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# Chapter 11

## Thermal protection systems

Maurizio Natali, Luigi Torre, and José Maria Kenny  
University of Perugia, Perugia, Italy

### Abstract

Ablative materials play a vital role for the entire aerospace industry. Although some non-polymeric materials have been successfully used as ablatives, *polymer ablatives* (PA) represent the most versatile class of *thermal protection system* (TPS) materials. Compared with oxide, inorganic polymer, and metal based TPS materials, PAs have some intrinsic advantages, such as high heat shock resistance and low density. PAs are used to manufacture TPS for protection of vehicles and probes during the hypersonic flight through a planetary atmosphere and are also used in the production of chemical propulsion systems such as liquid and solid rocket motors. In this chapter, the state of the art of traditional and nanostructured polymeric ablatives will be reviewed.

### 11.1 The hyperthermal environment

*Thermal protection system* (TPS) materials are at the base of the entire aerospace industry. Depending on the hyperthermal environment in which the material must work, many types of TPS materials have been developed. TPS materials are used to protect the structure, the aerodynamic surfaces, and the payload of probes and space vehicles from the heating developed during the hypersonic flight through a planetary atmosphere. Thus, the protective heat shield of the vehicle must work as an aerodynamic body, as a structural component, and as a thermal insulator. During the re-entry flight, due to the interaction of the vehicle with the atmosphere, its kinetic energy can be dissipated via two basic mechanisms. On one side, when non-ablative materials are used for TPS manufacturing, re-radiation is the main phenomenon used to insulate the body re-entering in the atmosphere. Ablation is the second process used to protect a space vehicle [1]. Some non-polymeric materials have been successfully used as TPS materials [2, 3]; however, *polymer ablatives*

(PA) represent the most important and versatile class of TPS materials. In fact, when compared to inorganic materials such as oxides and metals, PAs have some intrinsic advantages such as, high heat shock resistance, low density, good mechanical strength and thermal insulation properties. The heating of the vehicle is approximately proportional to the square of the speed of the body to be protected; it also depends on the density and composition of the atmosphere and on the shape of the heat shield. Accordingly, the type of TPS material must be determined on the base of these inputs. Among TPS materials, PAs are able to survive in a wide range of hyperthermal environments. In terms of heat fluxes, PAs can experience values ranging from  $\sim 30 \text{ W/cm}^2$  up to  $\sim 30 \cdot 10^3 \text{ W/cm}^2$  [4, 5].

Once the working conditions of the TPS are known, the selection of the TPS material is related to the balance between the ablative and insulation properties. When a TPS material is used outside its optimal region, it is subjected to excessive erosion. To evaluate the performance of the TPS and properly design the heat shield, a modeling of the material response is necessary. To get the essential parameters necessary to enable the modeling tools, a series of laboratory tests must be performed for the selected material; the length of heat flux pulse - intended as a function of the time - will determine the sizing of the TPS but will also influence the testing environment. To improve the modeling of a given TPS material, the heat shield can also be instrumented with a series of surface and in depth sensors. Thermocouples are typically embedded in the heat shield and, during the re-entry flight, these sensors will provide data on the response of the material [6, 7].

PAs are also used to produce rocket engines; a rocket engine is an open chamber which temporarily confines the combustion gases, thus producing a thrust. The successive regions of the rocket chamber are a convergent/divergent section (the throat) and a nozzle that expels the gas. The hyperthermal environment in which a rocket chamber must operate is extremely severe; the heat fluxes can exceed  $10^3 \text{ W/cm}^2$  with temperatures above  $3000^\circ\text{C}$  and pressures higher than 60 bar [8]. The by-products of the combustion reaction are mechanically erosive, chemically corrosive and thermally reactive. PAs are used to produce liquid and solid propellant based rockets also known as *solid rocket motors* (SRM) [9]; the use of PAs allows to produce low cost, reliable, passively cooled rocket chambers.

The necessity to characterize ablative materials has led to the identification of laboratory procedures and implementation of testing facilities able to reproduce the different hyperthermal environments in which TPS materials must operate. The mass flow, the pressure, speed, shear stresses, temperature and chemical composition of the gas, all play an important role in the testing of the TPS material. Liquid and solid rocket engines, arc- or plasma-jet torches and other types of high enthalpy gas stream generators have been successfully used to recreate the hyperthermal environment [10]. However, in most cases, some characteristics of the real environment are not well reproduced. Thus, full scale tests are generally required to obtain the final validation of a given TPS material. Among all these different facilities, one of the most practical and cost effective ways to test TPS materials is based on the use of an oxy-acetylene torch. Such test-bed will be described in a dedicated section.

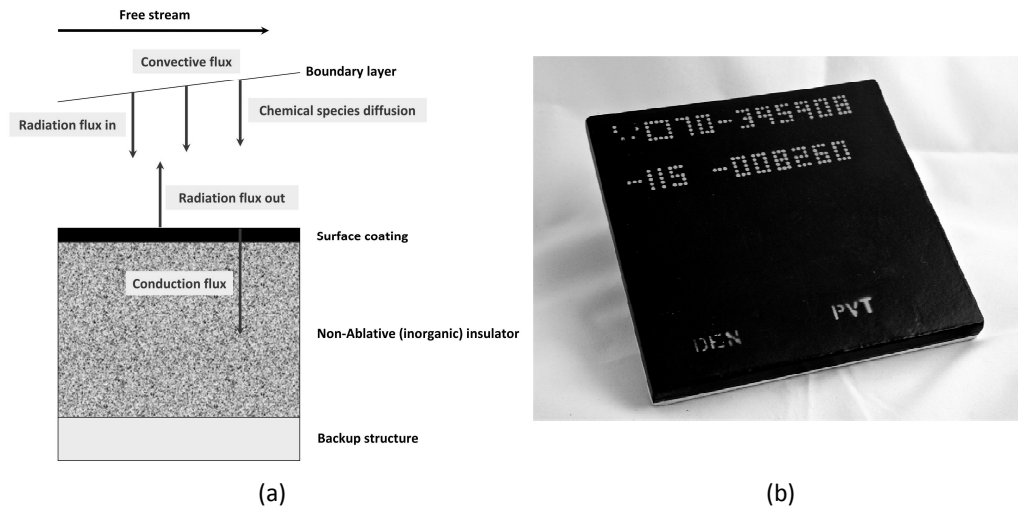


Figure 11.1: (a) Energy distribution for a non-ablative (or reusable) TPS material. (b) SSO HRSI tile. Reproduced with permission from NASA [11].

## 11.2 Non-ablative TPS materials

*Non ablative TPS materials* (NA-TPS) are based on the use of materials which after exposure to the entry environment experience no changes in the mass or properties of the material. For this class of TPS materials, re-radiation is the main phenomenon used to insulate the body re-entering in the atmosphere (Figure 11.1(a)). Typically, non-ablative TPS applications are limited to relatively mild hyperthermal environments; compared to ablative materials, NA-TPS should be able to ensure re-usability for a certain number of missions.

### 11.2.1 NA-TPS on the Space Shuttle

NA-TPS provide protection to space vehicles operating the re-entry flight like the *Space Shuttle Orbiter* (SSO). At the end of a mission, when the SSO re-entered the Earth's atmosphere, it traveled at a speed as high as  $\sim 7.6$  Km/s; surface temperatures above  $\sim 1650^\circ\text{C}$  were associated to this re-entry profile. The main role of the NA-TPS was to protect the SSOs airframe, which was primarily made of aluminum and it could withstand a maximum temperature of  $\sim 180^\circ\text{C}$ .

For the SSO, and similarly operating vehicles, a different type of heat shield was required. Expected to last 100 missions, the SSO required a lightweight, reusable TPS. The objective of the NA-TPS was twofold; to protect the SSO from re-entry heat, and to protect the airframe and major components from extremely cold temperature during the night phase of each orbit. In fact, the external temperature fluctuated from approximately  $-128^\circ$  to  $95^\circ\text{C}$  for each 90-minute orbit.

During the early stages of NASA's SSO, the following primary heat shield materials were considered: replaceable ablatives, re-radiative carbon/carbon composites, oxide insulators, and metals [12]. With the exception of control surfaces that ex-

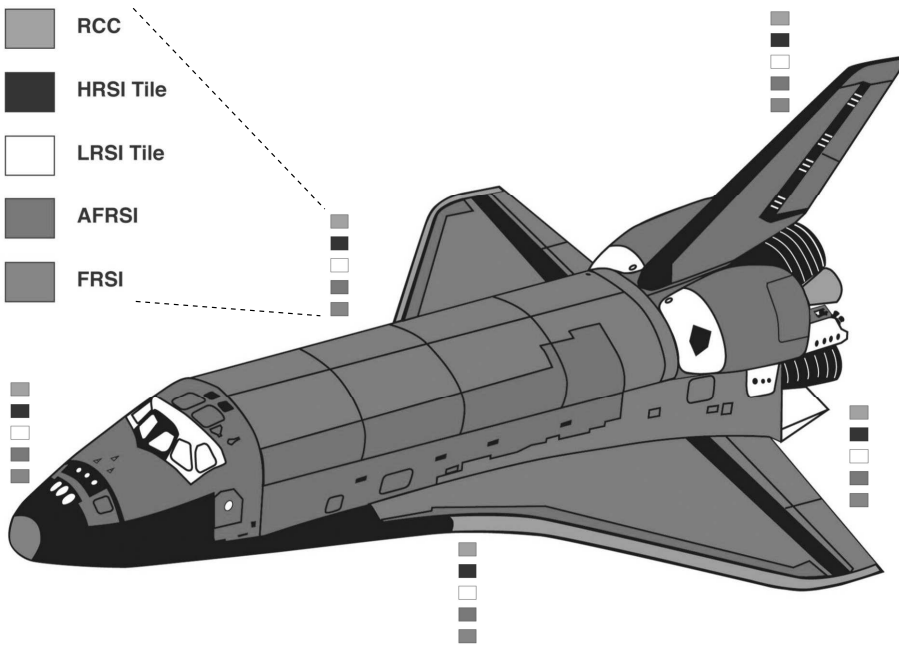


Figure 11.2: Space Shuttle non-ablative TPS. Different TPS solutions introduced for the SSO thermal management are indicated in the figure. Reprinted from [17] with permission from NASA [11].

perienced the highest temperatures, oxide insulators were eventually selected for all areas. Originally, most surfaces of the SSO were covered by insulation tiles [13], made of silica fibers bonded by a silicon oxide matrix. The materials and processing of SSO NA-TPS have considerably changed since early developments [14], with successive modifications having the goal of improving temperature and mechanical performance of the tiles. However, even after decades of research and with many successful improvements, the Space Shuttle NA-TPS intrinsically remained expensive to produce and maintain. As a matter of fact, the goal to achieve a low cost and low maintenance system was not achieved. Nonetheless, many relevant breakthroughs in the field of ceramics were enabled by these efforts, especially in terms of industrialization of the processes used to produce the oxide based fibers and the low density ceramic insulators at the base of the SSO NA-TPS tiles. A very detailed description of all technologies and processing steps involved in the manufacturing of the SSO NA-TPS was reported by [15]. NASA originally selected four basic materials for the SSO TPS. These basic materials were the *low- and high-temperature reusable surface insulation tiles* (LRSI and HRSI, respectively), the *felt reusable surface insulation* (FRSI) blankets, and the *reinforced carbon carbon* (RCC). The NA-TPS of the Columbia SSO was comprised of more than 32,000 individual tiles covering the lower and upper surfaces, with FRSI covering the upper payload bay. Figure 11.2 reports the layout of a SSO, highlighting the sections of the vehicle in which were applied the different TPS materials [16].