Heat Conduction into a Hypersonic Glide Vehicle

David Wright
Laboratory for Nuclear Security and Policy,
MIT Department of Nuclear Science and Engineering

Hypersonic weapons are defined as those that travel faster than Mach 5, or about 1.5 km/s. Any ballistic missile with a range greater than about 300 km is hypersonic. Boost-glide vehicles, rather than arcing above the atmosphere like ballistic missile, are instead launched on missile boosters and then enter the atmosphere and glide aerodynamically at high speeds for a significant fraction of their total range.

A boost-glide vehicle like the HTV-2 system[1] the United States has developed and tested may begin its glide with a speed of about 6 km/s at an altitude of about 50 km.[2] At this speed the vehicle can glide up to about 7,000 km, which it will cover in about 30 min.

Traveling at such high speeds in the atmosphere causes intense heating of the air around the vehicle, and some fraction of that heat is transferred to the vehicle. As a result, the surface temperature of the vehicle may approach 2,000 K for extended periods of time.

While the vehicle can be coated with materials that withstand sustained temperatures of this magnitude, holding the surface of the vehicle at a high temperature causes heat to conduct into the interior of the vehicle; this process is often called "heat soak." Given the long glide times during which these high surface temperatures persist, it is important to check whether the heat soak is large enough to raise interior temperatures of the glider high enough to damage its internal systems and payload.

This paper estimates the heat conduction into the interior of a hypersonic boost-glide vehicle using a simple model for one-dimensional heat transfer and some typical insulating materials.

Methodology

For this estimate, I use the analytic one-dimensional calculation of heat conduction that starts on page 48 of Daniel Mackowski's online notes on heat conduction.[3]

Mackowski assumes a slab of material of width $2L$ (which goes from $x = -L$ to $x = L$), initially at uniform temperature T_1. At time $t = 0$, the two walls are raised to a temperature T_2, and heat diffuses into the slab. The calculation determines the temperature distribution in the slab as a function of t and x.

[1] Wikipedia, "Hypersonic technology Vehicle 2," https://en.wikipedia.org/wiki/Hypersonic_Technology_Vehicle_2
[2] James M. Acton, "Hypersonic Boost-Glide Weapons," *Science & Global Security* 23 (2015): 191-219, http://scienceandglobalsecurity.org/archive/sgs23acton.pdf
[3] Daniel W. Mackowski, "Conduction Heat Transfer:Notes for MECH 7210," Mechanical Engineering Department, Auburn University, http://www.eng.auburn.edu/~dmckwski/mech7210/condbook.pdf

I assume the glider is initially at T_1 = 300 K, and for t > 0 the exterior wall of the glider is held at T_2 = 1900 K throughout its flight, which is what computer modeling of the HTV-2 shows.[4] This calculation will overestimate the heat soak into the body since it overestimates the surface temperature averaged over the body and the duration of glide, and ignores the fact that heat conduction into the body will lower the equilibrium surface temperature somewhat.

Mackowski defines dimensionless variables: $x' = x/L$, $t' = t\,\alpha/L^2$, and $T' = (T - T_2)/(T_1 - T_2)$ (note that the definition of T' in the reference is incorrect). T' starts at T' = 1 and at long times goes to T' = 0.

Here $\alpha = k/\rho C_p$ is the thermal diffusivity of the wall material in [m^2/s], where:

> k is the thermal conductivity in [J/m s K]
> ρ is the density in [kg/m^3]
> C_p is heat capacity in [J/kg K]

Mackowski gives the solution for $T'(x',t')$ in Fig. 3.2 on page 54 of his notes:

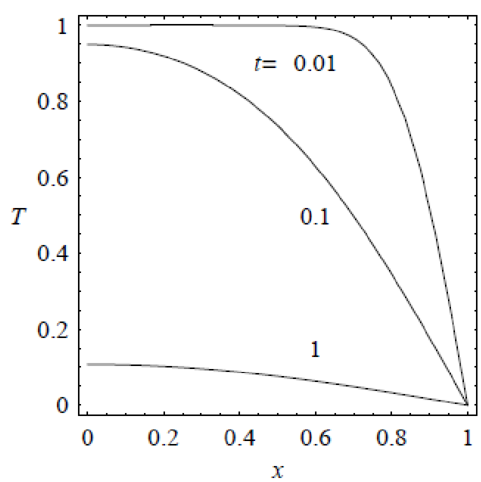

Fig. 3.2 from Mackowski: T, t and x in this figure are the dimensionless variables T', t', and x'.

Results for Two Insulating Materials

I now apply the results to the hypersonic case to two standard insulating materials.

(1) Refrasil Phenolic

Silica phenolic or "refrasil phenolic," is roughly 35 percent by weight phenolic resin impregnated into a fabric reinforced with high-purity glass fiber. Using these materials for ablating heatshields was considered state of the art in the 1960s because of their thermal,

[4] Cameron Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," to be published in *Science and Global Security*.

mechanical, and chemical properties. This material has an ablation temperature of 2700 K, so if it is used to cover the outside of the glider it would not ablate except possibly near the stagnation point at the tips of the wings. This material has the following properties:[5]

k = 0.5 J/m s K
ρ = 1632 kg/m^3
C_p = 1174 J/kg K
⇨ $\alpha = k/\rho C_p$ = 2.6 x 10^{-7} m^2/s

For this material, Mackowski's Fig. 3.2 gives a dimensional temperature at the center of the slab of $T'(x=0)$ = 0.95 at a time t' = 0.1.

Assume a layer of this material with a thickness of L = 5 cm.

Since T = 1900 – 1600 T' and t = 1x10^4 t', this corresponds to a temperature rise from 300 to 380 K at a distance 5 cm into the interior of the vehicle after 1000 s = 17 minutes. A time of 17 minutes is the glide time of a vehicle starting at 6 km/s and gliding for 5,500 km, which including the boost and ballistic phases gives a total range from launch of 8,600 km in our calculations.[6] Recall that this calculation overestimates the temperature rise for several reasons, discussed above.

Because t' scales as L^{-2}, the physical time t corresponding to t' = 0.1 increases rapidly with the thickness of the layer. In this case, increasing the thickness L of insulator from 5 to 7 cm would double the time needed for the temperature at the inside surface to increase to 380K, which would cover the maximum glide time of this vehicle.

To further reduce the heat conduction and the mass of the shielding, the layer of refrasil phenolic could be made thinner and backed by an insulating material with lower diffusivity and density, which may not be appropriate as an outer coating for the glider.

(2) Space Shuttle Tile

As a second example of an insulating material, consider the tiles that were designed for Space Shuttle reentry, which have the parameters:[7]

k ~ 0.07 J/m s K (this takes into account the T dependence for the times considered here)
ρ = 352.5 kg/m^3
C_p = 628 J/kg K
⇨ α = 3.2 x 10^{-7} m^2/s

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[5] C.J. Katiskas, G.K. Castle, and J.S. Higgins, Ablation Handbook, AVCO Corporation Technical Report AFML-TR-66-262, September 1966, p. 58.
[6] Tracy and Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles."
[7] "Appendix to Section 3: Space Shuttle Tile Thermal Protection System," notes for Mechanical and Aerospace Engineering class 5420, http://mae-nas.eng.usu.edu/MAE_5420_Web/section3/appendix3.pdf

This material will give similar results to the refrasil phenolic since the value of α is essentially the same.

The Space Shuttle tiles vary in thickness from one inch (2.54 cm) to five inches (12.7 cm) depending on the heating they will encounter in different parts of the Shuttle during reentry.[8] The reference in footnote 8 gives a maximum temperature for the tiles of 2,800 F (1,800 K), although other sources say the Shuttle is subjected to temperatures as high as 3000 F (1900 K) during reentry.

Because of the low density of these tiles they would give a lower mass of shielding than refrasil phenolic. For a body with size of the HTV-2 vehicle, the Shuttle shielding material would have a mass of 370 kg assuming an average thickness of 7.5 cm over an area of 14 m^2. My estimate of the total HTV-2 mass is roughly 1,000 kg.[9]

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[8] NASA, "Space Shuttle Tiles: Structures and Materials," https://www.nasa.gov/sites/default/files/atoms/files/shuttle_tiles_5_8v2.pdf

[9] David Wright, "Research note to hypersonic boost-glide weapons by James M. Acton: Analysis of the boost phase of the HTV-2 hypersonic glider tests," *Science & Global Security* 23:3 220-229, 2015, http://scienceandglobalsecurity.org/archive/sgs23wright.pdf