, J. L., Webb, G. L., and Pittmann, C. M., "Verification Tests of Durable Thermal Protection System Concepts," AIAA Paper 84-1767, June 1984.

[9]Yamamoto, M. and Kabayashi, T., "Research of Thermal Protection System for HOPE," Workshop on Structural Materials of Space Applications, ESTEC, European Space Research and Technology Centre, Noordwijk, The Netherlands, March 1988.