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AUTHOR: A. Savchenko and F. Gimranova

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Heat Protection for Space Ships

by

A. Savchenko and F. Gimranova

Protecting space ships returning from orbit against heat is one of the most important problems facing present day engineering. As entry is made into the dense layers of the atmosphere the space vehicle, or the nose cone of the missile, is subjected to intense aerodynamic heating as the molecules of air ahead of the moving body are compacted and the transition from molecular kinetic energy to heat energy takes place. Aerodynamic heating depends on the speed of flight, air density, ballistic shape of the nose cone, the angle of entry into the dense layers of the atmosphere, and on other factors. Heating reaching a maximum at high flight speeds in the lower layers of the atmosphere (fig. 1). The gas boundary layer with which the space vehicle is in contact can be heated to 7000°C, and higher.

The problem of heat protection for space ships is widely discussed in the foreign press. Attention is given first to materials with high heat capacity and heat conductivity (copper, beryllium, graphite) which, when built up into massive layers, bring about a reduction in temperature as a result of heat absorption. Ceramic materials, which have low heat conductivity, provide cooling by reflecting much of the thermal energy.

The use of laminated plastics is another way of reducing the temperature, and results from so-called ablative cooling, from the physical and chemical transformations of the material, associated with the destruction and carrying away of the material from the surface of the cone.

What is the explanation of the fact that plastics are more advantageous to use under very high temperature conditions and under the effects of a high velocity gas flow? First, their heat protecting properties and comparatively high capacity to absorb heat, based on chemical decomposition and change in the state of the substance. Second, during the ablation process the surface of the plastic undergoes rather intense heating and radiates some of the absorbed heat back into space. Third, the gaseous products which are formed reduce the surface temperature because of a thickening of the boundary layer.

Laminated plastics successfully combine good heat protection properties and high mechanical strength. Here they show to advantage over heat-resistant steels, and aluminum and titanium alloys. When subjected to heat shocks the inner layers of plastics are heated somewhat, but they retain their structure and strength, whereas aluminum alloys, for example, lose as much as 25% of their strength at 270°C.

When the space vehicle enters the atmosphere its temperature rises above the metal's melting point, and this can cause deformation. The use of laminated plastics eliminates the possibility of the vehicle deforming, while, at the same time, reduces its weight.

As will be seen from Table 1, it takes almost 3 times as much ceramic material, and 50 times more copper, than it does laminated plastic to provide the same heat protection.

Just how great are the heat protective properties of plastics will become evident when the ablation process in these materials is considered.

A material which provides protection against heat absorbs some of the heat resulting from increase in temperature. Despite the increase in temperature on the surface of the cone, transmission of heat to the inner part of the cone is limited by the low heat conductivity of plastics.

High temperatures and high velocities of the surrounding gases establish conditions for the chemical and physical changes in the components (fig. 2).

The organic components, the binder, are subjected to pyrolysis,* or they burn. Gaseous products and a porous carbon layer form.

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* Pyrolysis is the decomposition of complex products into simpler ones as a result of high temperature.

The gaseous products of pyrolysis, which are at a comparatively low temperature, absorb the thermal energy near the nose cone and, falling into the gas boundary layer, increase its thickness. The result is that a surface which is subjected to ablation is found to be in a layer of relatively cold gas.

The inorganic components, the fillers, since they absorb heat, are subjected to phase conversion from the solid to the liquid state. Some of the molten substance evaporates and is carried away from the surface by the air flow. Heat is also absorbed upon distillation of the volatile components of the filler.

All processes in the organic and inorganic components take place in the relatively thin surface layer. Under the layer which is being carbonized is the layer in which decomposition begins. These layers form the ablation front, which gradually shifts through the thickness of the layers.

The laminated plastics give off a great many low molecular products as they are destroyed and these form a solid, porous, carbon layer. These products are most useful for heat protection. So far as the ablation rate is concerned, the phenolic and silicone resins are the best (fig. 3). Phenolic plastics have the thickest carbonizable layer and suffer the least loss of strength under thermal shock.

The use of quartz and ceramic fibers is of interest. Plastics reinforced with these fibers are exceptionally heat resistant. For example, phenolic base plastics and quartz fiber were considerably better than stainless steel when strength tested during burn out.

Graphite fiber, a recent innovation, is a future reinforcing material. It has high strength at temperatures as high as 2500°C.

An organic fiber, "Pluton," which is more heat-resistant than most mineral fibers, and which will not melt at 2900°C, has been synthesized in the United States. Cloth made of this fiber will not burn when molten steel is allowed to solidify on it. The fiber retains its flexibility and strength after intensive heating.

It is suggested that the recently developed glass crystalline materials, the so-called pyroceramics, be widely used to protect space vehicles. These materials have a low heat expansion factor, high strength, and exceptionally high thermal stability. The temperature at which various of the pyroceramics soften ranges between 1200 and 1370°C. Pyroceramics have fixed dielectric properties and will pass decimeter radio waves.

As will be seen from Figure 4, at comparatively low temperatures the ablation rate is minimum for plastics reinforced with glass and quartz fibers, and maximum for plastics with nylon fiber. On the other hand, in the high temperature area plastics reinforced with nylon fibers have a lower ablation rate than do plastics which contain glass and quartz fiber.

Heat of ablation characterizes the ability of a material to absorb and dissipate heat. Its magnitude can be determined by the binder and filler (Table 2).

Reinforcing material for manufacturing laminated plastics is used in the form of cloth, mats, and continuous and chopped fiber. Experience has shown that the most effective plastics are those reinforced with cloth and continuous fiber.

The roughness of the surface during the destruction process influences the effectiveness of the ablative system. Even slight roughness causes swirling in the flow, and this accelerates the transfer of heat from the boundary layer to the body and reduces the magnitude of absorbed heat (Table 2). The material is destroyed as a result of the heat and aerodynamic friction.

Attempts to improve heat protection by the application of refractory materials (aluminum oxide, molybdenum on aluminum, aluminum oxide on zirconium oxide, and others) to laminated plastics have not always had favorable results. The gases which form when the plastic is destroyed accumulate under the coating and, upon reaching a predetermined pressure, can damage it. The flying pieces can also destroy the rest of the surface. The uneven destruction of the coating causes turbulence in the flow of gases, and this accelerates the destruction of the nose cone.

Thermal protection by ablation from laminated plastics has been tested under real conditions during the flight of "Jupiter" ballistic missiles, types AM-5, AM-6, and AM-18, using nose cones of different configurations. The results confirmed the advantages of using laminated plastics to provide heat protection for missiles and space ships.

Laminated plastics are usually combined with foam plastic, or honeycombed panels, which have an extraordinarily low heat conductivity coefficient, in order to improve heat protection. The outer envelope of the American communications satellite, "Courier 1B" is a honeycomb panel made of nylon placed between the glass plastic layers, for example.

New types of high-strength, thermal and fire resistant fillers and binders will lend themselves to further introduction of laminated plastics in space equipment as a means of protecting such equipment against thermal effects.

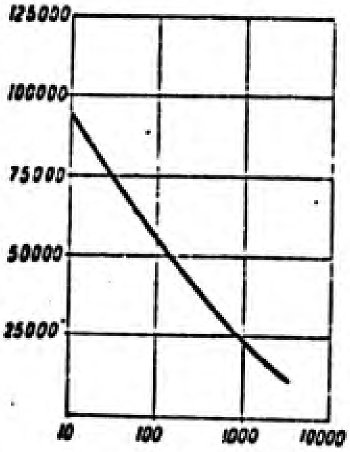

Figure 1. Density of the heat flow on the surface of a nose cone with a radius of 1.2 meters at a flight speed of 7,000 meters/second. Vertical scale: altitude, meters.

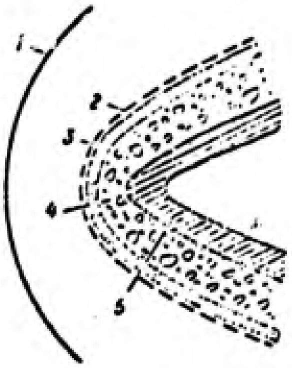

Figure 2. Schematic diagram of the ablation process. 1 - shock wave; 2 - gas boundary layer; 3 - molten layer; 4 - porous carbonized layer; 5 - layer in which decomposition takes place

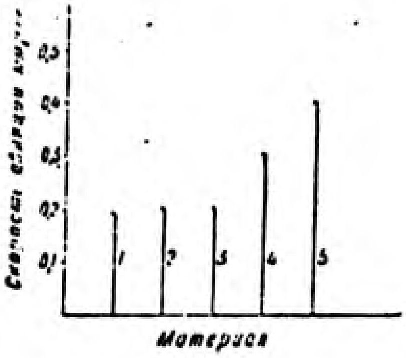

Figure 3. Ablation rate for glass plastics with different resin bases (heat flow 270 kcal/m^2/sec): 1 - phenolic; 2-silicone; 3 - melamine; 4 - polyepoxy; 5 - polyester. Vertical scale: ablation rate, mm/sec; Horizontal scale: material

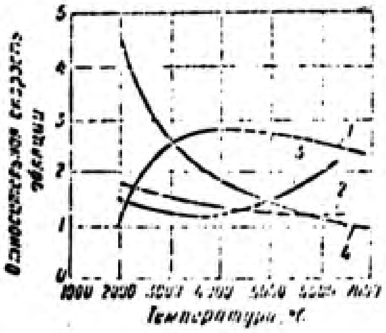

Figure 4. Effect of temperature on the ablation rate for phenolic reinforced plastics: 1 - glass fiber (27% resin); 2 - glass fiber (65% resin); 3 - quartz fiber (41% resin); 4 - nylon fiber. Vertical scale: relative ablation rate; Horizontal scale: temperature, °C

Table 1. Minimum amount of material required to protect the nose of a ballistic missile against heat (heat flow, 270 kcal/m^2/second)

Material	Weight, kg
Quartz fiber - phenolic resin	91
Glass fiber - melamine resin	180
Noncombustible ceramic	250
Beryllium	600
Copper	4500

Table 2. Amount of heat absorbed during the ablation of reinforced phenolic plastics in a subsonic arc with water stabilization at 12,730°C

Reinforcing fiber	Nature of flow	Absorbed heat, kcal/kg
Glass	Turbulent	1000
Glass	Laminar	2500
Quartz	Turbulent	3000
Nylon	Turbulent	5000