

# Tutorial on Ablative TPS

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- Why this tutorial?
- Ablative TPS - early studies
- Organic resin composites
- Surface recession mechanisms/modeling
- High fidelity model development
- Testing approaches/requirements
- Future needs

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# Ablative TPS Community in the 60s and 70s



# Ablative TPS Community in the 80s



# Ablative TPS Community in the 90s



Time is not  
our friend

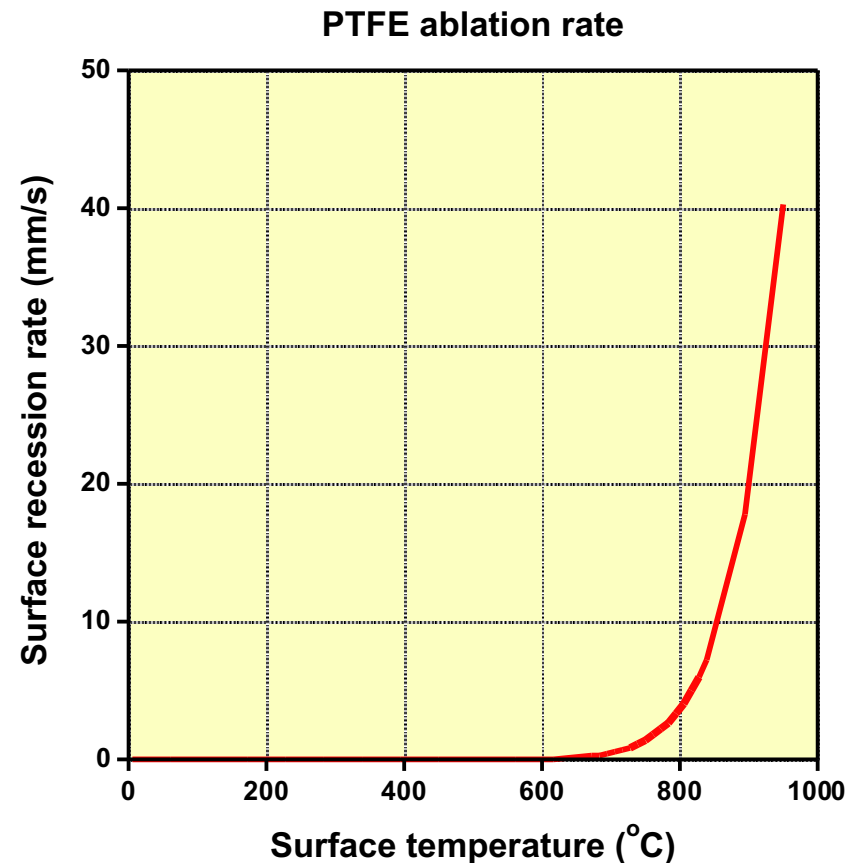


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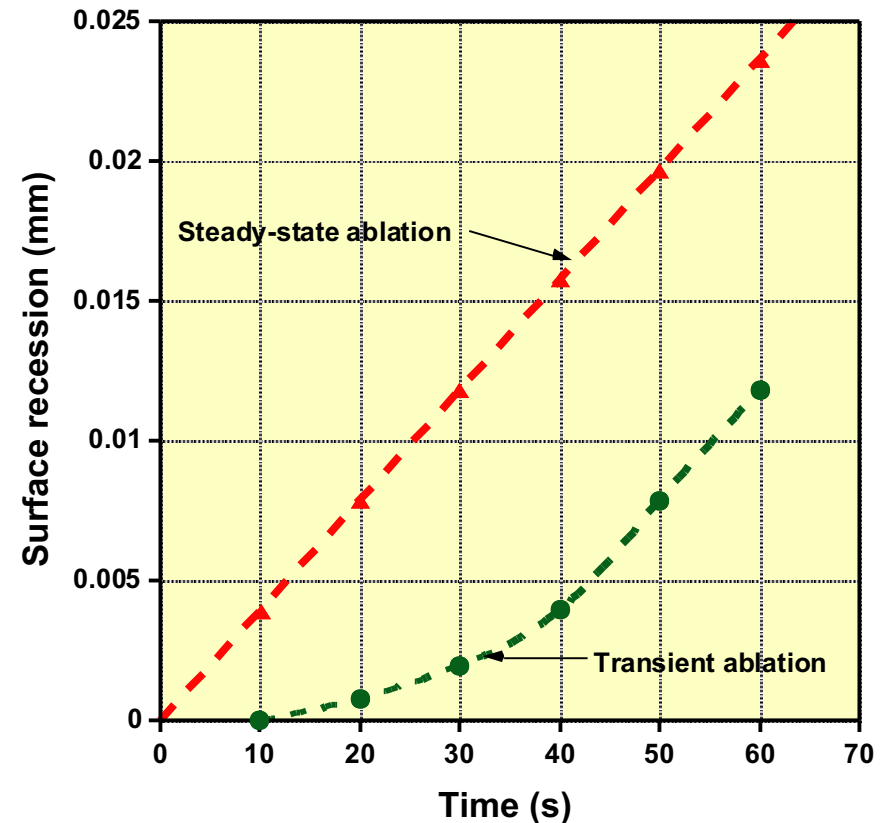
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The first material seriously studied for ablative TPS applications was **teflon**

- Unfortunately, the study of teflon ablation led to some misconceptions about ablation that persist to this day
- Because teflon ablates over a very narrow surface temperature range, early models were *constrained* by the concept of an “ablation temperature”
- This led to the development of the “heat of ablation” concept which is poorly understood and typically misapplied



- The “heat of ablation” ( $Q^*$ ), is often referred to as a material “property.” It is not a property – it is a **data correlation parameter**! Furthermore, it is a data correlation parameter that is only valid at **steady-state ablation conditions**. It is this last requirement that is often ignored leading to confusion and meaningless comparisons



- The term  $Q^*$ , commonly referred to as the *heat of ablation*, was defined by the reentry community during the late '50s as a convenient way to *correlate arc jet ablation data*. Based on what was known at the time, teflon was a simple sublimator that appeared to ablate at a relatively constant surface temperature. The energy “absorbed” by the ablation process was only attributable to two phenomena: vaporization and transpiration.
- As researchers began to develop analytical techniques to predict ablation rates and thermal response, they formulated a surface energy equation that essentially described the phenomena they knew about. The early formulations could be written simply as:

$$\dot{q}_{conv} - \dot{q}_{rerad} = \dot{q}_{cond} + \dot{q}_{vap} + \dot{q}_{trans} \quad (1)$$

$\dot{q}_{conv}$  is the net convective heating rate to the surface in the absence of ablation

$\dot{q}_{rerad}$  is the reradiated heat flux from the surface

$\dot{q}_{cond}$  is the net heat flux conducted into the material

$\dot{q}_{vap}$  is the energy absorbed in vaporization of the surface material

$\dot{q}_{trans}$  is the energy flux “absorbed” due to transpiration of ablation products into the boundary layer

Specifically, the surface energy equation was written as:

$$\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \varepsilon T_w^4 = \dot{q}_{cond} + \rho \dot{s} \Delta H_v + \rho \dot{s} \eta (H_r - H_{air}^{T_w}) \quad (2)$$

- $\dot{q}_{cw}$  is the cold-wall heat flux (either measured by a calorimeter in test or calculated by an aero heating code)
- $H_r$  is the recovery enthalpy (based on some reference state, e.g., 298 K)
- $H_{air}^{T_w}$  is the enthalpy of air at surface pressure and temperature
- $\sigma$  is the Stefan-Boltzmann constant
- $\varepsilon$  is the hemispherical emissivity of the ablating surface
- $T_w$  is the surface temperature
- $\rho$  is the material density
- $\dot{s}$  is the surface recession rate
- $\Delta H_v$  is the heat of vaporization
- $\eta$  is the transpiration coefficient

- The most important *approximation*, comes from the constraint of **steady-state ablation**. Under those conditions, it can be shown that the heat flux conducted into the material can be simply represented as:

$$\dot{q}_{cond_{ss}} = \rho \dot{s} c_p (T_w - T_0) \quad (3)$$

where  $T_0$  is the initial temperature of the material. When Eq. (3) is substituted into Eq. (2) you get the energy equation for steady-state ablation, i.e.,

$$\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \epsilon T_w^4 = \rho \dot{s} c_p (T_w - T_0) + \rho \dot{s} \Delta H_v + \rho \dot{s} \eta (H_r - H_{air}^{T_w}) \quad (4)$$

- Grouping similar terms, Eq. (4) is re-written as:

$$\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \varepsilon T_w^4 = \rho \dot{s} (c_p \Delta T + \Delta H_v + \eta \Delta H) \quad (5)$$

- If you study Eq. (5) you can identify the parameters that are known (or could be measured) in a test as contrasted with the unknowns. That leaves the following unknowns:  $\Delta H_v$  and  $\eta$ .

If you rewrite Eq. (5) by dividing both sides by  $\rho \dot{s}$ , the resulting equation has knowns on the left side and unknowns on the right side. That led to the original definition of  $Q^*$ , i.e.,

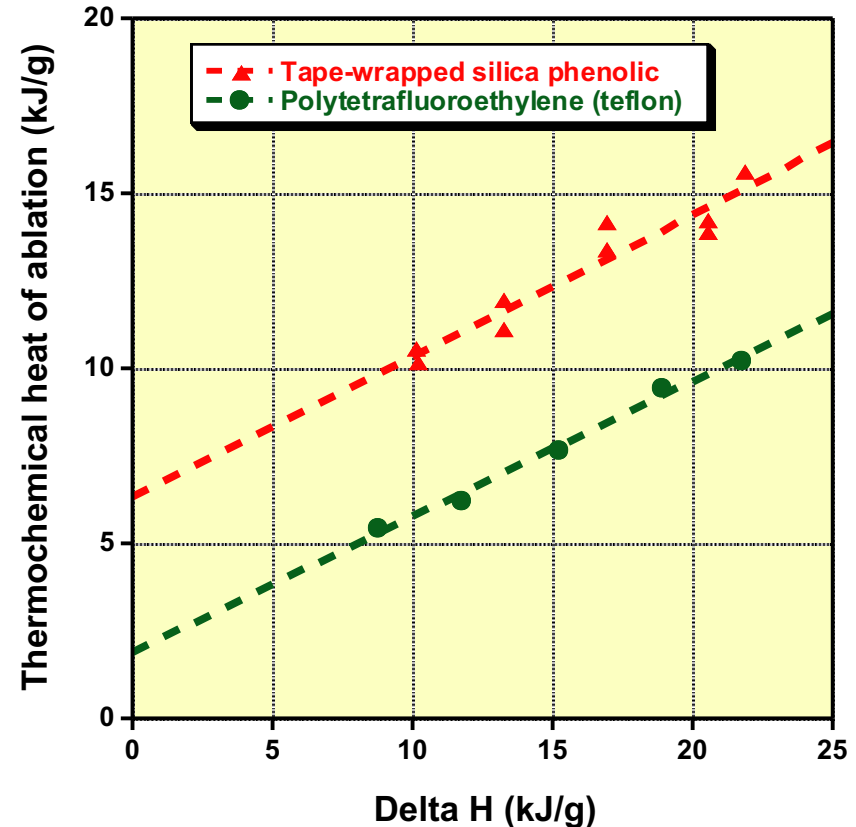
$$Q^* = \frac{\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \varepsilon T_w^4}{\rho \dot{s}} = c_p \Delta T + \Delta H_v + \eta \Delta H \quad (6)$$

- Examination of the RHS of Eq. (6) shows that  $Q^*$  is linear in  $\Delta H$ . Consequently, arc jet test data was correlated by calculating  $Q^*$  for each test from:

$$Q^* = \frac{\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \varepsilon T_w^4}{\rho \dot{s}} \quad (7)$$

and plotting it vs.  $\Delta H$ , i.e.,  $(H_r - H_{air}^{T_w})$ . A linear fit through the data produces a line whose slope is taken as  $\eta$  and whose y-intercept is taken as  $c_p \Delta T + \Delta H_v$ . Since  $c_p$  and  $\Delta T$  are known or were determined in the test, one also derives  $\Delta H_v$  from the linear fit of the data.

- Example:<sup>†</sup>
  - Tape-wrapped silica phenolic ( $\rho = 1.63 \text{ g/cm}^3$ )
  - PTFE ( $\rho = 2.18 \text{ g/cm}^3$ )
  - Tests in Avco's Model 500 arc jet (circa 1965)
  - Flat-faced stagnation samples in air
  - Cold-wall heat fluxes in the range from  $\approx 0.7 - 1.5 \text{ kW/cm}^2$



<sup>†</sup>"Ablation Handbook, Entry Materials Data and Design," AFML-TR-66-262, September 1966.

- Material thermal/ablation analyses were done with transient thermal codes using Eq. (2) as the surface energy equation (SEB), i.e.,

$$\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \varepsilon T_w^4 = \dot{q}_{cond} + \rho \dot{s} \Delta H_v + \rho \dot{s} \eta (H_r - H_{air}^{T_w}) \quad (2)$$

where the values of  $\eta$  and  $\Delta H_v$ , derived from correlation of  $Q^*$  data are inputs to the SEB. The remaining constraint is given by:

$$\dot{s} = 0, T_w < T_A$$

$$\dot{s} > 0, T_w = T_A$$

The definition of  $Q^*$  given in Eq. (6) is called the **thermochemical heat of ablation** and, as discussed previously, was derived from a surface energy equation and has some relevance to analysis. There are other definitions that have also been used.

The **cold-wall heat of ablation** is simply defined as:

$$Q_{cw}^* = \frac{\dot{q}_{cw}}{\rho \dot{s}}$$

and the **hot-wall heat of ablation** is defined as:

$$Q_{hw}^* = \frac{\dot{q}_{cw} \left( \frac{H_r - H_{air}^{T_w}}{H_r} \right)}{\rho \dot{s}}$$

These parameters might be useful for quick-look comparisons of different materials tested at similar conditions, but have no physical significance.

- Early studies used the *heat of ablation* ( $Q^*$ ) as a data correlation parameter from which fundamental “properties” were derived for use with transient thermal/ablation codes
  - $Q^*$  can only be derived from steady-state ablation data
- The early focus on teflon ablation led to the misconception that all materials could be modeled in terms of an “ablation temperature”
  - This erroneous assumption became readily apparent in subsequent studies of the ablation of glass, graphite and organic resin composites

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