High-Performance Heat Shields for Planetary Entry Systems

R. Rouméas
Structures and Mechanisms Division, ESA Directorate for Technical and Operational Support, ESTEC, Noordwijk, The Netherlands

T. Pichon & A. Lacombe
SEP Division, SNECMA, Bordeaux, France

Given that the mission scenarios of several potential future European space projects will require spacecraft entries into the atmospheres of various planetary bodies, including Earth, a number of advanced heat-shield technologies are currently under investigation. Besides the cold-structure option using materials such as beryllium, SEP has been developing a very promising concept using a hot structure of carbon/carbon or carbon/silicon-carbide. Depending on the particular mission requirements, this hot structure can be protected from extreme heat fluxes by an additional ablative layer. This modular approach, which allows the thermal protection system's performance to be tailored to the exact needs of the mission, forms the basis of the Sepcore® concept (Fig. 1).

The Sepcore® concept

The Sepcore® concept has a three-layer sandwich structure which can be adapted to a specific mission profile. The core of the system is a high-temperature-resistant ceramic matrix composite structure onto which a thin ablative layer is deposited. The payload is protected from the hot structure by a lightweight insulator. This layering approach allows one to design the heat shield with just the strictly necessary thickness of ablative material, which will be charred. The additional thickness of ablative material used in conventional heat shields to soak up the extra heat is replaced in the Sepcore® concept by lightweight internal insulation.

The main advantages of this concept are a potential mass saving of up to 50% (depending on the mission), its adaptability to particular mission requirements, and an increased failure tolerance due to the high temperature capacity of the carbon/silicon-carbide (C/SiC) structure.

The Sepcore® mock-up

In order to investigate the manufacturing feasibility of the Sepcore® concept, a reduced scale mock-up was designed and manufactured (Fig. 2). The mock-up's design complied with the high-energy reentry requirements of the proposed Comet Nucleus Sample Return (CNSR) mission (Fig. 3). The mock-up itself is made up of several components:

- a 15 mm-thick carbon/phenolic ablative heat shield
- a 1 mm-thick C/SiC hot structure stiffened by stitched and co-infiltrated 15 mm-high stiffeners
- an RTV bonding layer between the ablative layer and the hot structure, to prevent voids during assembly
- a high-temperature fastening system including carbon/carbon (C/C) screws, one central insert and three lateral inserts
- an isostatic six-strut payload-support structure
- an internal lightweight multi-layer insulation made of radiative barriers held in place by alumina felt pads.

As the mock-up was practically manufactured to test standards, it was decided to upgrade and configure it for testing under conditions representative of a re-entry in the IRS plasma test facility in Germany, with the pre- and post-test analysis carried out by FGE in the United Kingdom.

Testing the mock-up

The fully equipped mock-up is a cylinder 400 mm in diameter and 220 mm long and weighs approximately 13.8 kg, the Sepcore® heat shield weighing just 2.3 kg. It was linked to the test facility's sample support system via special test equipment, as shown in Figure 4.

A plasma generator was used to apply a heat flux to the front face of the mock-up. The test gas used as the plasma source propellant was 80% nitrogen and 20% oxygen. The incoming flux was limited to the ablative layer, i.e. a circular area 320 mm in diameter, with the radial distribution indicated in Figure 5.

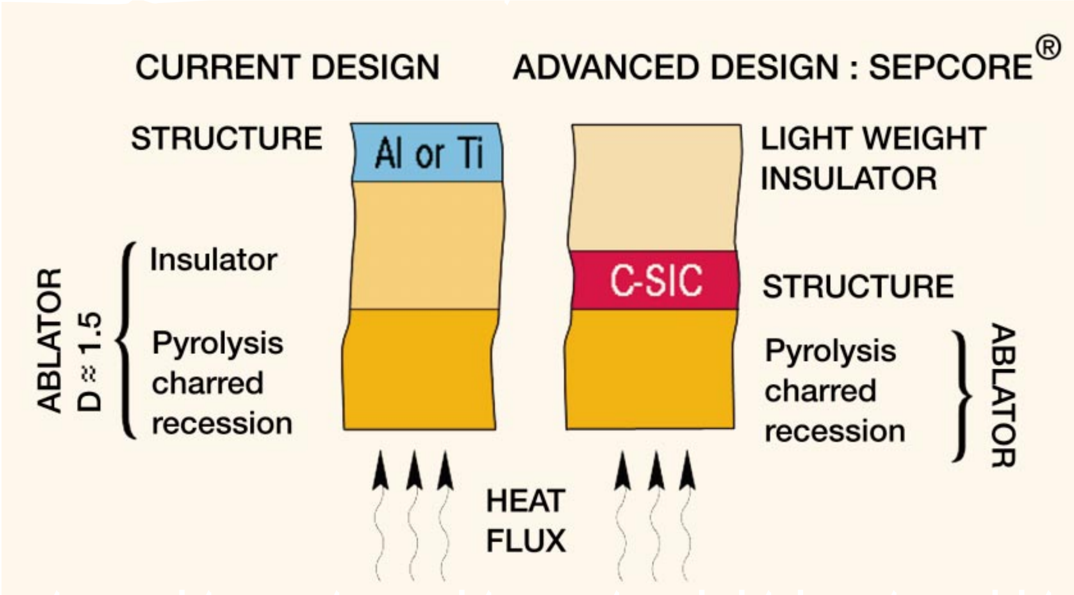
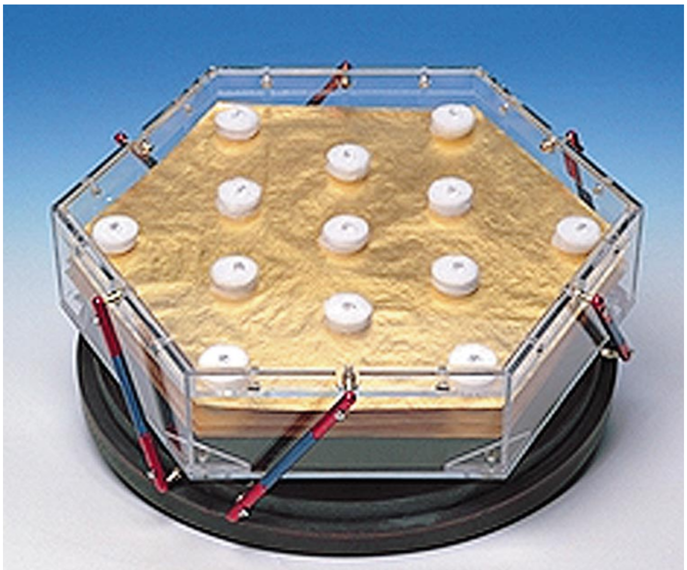


Figure 1. Current and advanced thermal-protection-system concepts



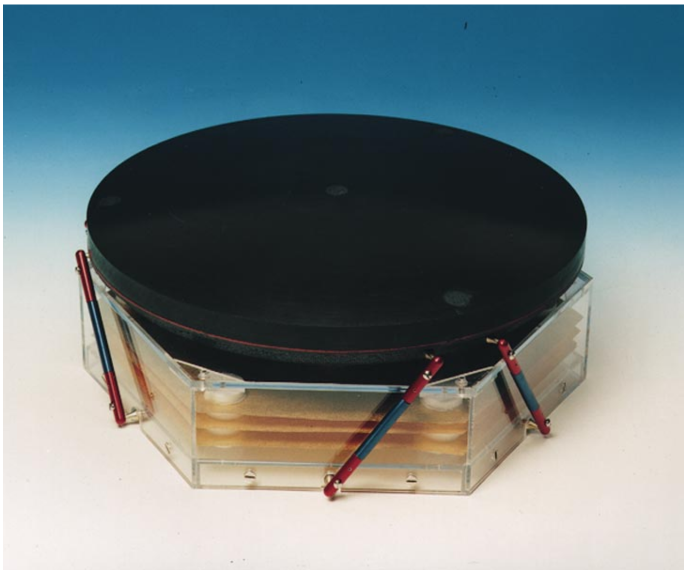


Figure 2. The Sepcore® mock-up

Preliminary testing on a graphite plate to check the possibility of achieving 10 MW/m^2 without interaction between test sample and plasma generator was carried out successfully. To avoid transient-phase heating, the plasma flow was ignited and stabilised with the mock-up in stowed condition. The mock-up was then moved into the test position as rapidly as possible to limit the transition phase from low heat flux to the nominal value of 10 MW/m^2 at an ambient pressure of less than 50 Pa.

The test end-criteria were :

- C/SiC structure back face temperature exceeds 1000°C
- aluminium struts reach 170°C
- testing time reaches 600 s.

Testing was stopped when the first criterion was fulfilled, after 270 s of firing.

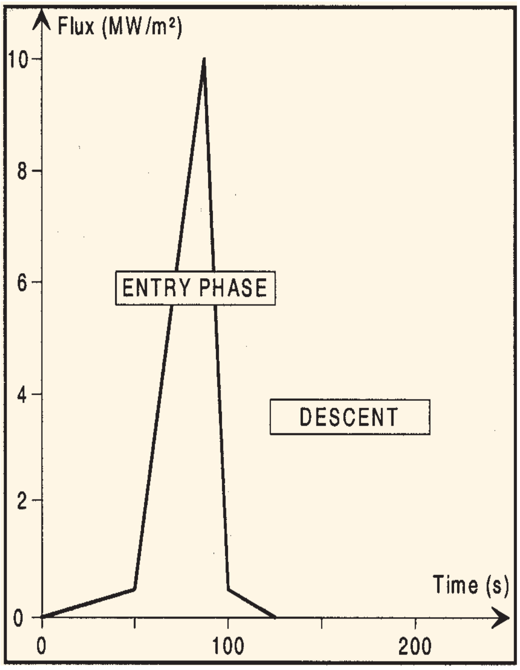
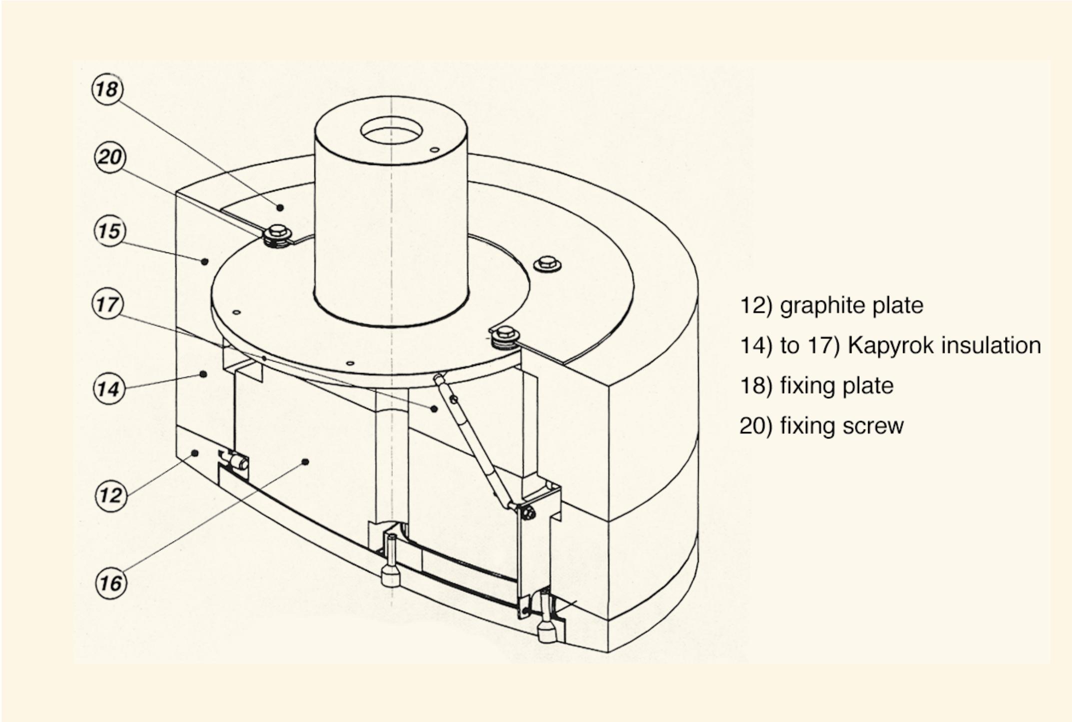


Figure 3. Re-entry heat flux data for the CNSR mission

Figure 4. Mock-up test equipment



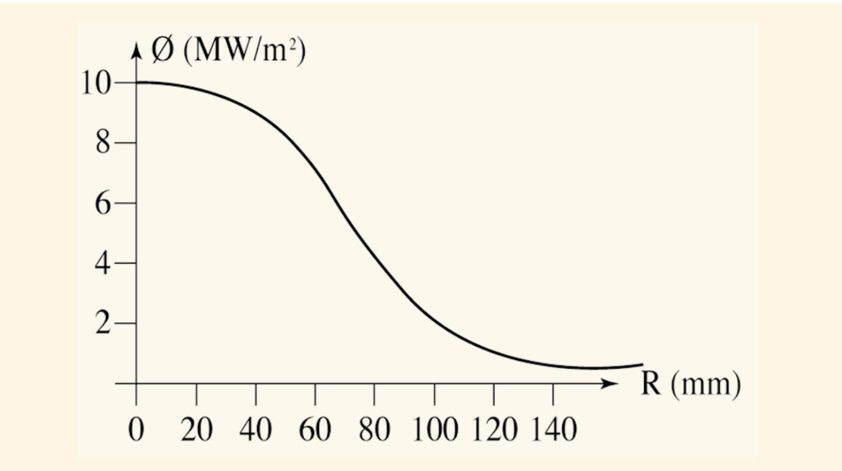


Figure 5. Heat-flux distribution applied in the mock-up test

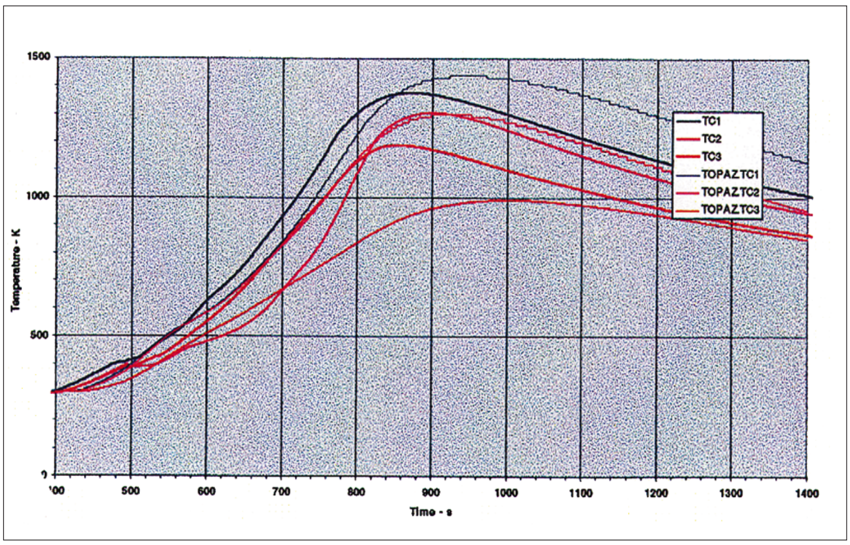


Figure 6. Test/analysis temperature comparison

Test results and analysis

The thermal performance of the Sepcore® mock-up was better than first predicted by analysis, which shows good design potential for further mass reduction in the ablator. After readjusting the material properties in the analytical model, good matching was achieved between the test results and calculated temperatures.

Satisfactory mechanical prediction was also achieved for the stiffeners of the C/SiC structure. Results on the skin were not as precise, due to insufficiently refined modelling of the link between the ablator and the structure. Escape of the pyrolysis gasses through the venting holes proved to be very efficient, contributing to the lower temperatures observed. On the other hand, the ablator delaminated from the C/SiC hot structure at the end of the test, in the region where the ablator plies were not drilled. This proved that it is necessary to vent the entire ablator.

A characterisation and morphological analysis was performed which confirmed the tensile failure mode of the C/C screws, due to the pressure build-up of pyrolysis gasses in the unvented part of the ablator. It also showed that the ablative material was fully pyrolised, but without any surface recession, which indicates a higher than expected surface enthalpy during the test. The C/SiC structure was undamaged.

Technology testing

Two sets of technology test samples were also designed and tested in SEP's Bordeaux (F) laboratory and ETCA's Odeillo (F) solar furnace

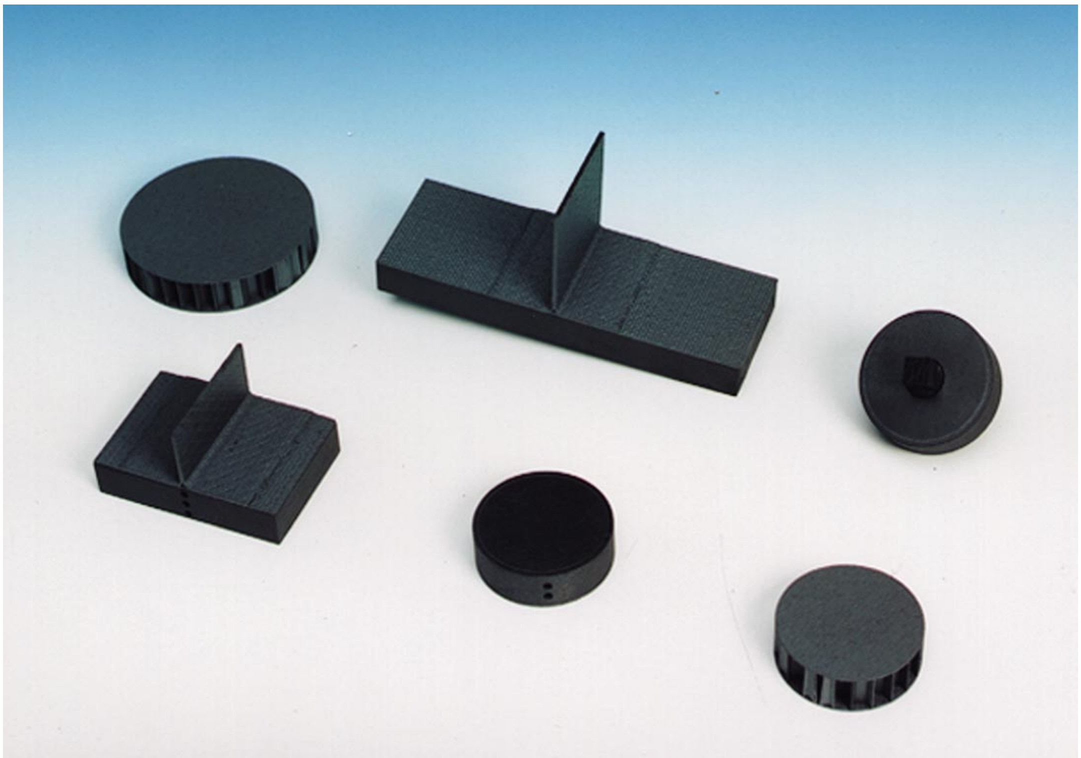


Figure 7. The technological test samples

in support of the experimental validation of the Sepcore® concept (Fig. 7). The objectives were twofold:

– to represent those zones of the Sepcore® mock-up, and hence also of the heat shields, that exhibit very specific behaviours under thermal and mechanical loads, in order to improve our overall understanding
– to evaluate candidate improvements to the Sepcore® concept, with a view to implementing them in future developments if they proved interesting.

The sets of test samples were manufactured to be representative of:

– the link between the skin and the stiffener of the C/SiC hot structure
– assembly technologies between the ablative layer and the C/SiC hot structure
– a C/SiC sandwich to be used for the hot structure.

The skin/stiffener link test specimen showed that the concept of sewn and co-infiltrated parts could withstand the thermal and mechanical loads encountered during a re-entry. The assembly technology specimen demonstrated that the concept is indeed suitable for the planned application, but that special care will have to be taken to dimension the insulation beneath the bolts correctly, as the heat fluxes are higher in this area due to the higher conductivity of the screw. No delamination between the ablator and the C/SiC hot structure was observed.

Direct moulding of the ablator onto the C/SiC hot structure was foreseen as an alternative means of bonding the ablator. However, this proved not to be feasible and the RTV bonding was retained as the baseline solution.

Finally, although the C/SiC sandwich hot structure is interesting due to its high specific stiffness, it is not sufficiently well developed to be incorporated into the Sepcore® concept. In particular, the bonding between the C/SiC honeycomb structure and the two skins will have to be improved, so as to prevent premature delamination.

Conclusion

The tests described above demonstrated that the thermal performance of the Sepcore® mock-up is better than first predicted by analysis, providing the potential for further mass reduction in the ablator whilst maintaining the same level of performance. Both the concept and its architecture have been proven, and a modular, low-mass, high-performance heat shield is now available for the European reentry vehicles currently under development and for future missions with similarly demanding requirements.