Tutorial on Ablative TPS

Bernard Laub
NASA Ames Research Center
Moffett Field, CA 94035

Donald M. Curry
NASA Johnson Space Center
Houston, TX 77058

22 August 2004

Outline

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

Outline

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

Ablative TPS Community in the 60s and 70s

Ablative TPS Community in the 80s

Ablative TPS Community in the 90s

Ablative TPS Community Today

Time is not
our friend

Outline

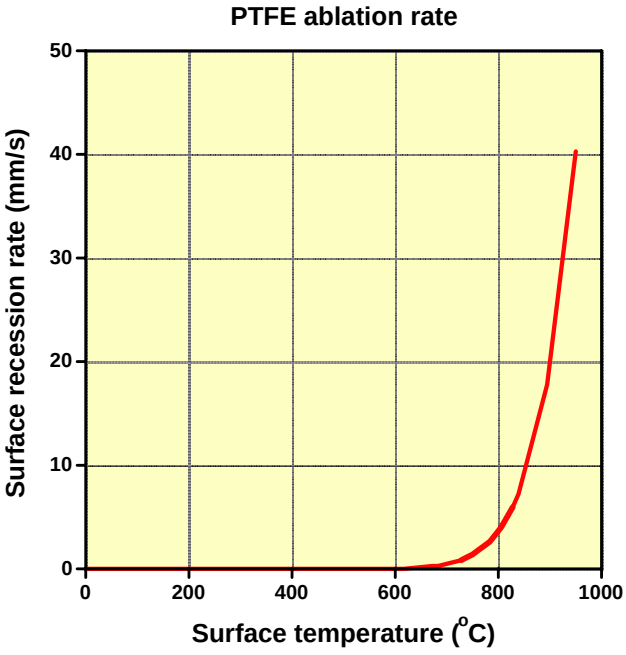
- Why this tutorial?
- **Ablative TPS - early studies**
- Organic resin composites
- Surface recession mechanisms/modeling
- High fidelity model development
- Testing approaches/requirements
- Future needs

The first material seriously studied for ablative TPS applications was …

The first material seriously studied for ablative TPS applications was teflon

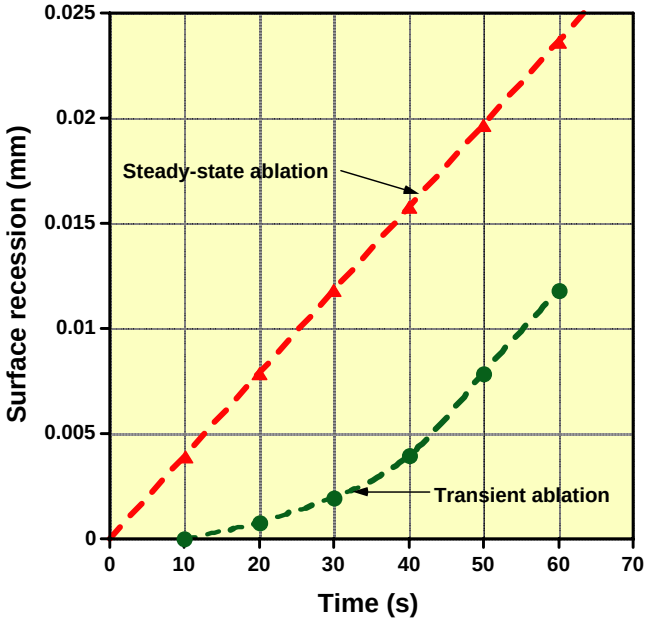
Implications of teflon studies

- 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



Heat of Ablation - 1

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



Heat of Ablation - 2

- 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 sublimer 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:

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

$\dot{q}_{conv}$ 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

Heat of Ablation - 3

Specifically, the surface energy equation was written as:

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

$\dot{q}_{cw}$	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
σ	is the Stefan-Boltzmann constant
ε	is the hemispherical emissivity of the ablating surface
T_w	is the surface temperature
ρ	is the material density
$\dot{s}$	is the surface recession rate
ΔH_v	is the heat of vaporization
η	is the transpiration coefficient

Heat of Ablation - 4

- 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:

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

where T_o 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.,

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

Heat of Ablation - 5

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

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

- 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: ΔH_v and η.

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.,

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

Heat of Ablation - 6

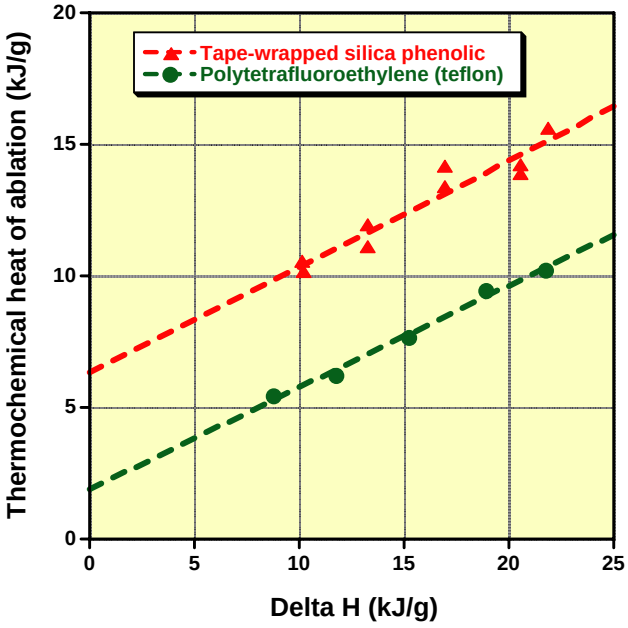
- Examination of the RHS of Eq. (6) shows that Q* is linear in ΔH. Consequently, arc jet test data was correlated by calculating Q* for each test from:

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

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

Heat of Ablation - 7

- Example:†
  - Tape-wrapped silica phenolic (ρ = 1.63 g/cm^3)
  - PTFE (ρ = 2.18 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 ≈ 0.7 - 1.5 kW/cm^2



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

Heat of Ablation - 8

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

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

where the values of η and ΔH_v, derived from correlation of Q* data are inputs to the SEB. The remaining constraint is given by:

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

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

Heat of Ablation - 9

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:

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

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

Topic Summary

- 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 <u>only</u> 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

References

1. Katsikas, C.J., Castle, G.K. and Higgins, J.S., “Ablation Handbook – Entry Materials Data and Design,” AFML-TR-66-262, September 1966.
2. Holzknecht, B., “An Analytical Model of the Transient Ablation of Polytetrafluoroethylene Layers,” *Int. J. Heat Mass Transfer*, Vol. 20, pp./ 661-668, 1977.
3. Clark, B.L., “A Parametric Study of the Transient Ablation of Teflon,” *J. Heat Transfer,* pp. 347-354, November 1972.
4. Friedman, H., “The Mechanisms of Polytetrafluoroethylene Pyrolysis, General Electric Report TIS R59SD385, June 1959.
5. Heister, N.K. and C.F. Clark, “Feasibility of Standard Evaluation Procedure for Ablating Materials, NASA CR-379, February 1966.
6. Steg, L. and H.Lew, “Hypersonic Ablation,” General Electric Report TIS R62SD55. May 1962.
7. Hurwicz, H., “Aerothermochemistry Studies in Ablation,” 5th AGARD Combustion and Propulsion Colloquium, April 1962.
8. Bethe H.A. and M.C. Adams, “A Theory for the Ablation of Glassy Materials,” *J. Aerospace Sci*., Vol. 26, pp. 321-328, 1959.
9. Scala, S.M., “The Ablation of Graphite in Dissociated Air, Part I: Theory,” General Electric Report R62SD72, September 1962.
10. Beecher, N. and R.E. Rosensweig, “Ablation Mechanisms in Plastics with Inorganic Reinforcement,” *ARS J*., Vol. 31, pp. 532-539, 1961.