ICAS-88-2.3.2

METALLIC THERMAL PROTECTION CONCEPT FOR AERODYNAMIC CONTROLLED HYPERSONIC VEHICLES

H. Grallert, K. Keller
Messerschmitt-Bölkow-Blohm GmbH
Space Communications and Propulsion Systems Division
Munich, Fed. Rep. of Germany

Abstract

Since the first development and operation of reusable hypersonic vehicles, metallic and ceramic reradiative thermal protection systems have been emphasized and investigated. Due to temporaty advantages of rigid ceramic tiles with respect to specific weight this protection concept has been applied primarily in the US-Space Shuttle Program. Meanwhile, some inherent disadvantages have led to increased development activities in the area of metallic and advanced ceramic composites TPS. Newer metallic TPS developments show competitive specific weight and in addition they indicate some advantages like 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 e.g. 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 favourably applicable in the temperature range from 200 °C to 1300 °C. For higher temperatures advanced ceramic composites are preferable if some basic ceramic material problems have been solved. For temperatures ranging from 200 °C to 1300 °C a comparison of metallic and ceramic TPS design characteristics will be presented.

1. 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 reentry 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 economicly only by applying frequently reusable components and elements. Therefore hot structures and thermal protection systems have to be designed with respect to low maintenance/repair effort.

The aerothermodynamic load characteristics of the vehicle surface is defined above all by the vehicled class concerned. The upper stage of SÄNGER to be designed for reentry and named HORUS 3 is a pressure dominated vehicle like the US-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. Net mass budgets of related concepts have shown that the TPS mass fraction is usually 15 to 20 %. Therefore the TPS mass has to be minimized.

Furthermore advanced launcher systems promise a reduction in cost. This requires among others a reduction in TPS cost, which apart from low maintenance/refurbishment cost implies the use of a basic construction principle being easily to adapt to specific local requirements.

2. 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.

The critical design load cases of SÄNGER are:

(a) HORUS 3: High temperatur load with relatively short duration during reentry (in the order of 20 minutes).

(b) First stage: Moderate temperature load with longer duration during an extended cruise phase.

Representative temperature ranges are shown in Figures 3 and 4. The temperatures have been computed with software verified with data from the SHUTTLE-Orbiter flights (Figure 1).

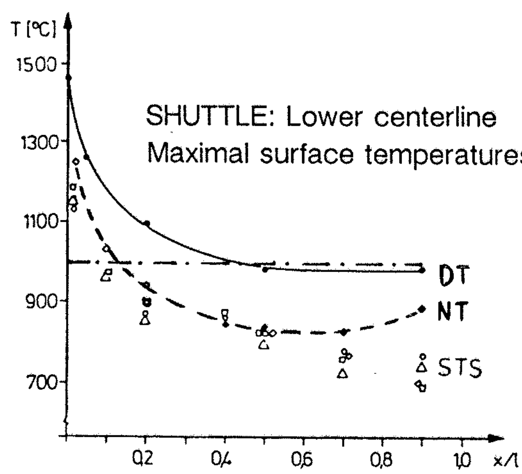

Figure 1: SHUTTLE surface temperatures. (DT: Design temperatures, NT: simulated nominal temperatures, STS: flight data)

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 part higher overestimation (turbulent heating). However, nonequilibrium real gas flow causes additional heat to surfaces with higher catalycity than the SHUTTLE surface one, further earlier transition 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 reentry vehicle. The dashed line corresponds to the model parameters as used in the SHUTTLE simulation.

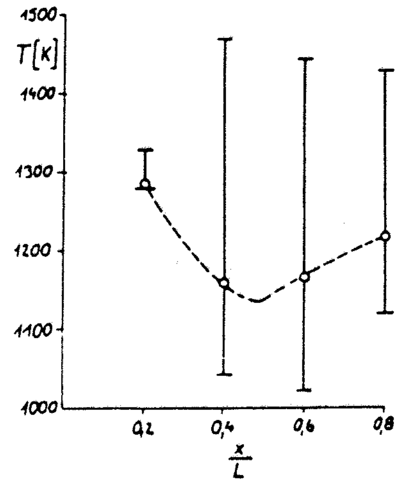

Figure 2: Transition model uncertainties.

For a reentry vehicle with similar size and surface characteristics, quite accurate and reliable predictions are expected from the computation tools applied in SHUTTLE simulation. Consideration of moderately higher atomic recombination and surface roughness yields the curve marked DT in Figure 3, whereas the curve NT is based on surface properties close to the SHUTTLE.

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

For the SÄNGER first stage the flow is in real gas equilibrium but fully turbulent. Hence, catalycity and surface roughness are of less importance compared to the reentry stage.

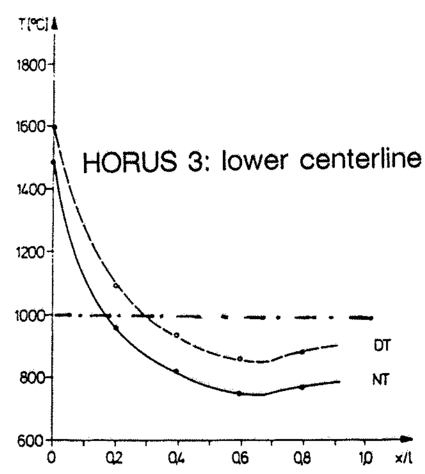

Figure 3: SÄNGER upper stage surface temperatures.

Even the difference between equilibrium real gas and perfect gas model predictions is quite low in this case. Only a difference of about 30 °C to 40 °C in surface temperature has been found for all areas except the stagnation areas. Primary important for the surface temperatures of the lower stage are the actual trajectory selected and the surface materials envisaged with an emisivity higher e.g. the one of polished titanium.

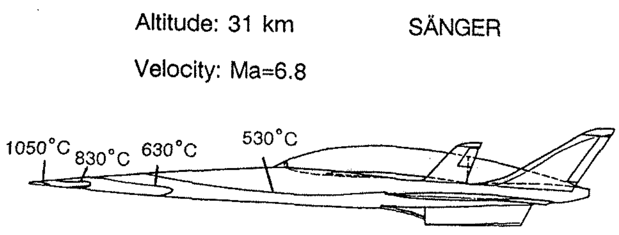

Figure 4: Predicted temperatures at SÄNGER first stage.

From the calculations performed for the winged launcher stage of SÄNGER about 95 % of the total surface region are expected to be loaded with temperatures below 900 °C.

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

3. Thermal protection system candidates

Reusable thermal protection systems are divided in two classes:

(a) Hot structures carrying mechanical loads.
(b) Thermal protection of cold load carrying structures.

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

Fibre 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 the temperatures below 500 °C two candidate solutions are in competition:

o Metallic multiwall panels [4,7]
o Flexible surface insulation [1,2]

It should be noted, that advanced flexible surface insulation might be extended to application temperatures of approx. 650 °C (1). Metallic multiwall panels have been successfully verified by test (8) up to some 550 °C and they were found to be weight comparitive.

Table 1: Characteristics of TPS Candidates

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	Luvward 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 *	Oxidation *	Oxidation
Thickness at comparable conditions	Not applicable	moderate	high	moderate	low	Not applicable
Thermal expansion	low	low	low	high	high	low

*) above 1000° C

As mentioned in section 2 TPS for the temperature regime between 500 °C and 1000 °C is emphasized in this paper. In principle four basic candidate TPS can been characterised which are also applicable at higher temperatures (cf., Table 1):

(1) Rigid ceramic tiles (Figure 5).
(2) Ceramic shingles combined with internal insulation (Figure 6).
(3) Metallic corrugated heat shields combined with internal insulation.
(4) Metallic multiwall panels optionally combined with internal insulation (Figure 7).

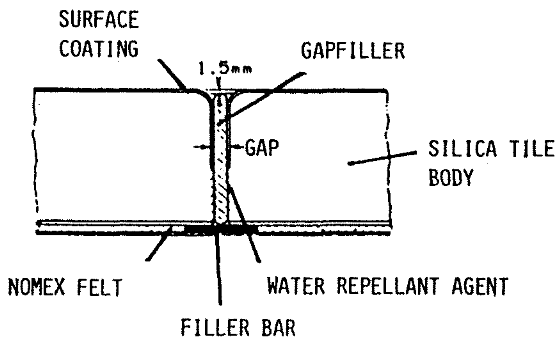

Figure 5: RIGID Ceramic Tile Concept.

Rigid ceramic tiles are applicable up to approx. 1250 °C. Their density is above 150 kg/m^3. They are manufactured from SiO_2 fibres [1] and adhesively bonded to a strain isolator pad which itself is bonded to the cold structure. Although the thermal performance of the tiles is excellent their disadvantages are brittleness, rain erosion and humidity sensibility. To improve these characteristics a borosilicate class coating is applied. The adhesive is sensible to overheating which led to loss of tiles in the STS flight program [1]. A further drawback is the tile bodies scattering in mechanical characteristics.

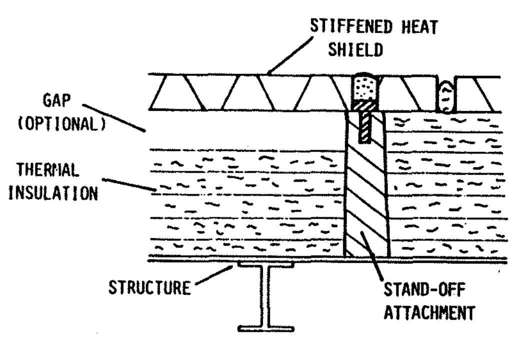

Figure 6: Standoff Shingle Concept.

Ceramic shingles will be applied for HERMES and are constructed e.g. as a dual strap panel with approximately 0,6 mm material thickness, and an internal multiscreen insulation wich is integrated in small compartments or bags [2]. Pressure loads from the environment are transfered by each shingle via four supports onto the cold structure. For that purpose it is intended to use screws and shear pins protected by ceramic plugs. The rigid ceramic shingle will be manufactured either from carbon fibres in silicone carbide matrix (C/SiC) or from silicone carbide fibres in silicone carbide matrix (SiC/SiC). The latter composite material will be applicable up to some 1250 °C and does not need any additional coating.

Stand-off 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 Programme [3] and in the French VERAS Programme. The stiffened metallic heat shield is constructed with 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 (approx. 1300 °C) and requires above 1000 °C a reliable coating against oxidation. Adjacent panels are shifted and are overlapping to reduce gap penetration. This concept has been successfully tested up to 1000 °C and technological improvements concerning stand-off elements and sealing against subsurface flows (cf., Figure 12) have been made [3].

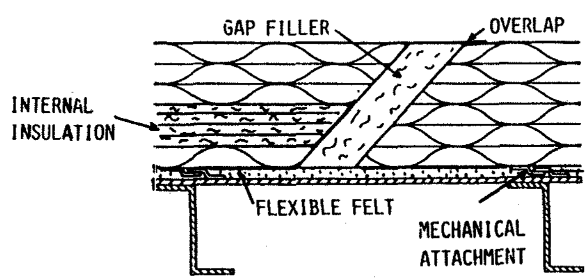

Figure 7: Multiwall Panel Concept.

Last but not least the metallic multiwall TPS concept represents a synthesis of earlier TPS concepts. Thin metallic foils (50 to 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 enables a flexible system applicable even at sperically curved surface areas. The upper temperature limit is defined by the materials used, e.g. about 1000 °C for Nickel or Cobalt based alloys and about 1300 °C for Molybdänium based alloys [5]. The latter in each case need an oxidation resistant coating. Mechanical attachment of the multiwall panels to the cold struture will be done by clips (4,7).

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

4. Concept selection

The design criteria for the HORUS/SÄNGER thermal protection concepts are divided in

(a) Basic design criteria.
(b) Requirements for materials.
(c) Criteria for surface characteristics.
(d) Construction criteria.

The basic criteria comprise:

- Reusability: This basic requirement excludes the use of ablative solutions. All solutions discussed in the previous section are reusable.
- Safety: The safety requirements are higher for a manned spacecraft. One of the critical tasks is the reliable attachment, which consequently favours mechanically attached systems compared to adhesively bonded systems (e.g. adhesive failure during early STS flights).
- Low maintenance: A thermal protection system with low maintenance will save cost. Favourable concepts (cf., Table 1) are: Flexible surface insulations, ceramic shingles and multiwall panels.
- Minimum weight: For 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. A sensitivity analysis (cf., Figure 8) indicated

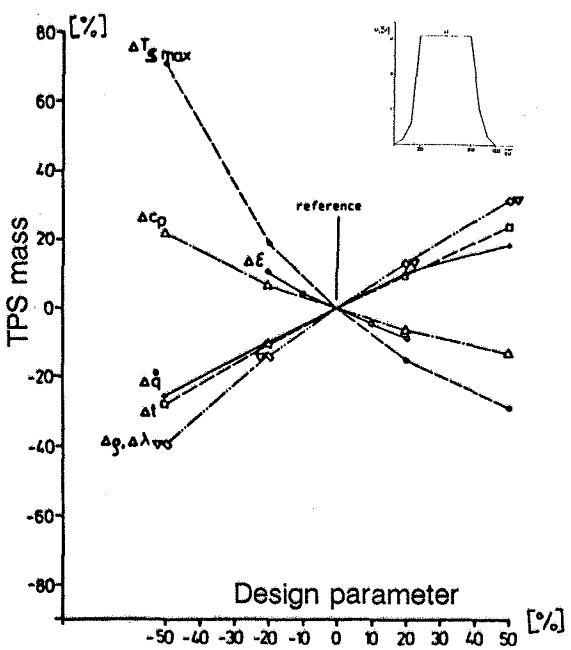

Figure 8: Sensitivity of TPS mass against different design parameter variations.

that the highest weight saving potential as calculated for a representative reentry 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 40 % and an increase in admissible cold structure temperature yields a weight reduction of about 30 %.

Future reinforced plastics and aluminium based alloys (e.g. Lithium-Aluminium 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 thermally a quite excellent solution. Progress is achievable only by alternative concepts. Figure 9 presents a trend analysis for representative transient thermal loads and design assumptions that are not too pessimistic.

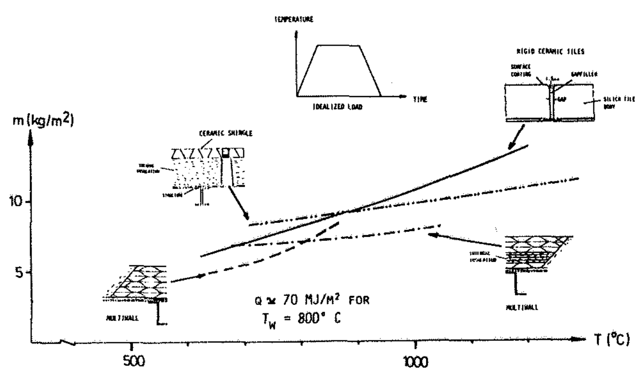

Figure 9: Trend of TPS mass per area versus temperature for main TPS concepts.

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

Further weight reduction is promised by metallic multiwall systems combined with internal multiscreen insulation, at least in the temperature range 700 °C to about 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 reentry an optimisation of metallic foil thickness is possible (cf., Figure 10). Consequently, optimized homogeneous multiwall panels might the superior in the range of 500 °C to 800 °C.

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

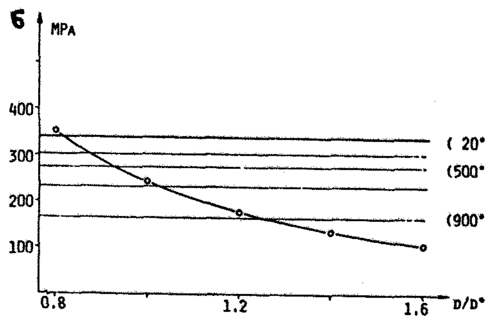

Figure 10: Structural tension as a function of the foil thickness ratio for multi-wall TPS.

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

The material selections criteria comprise

- o Temperature resistance: The materials selected should provide sufficient mechanical strength up to the corresponding maximum use temperature.
- o Chemical resistance: This mainly implies that no notable material degradation in oxidizing environment should take place. 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.
- o Damage tolerance: Failure mechanism for metals are quite well understood whereas for reinforced ceramics little knowledge is available today.
- o Low scattering of material characteristics: This is usually guaranted for metals but not for ceramics. Figure 11 shows the scattering in strength for Ceramic tiles of the Shuttle. For reinforced ceramics the data as described by several manufacturers show large scattering.

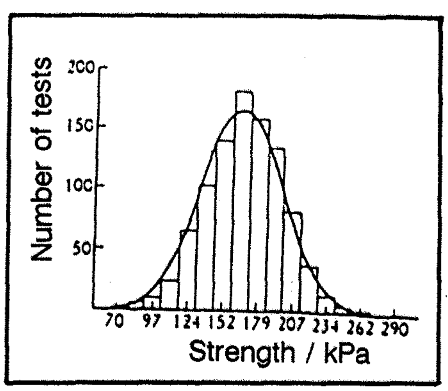

Figure 11: Scattering of strength of Rigid Ceramic Tiles.

The surface criteria comprise

- o Low catalycity: High catalycity, i.e. high atomic recombination implies higher heat loads. A 50 % increase in the heat load level yields nearly 20 % increase in TPS mass. The borosilicate glass coating provides quite low catalycity, whereas SiC/SiC ceramics and metal oxides prove higher catalycities.
- o High emissivity: This enables the reradiation of a large amount of aerothermal heat to space and thus yields reduced surface temperatures.
- o Smoothness: Rough surfaces, especially with concentrated roughness at the front section of the vehicle induce early transition to turbulent flow and therefore higher heating peaks for reentry vehicles. Early transition has a strong impact on the material selection and less impact on total TPS mass.
- o 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 systems by means of the overlap of the edges of adjacent panels (8).

The construction criteria comprise:

- o Reduced height of TPS elements: Saving in panel height yields volume gain, e.g. for a reentry vehicle with about 740 m^2 external surface each centimeter in height reduction yields a volume gain of about 7.4 m^3. This criterion is even more important for vehicles of small size due to the unfavourable surface to volume ratio.
- o Limitation of subsurface flows: During combined thermal/mechanical tests performed by 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.

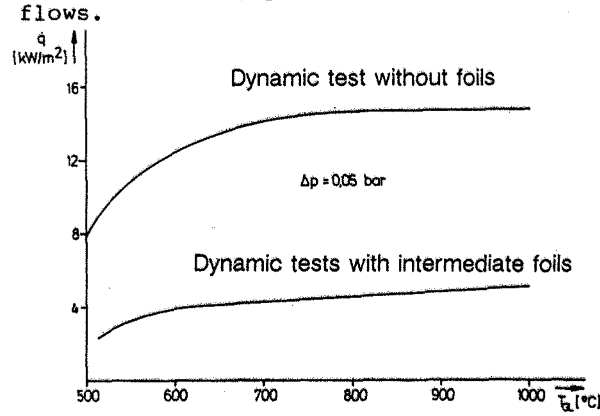

Figure 12: Limitation of subsurface flows by internal metallic foils.

o Compensation of thermal expansion: Thermal expansion requires expansion gaps. The necessary gap has to be smaller for ceramic TPS solutions than for metallic solutions. To avoid large gaps the size of metallic panels therefore is limited.

Considering the load environment and the fulfillment of the above design criteria, metallic multiwall panels seem to be a viable solution for the SÄNGER concept.

5. Metallic multiwall systems

For the multiwall solution proposed above (design principle see Figure 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 candidate metallic materials.

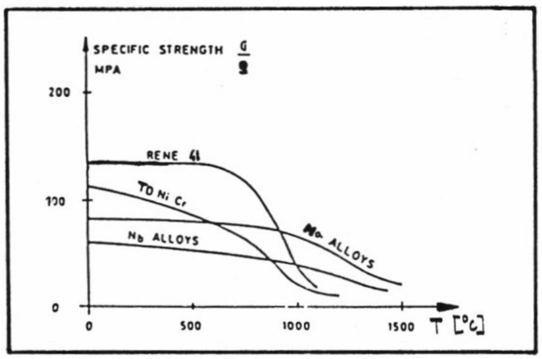

Figure 13: Tensile strength vs temperature.

From all the materials investigated the following alloys have been narrowed:

o Titanium alloys (up to 500 °C)
o Cobalt/Nickel base alloys (up to 1000 °C)
o NiCrSi Steel (up to 1150 °C)
o Coated refractory alloys (up to 1300 °C)

For several alloys oxidation tests have been performed, two of them shown in Figure 14 for 50 simulated reentry cycles (5).

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

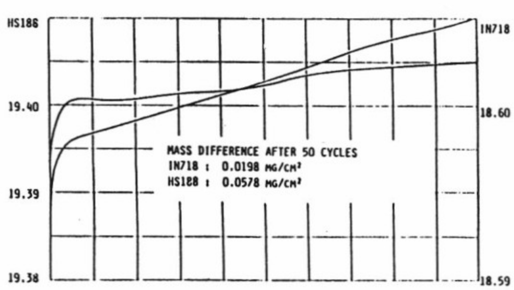

Figure 14: Measured oxydation rates

Besides this criterion the impact of oxidation on thermooptical properties is evident. Table 2 gives measured emissivities after 50 cycles at room temperatures (RT). No catastrophic degradation was observed.

Table 2: Measured emissivities (RT)

Foils	As Supplied	Oxydized
IN 718	0,136	0,188
HS 188	0,149	0,291

Accurate forming and heat resistant joining of thin metallic foils requires adequate tooling and methods. To identify and verify the optimum and cost efficient processing various laboratory samples have been manufactured using different processing tools and parameters. Figure 15 shows a 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 the dimpled foils to the multiwall package has been performed by diffusion bonding (DB). The same joining process is applicable to combine planar and dimpled foils for shear strength reinforcement.
The total process is well suited to manufacture curved panels, too.

From the structural analysis performed the major parameters
o Foil thickness
o Dimple pattern
o Dimple form
habe been identified to provide optimisation potential.

Figures 16 and 17 show the distribution of different thermal regions requiring appropriate TPS solutions.

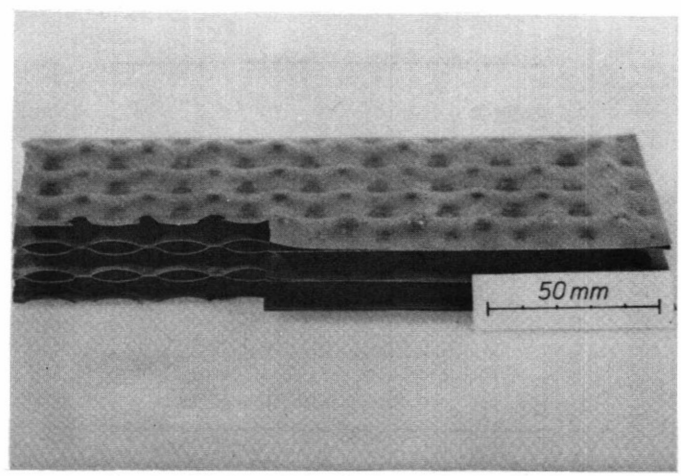

Figure 15: Multiwall TPS sample (IN718)

For the region No. 4 the homogenous multiwall solution based on titanium alloys is preferred. Alternatively flexible surface insulations may be applied.
For the region No. 3 multiwall panels combined with internal multiscreen insulation are preferred. As backup solution ceramic shingles with multiscreen insulation is envisaged.

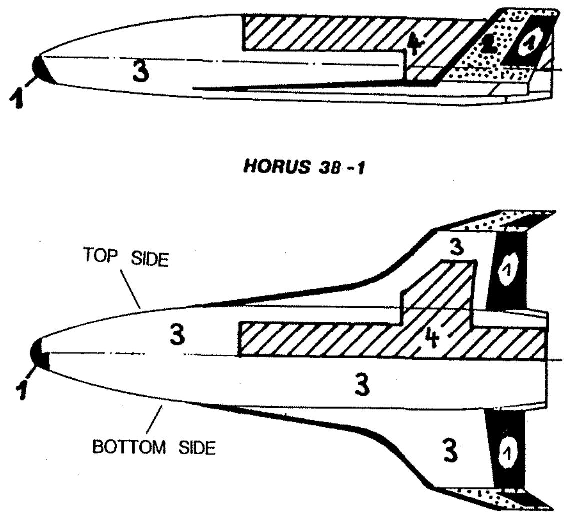

Figure 16: Surface regions of HORUS 3

For the region No. 2 multiwall solutions are preferable for the SÄNGER first stage.

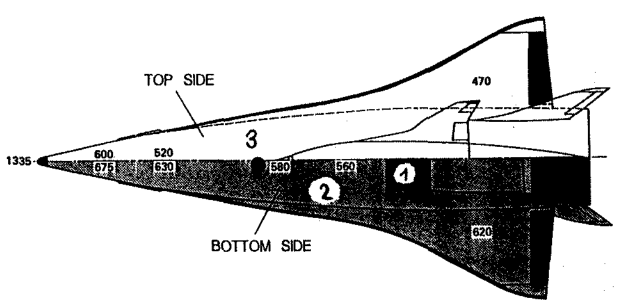

Figure 17: Surface regions of SÄNGER first stage

6. Conclusions

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

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

- o Low mass per area.
- o Simple and safe attachment.
- o Low scattering of metallic characteristics.
- o High durability and material toughness.
- o Application temperature up to 1300 °C if the related coating problem can be solved.
- o Commonalized design concept flexibly adaptable to the specific load requirements.
- o Potentially low manufacturing and maintenance cost.

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

References

(1) J.P. Arrington, J.J. Jones: Shuttle Performance Lessons Learned; NASA-CP-2283, 1983.

(2) D. Chaumette, J.C. Cretenet: HERMES Thermal Protection System Overview; IAF, Innsbruck, Oct. 4-11, 1986.

(3) H. Grallert: Wärmeschutzsysteme für aerodynamisch gesteuerte Wiedereintrittskörper. Raumfahrtforschung 4, 1974.

(4) H. Grallert, W. Keinath, K. Keller: Metallische Wärmeschutzentwicklung; MBB-TN-RA403-372/87, 1987.

(5) H. Grallert, K. Keller: Investigations for Advanced Thermal Protection Systems; EGEE, Munich, Nov. 13./20.th, 1987.

(6) K. Keller: Bewertung semiempirischer Hyperschall-Aufzeichnungen; MBB-TN-RR33-53/86.

(7) H.N. Kelly, G.L. Webb: Assessment of Alternate Thermal Protection Systems for the Space Shuttle Orbiter; AIAA-82-0833, 1982.

(8) J.L. Shideler, G.L. Webb, C.M. Pittmann: Verification Tests of Durable Thermal Protection System Concepts; AIAA-84-1767, 1984.

(9) M. Yamamoto, T. Kabayashi: Research of Thermal Protection System for HOPE; ESTEC, Noordwijk, March 23-25th, 1988.