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Improvements to the Aeroheating and Thermal Analysis Code (ATAC)

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Outline

- Overview of ATAC capabilities and methodologies
- Example Cases
- New Capabilities
  - Rolling Vehicle Analysis
  - TPS Optimization
  - Burn through of ablating material layer
  - Full trajectory analysis, i.e., exo atmospheric flight
  - Particle erosion analysis
- Future Code Enhancements

ATAC Description

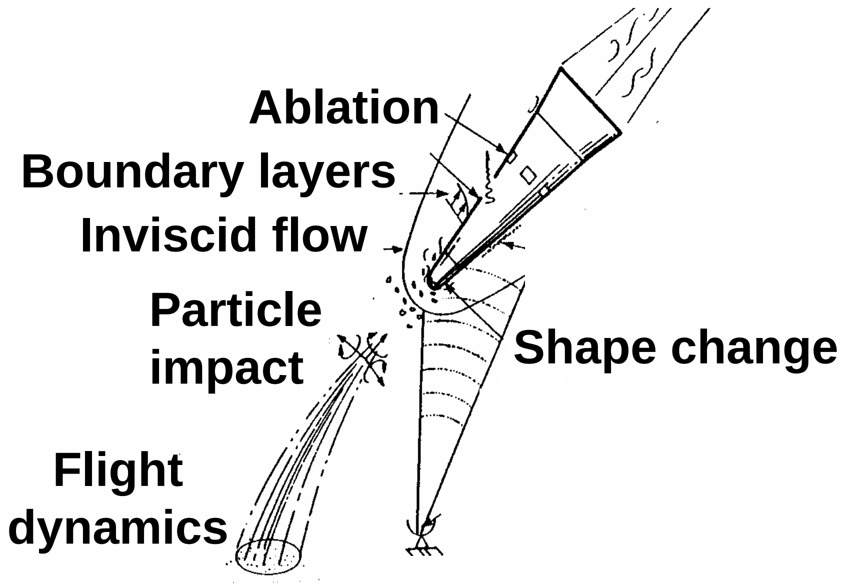
ATAC is an integrated aerodynamic heating/thermal response computer code used for a range of applications within the aerospace community

- Heatshield and missile TPS design
- Thermostructural analysis – provides pressure and heating boundary conditions to finite element analysis codes
- IR signature analysis

Background

ATAC is a computer program which models the response of a flight vehicle to an aero-heating environment. The essential elements of the code are procedures to model the following:

- Geometry definition
- Freestream properties
- Inviscid flowfield
  - Surface pressure
  - Shock shape
- Boundary layer heating
- Material response and ablation
- Change in the geometry of the vehicle



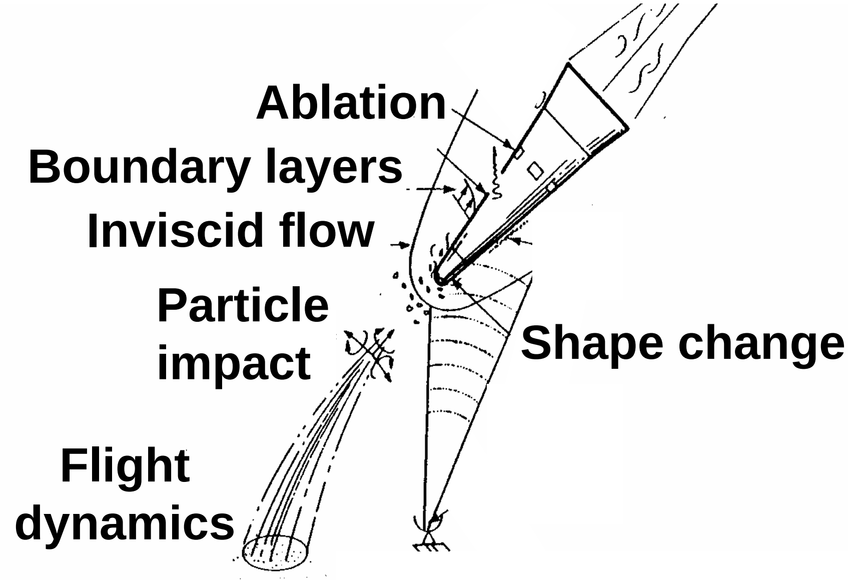
Background (cont)

Additional options which may be included are:

- Particle impact erosion
- Coupled shape change / flight dynamics
- In-depth thermal response

Other factors that must be considered include:

- Efficiency
- Robustness
- Accuracy



Code Capabilities

The Aeroheating and Thermal Analysis Code (ATAC) is a state-of-the-art shape change code and includes the following models

- Geometry model - bicubic patch
- Freestream properties - 6 environment options and 21 atmosphere models
  - 3 DOF trajectory
  - Flight
  - Wind tunnel
  - Ballistic range
  - General
  - Arc heater

Code Procedures

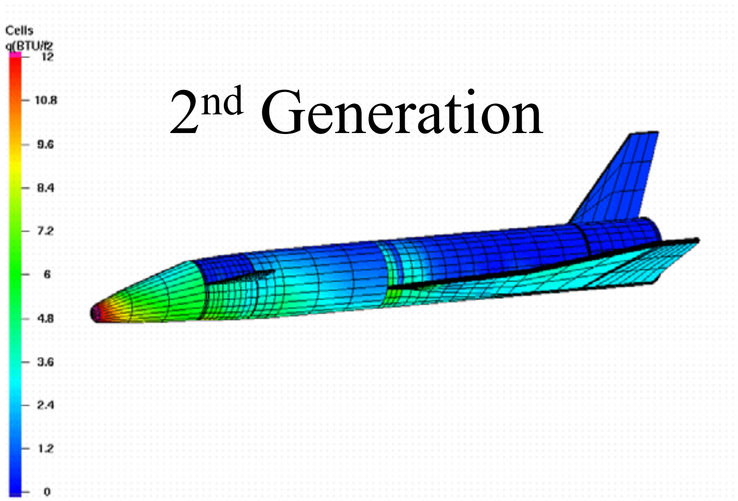
- Inviscid flow
  - Streamline tracing - method of steepest descent
  - Surface pressure
    - Windward - PANT Correlations, Newtonian
    - Leeward - Newtonian, Prandtl-Meyer small disturbance, separation correlations
  - Shock shape - thin shock layer global mass and momentum conservation
- Boundary layer heating - MEIT continuum solution bridged with free molecular solution

Code Procedures (cont)

- Material response and ablation - Aerotherm surface energy balance procedure
- Shape change - multi-dimensional spline fitting for bicubic patch definition
- Particle impact erosion
  - Shock layer interaction - Jaffe, Ranger-Nicholls, Reinecke-Waldman
  - Erosion - generalized G-law, carbon phenolic model, tungsten model
- In-depth thermal response at each nodal point - CMA 1D conduction with charring/ablation

Example Shapes Modeled with ATAC

2nd Generation



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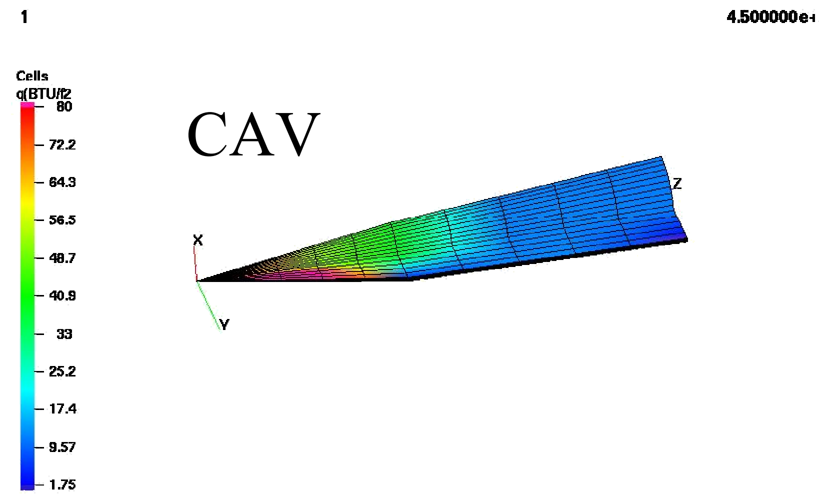
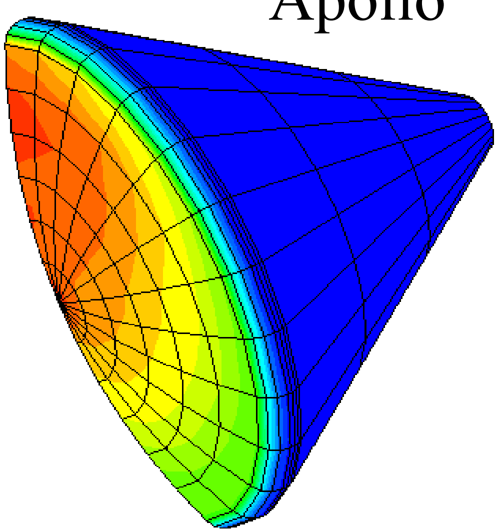
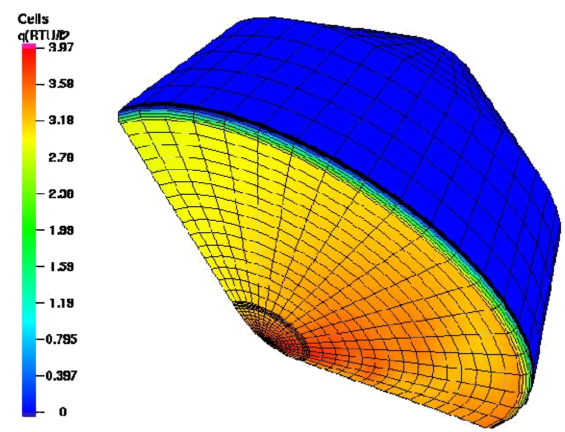


Apollo



Mars Science Lab



Surface Pressure

Windward

- Dahm-Love correlations developed under the PANT program
- Newtonian
- Modified Newtonian using Andrew's correlation for subsonic flight and Vendemia's model downstream of the tangency point

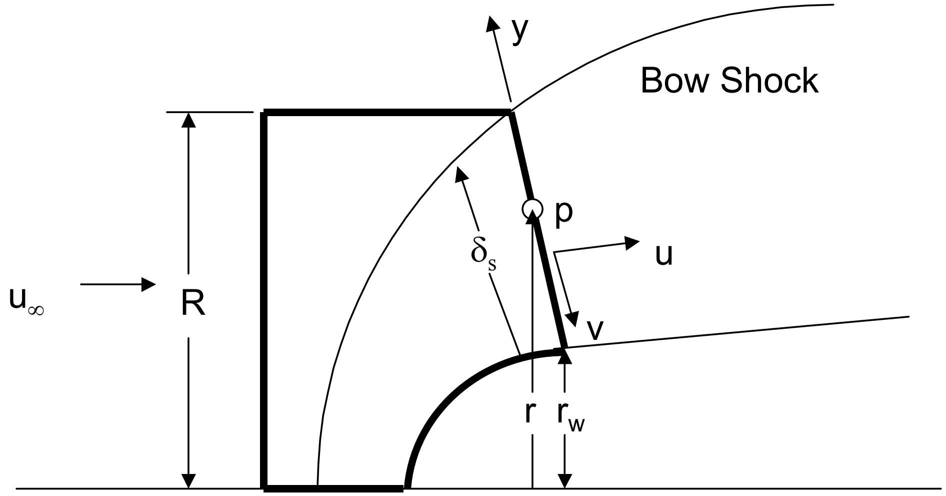
Leeward

- Newtonian, $c_p = 0$
- Prandtl-Meyer small disturbance theory
- Separation correlations

Shock Shape

Thin-shock layer integral technique

- Continuity and axial momentum equations in an integral form
- Integrands vary linearly between body and shock
- Equations solved for the shock stand off distance and shock angle



Continuity

$$\rho_\infty u_\infty \pi R^2 = 2\pi \int_0^{\delta_s} \rho u r dy$$

Axial Momentum

$$\left(p_\infty + \rho_\infty u_\infty^2\right)\pi R^2 = \int_0^{\delta_s} \rho u (u \cos\theta + v \sin\theta)\, 2\pi r dy + \int_0^{s} (p_w \sin\theta) 2\pi r_w ds + \int_0^{\delta_t} (p \cos\theta) 2\pi r dy$$

Boundary Layer Model

Momentum Equation

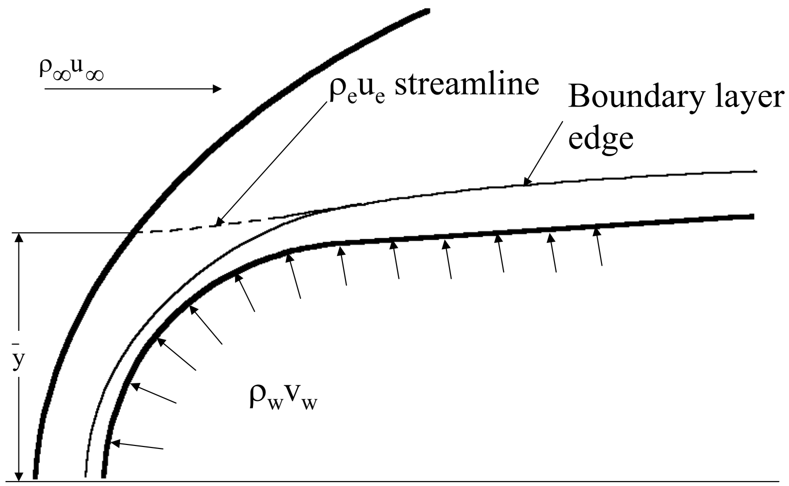
$$\frac{1}{r\rho_e u_e^2}\frac{d}{ds}(r\rho_e u_e^2\Theta) = \frac{C_f}{2} + \frac{(\rho v)_w u_{i,w}}{\rho_e u_e^2} + \frac{H\Theta}{\rho_e u_e^2}\frac{dp}{ds}$$

Energy Equation

$$\frac{1}{r\rho_e u_e(h_{t,e} - h_w)}\frac{d}{ds}\left(r\rho_e u_e\left(h_{t,e} - h_w\right)\Phi\right) = C_h\frac{h_r - h_w}{h_{t,e} - h_w} + \frac{(\rho v)_w\left(h_{t,i,w} - h_w\right)}{\rho_e u_e(h_{t,e} - h_w)}$$

Entrainment Equation

$$\rho_\infty u_\infty \bar{y}^2 = 2rF\mu_e \operatorname{Re}_\theta - 2\int_0^\infty r(\rho v)_w\, ds$$



Boundary Layer Model

Influence Coefficients

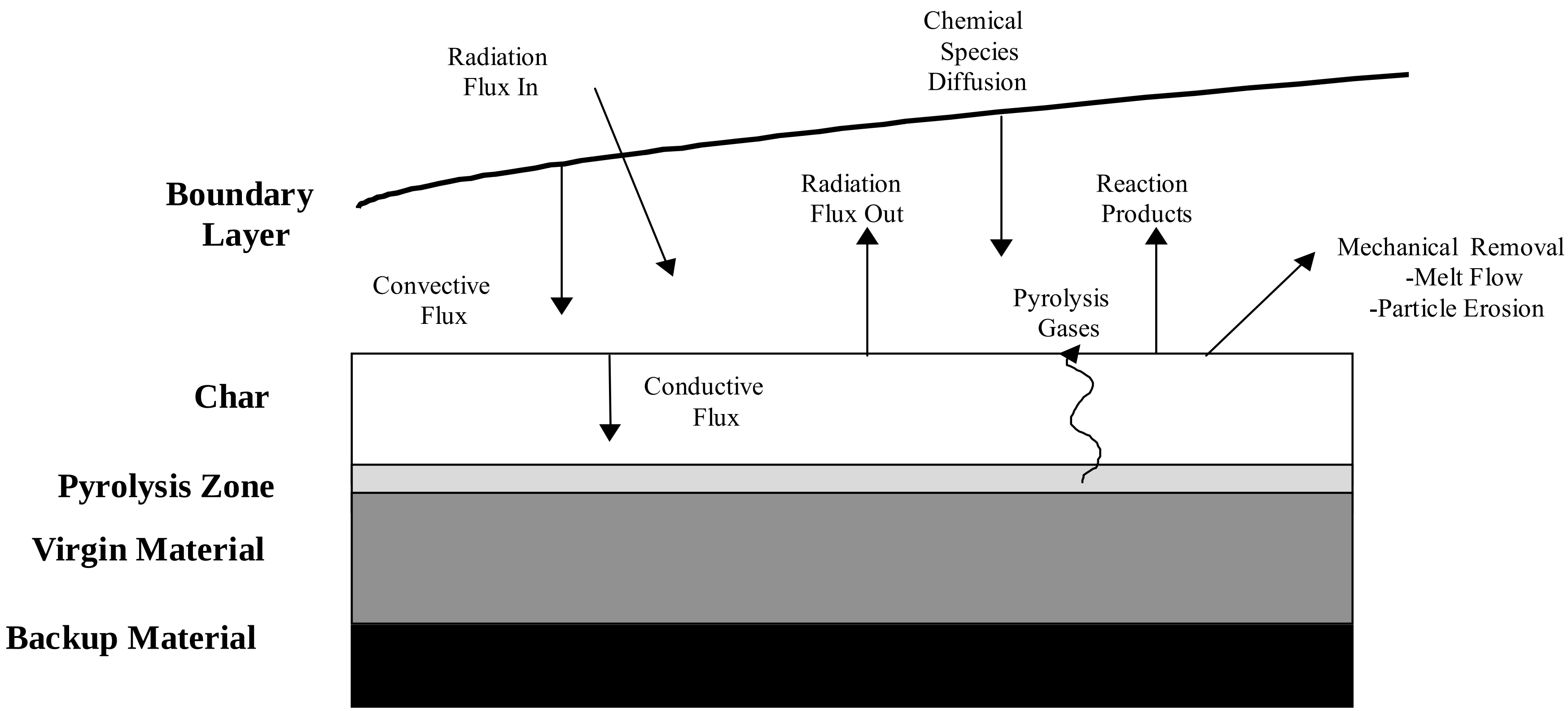
Basic laws were developed for incompressible flow along an impervious, isothermal flat plate. Non-ideal effects are modeled through the use of influence coefficients

$$C_{x,y} = C_{x,y,0} \prod^{z} I_{x,y,z} \text{ for } x = h, f \text{ and } y = \ell, t$$

$I_{x,y,z}$ includes models for:

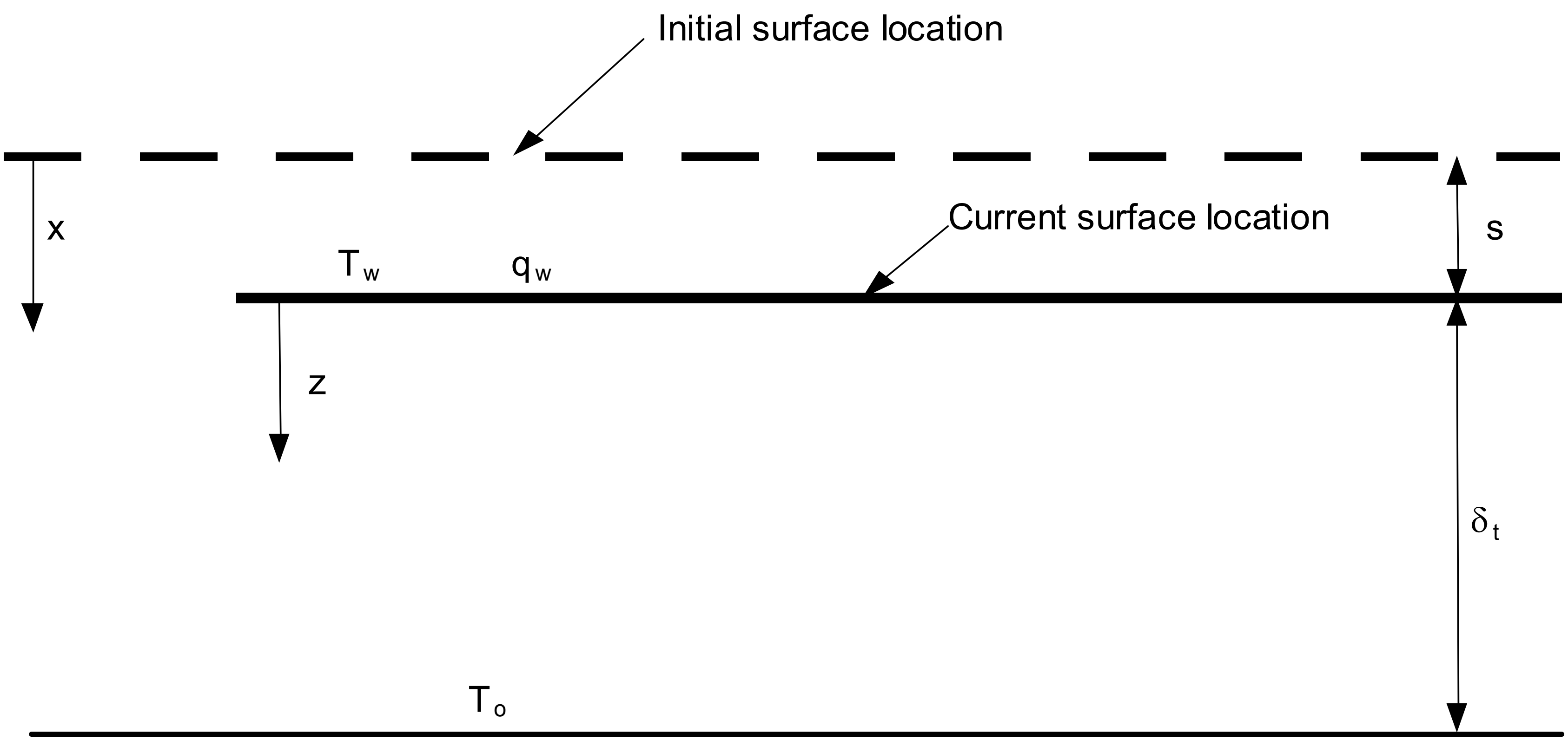
- Acceleration (Pressure Gradient)
- Real gas and Mach number
- Blowing
- Surface roughness

Surface Response



In-Depth Thermal Response

$$\rho c_p \frac{\partial T}{\partial \theta}\Big)_z = \frac{1}{A}\frac{\partial}{\partial z}\left(kA\frac{\partial T}{\partial z}\right)_\theta + \left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial \theta}\Big)_x + \dot{s}\,\rho c_p \frac{\partial T}{\partial z}\Big)_\theta + \frac{\dot{m}_g}{A}\frac{\partial h_g}{\partial z}\Big)_\theta$$



In –Depth Decomposition

Three-component decomposition model:

$$\rho = \Gamma\left(\rho_A + \rho_B\right) + \left(1 - \Gamma\right)\rho_C$$

Each of the three components decompose following Arrhenius relationship:

$$\left.\frac{\partial \rho_i}{\partial \theta}\right)_x = -B_i \exp\left(\frac{-E_{a_i}}{RT}\right)\rho_{o_i}\left(\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}}\right)^{\varphi_i}$$

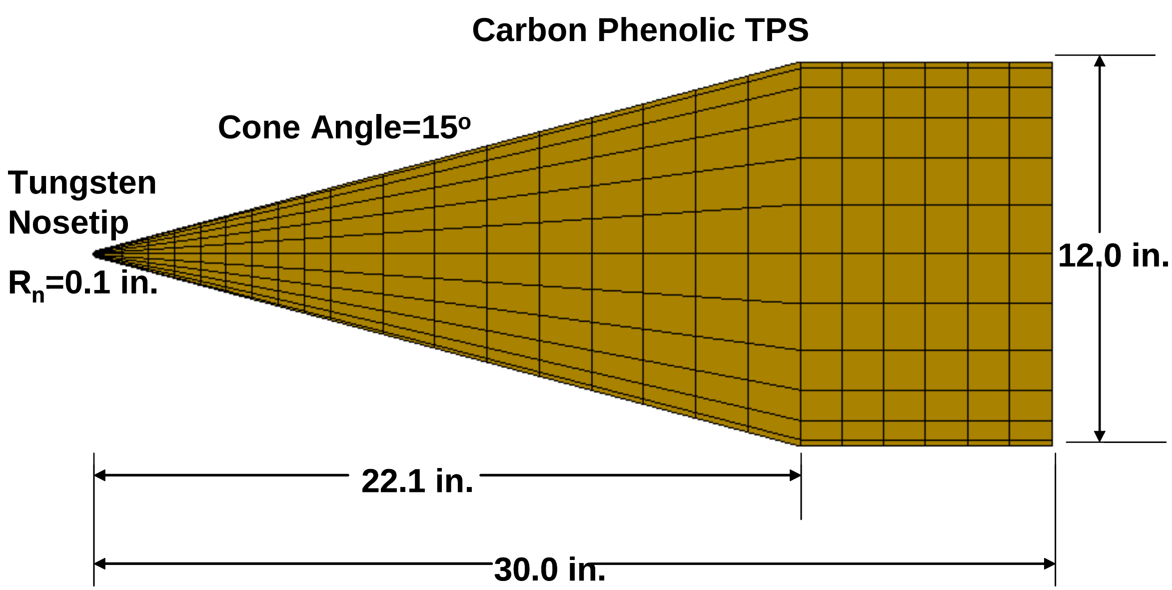
The present code can treat up to 30 decomposing surface and backup materials

Recent Improvements to ATAC

- Rolling Vehicle Analysis
  - Burn through of ablating material layer
  - TPS Optimization
  - Complete trajectory analysis, i.e., exo atmospheric flight
  - Particle erosion analysis (code outputs)

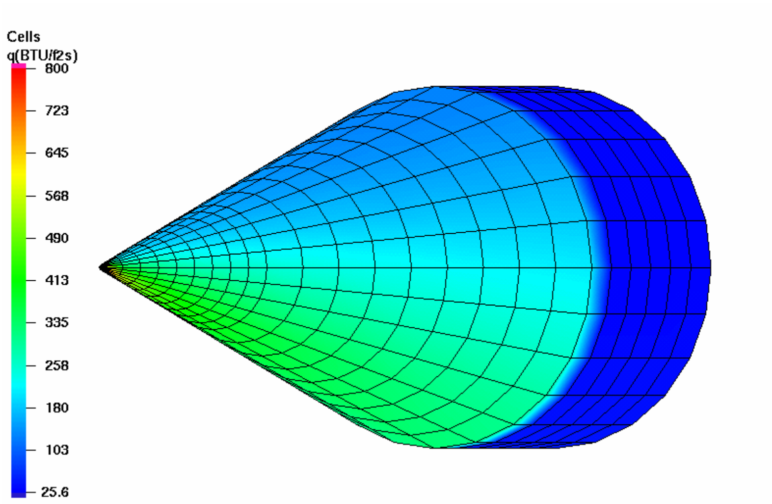
Rolling Vehicle Analysis

- Example case has been conducted to illustrate the benefits of rolling on reducing vehicle TPS requirements
- Mach 10 flight at 70,000 ft. altitude for 120 seconds. Angle of attack = 5 degrees

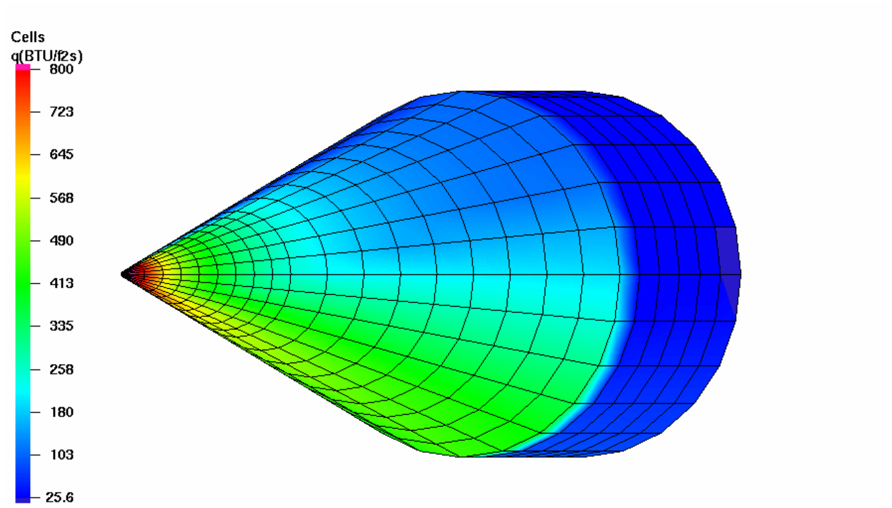


Rolling Vehicle Analysis – Heating Rates

- Even moderate angles of attack significantly increase heating conditions and recession levels
- This can result in significant increases in required TPS



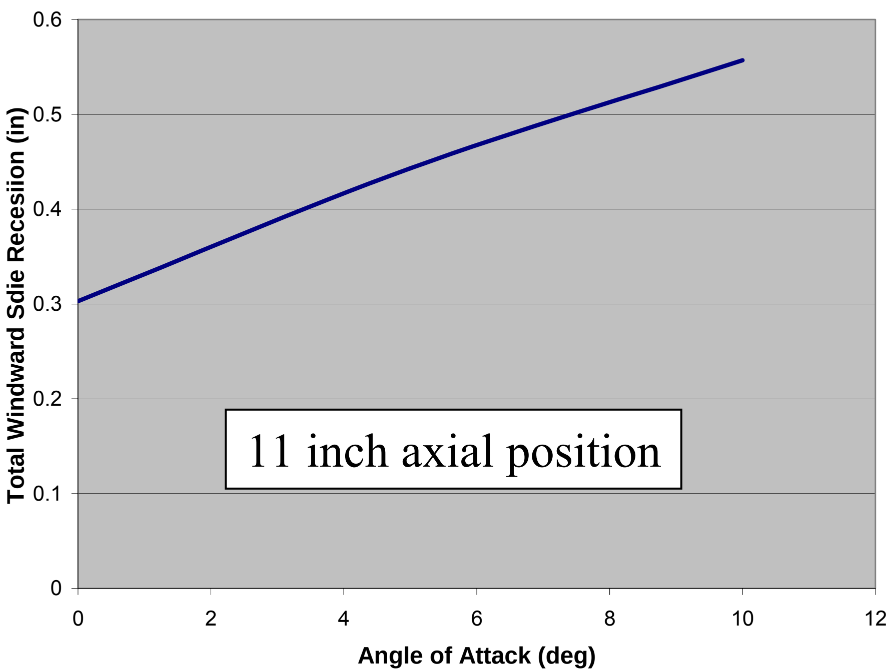
Heat flux for 5 deg AOA



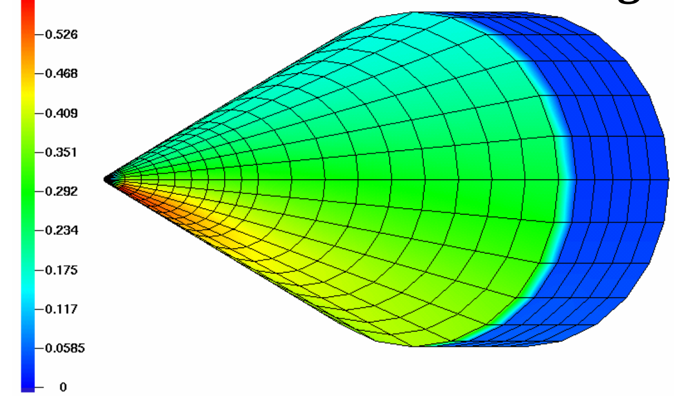
Heat flux for 10 deg AOA

Rolling Vehicle Analysis – Recession Levels

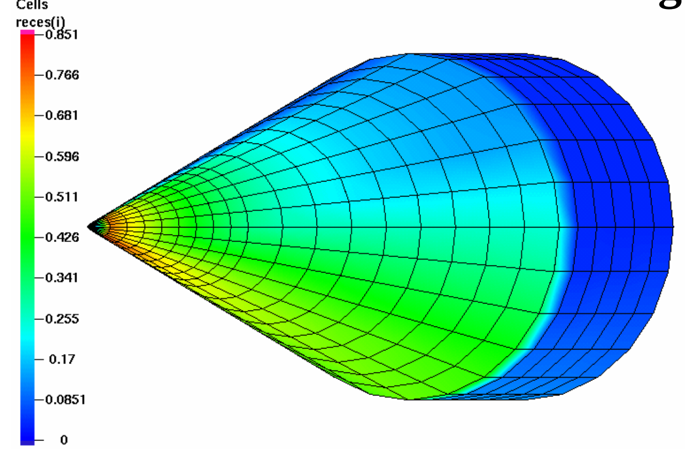
- Recession levels almost double for even moderate angles of attack



Recession for 5 deg AOA



Recession for 10 deg AOA



Roll Rates Effects

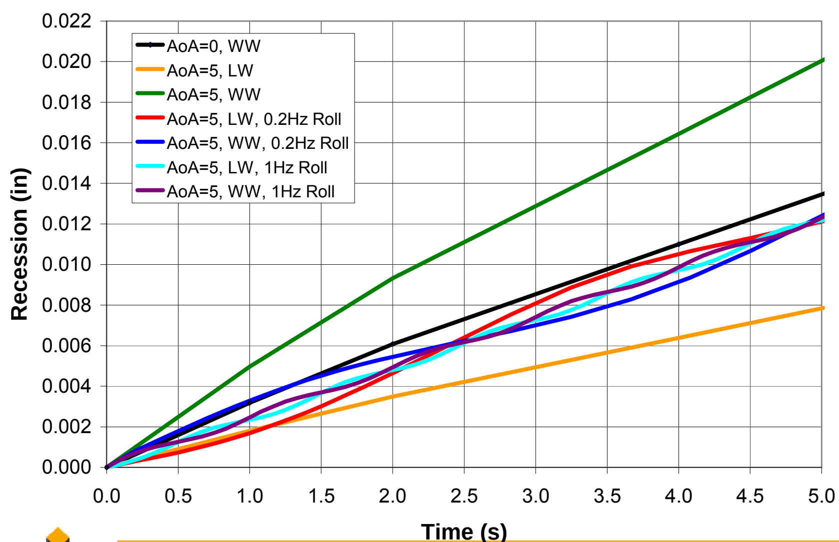
• Rolling the vehicle can substantially reduce the worst case recession conditions. Requirements are driven to zero AOA levels

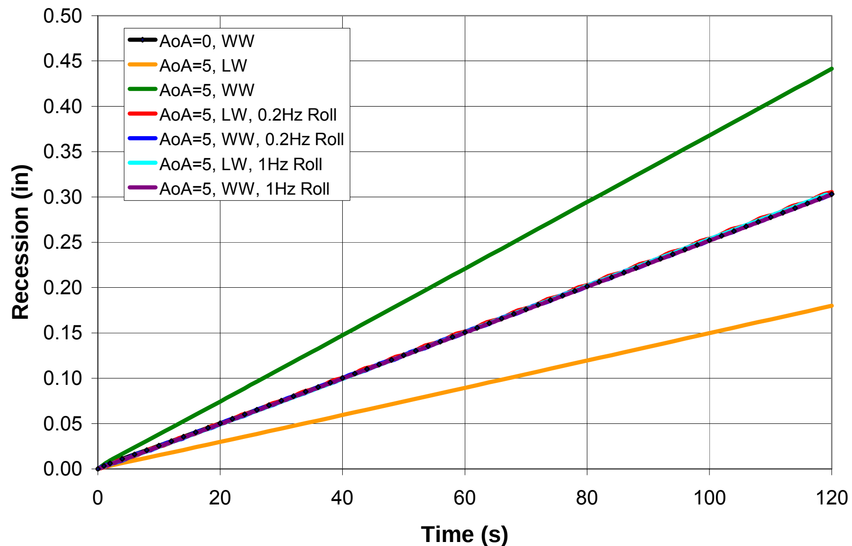
• The required roll rate is a function of the total flight time at AOA. The longer at AOA the lower the roll rate requirement

• Determination of the requirements is more complicated for a transient flight condition

• The code is also very useful for lifting body shapes where the vehicle may be rolled ± 30 degrees, i.e., a roll position or roll rate can be specified

• Boundary layer transition can further complicate the observed trends



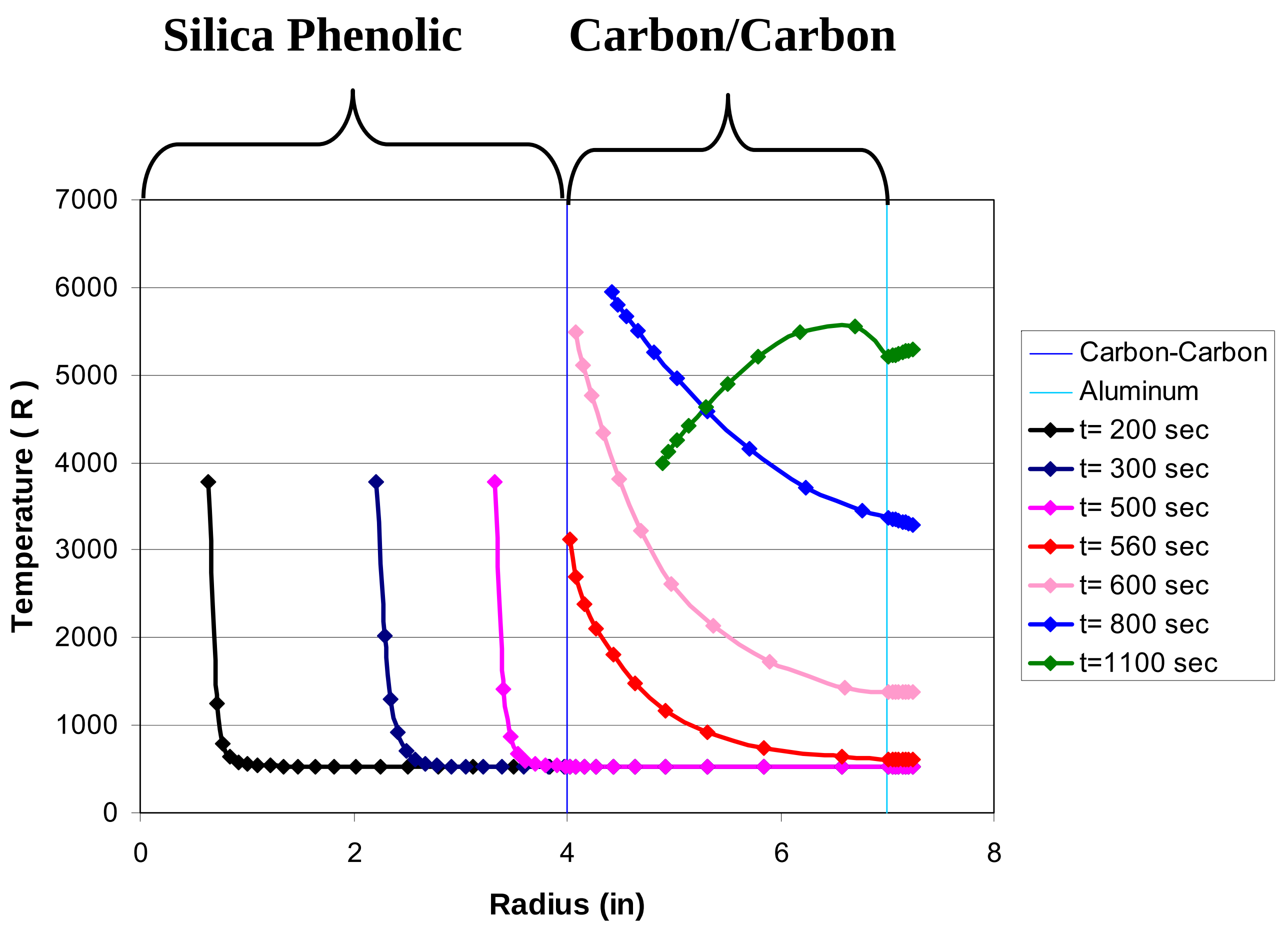


Burn Through Capability

- Earlier versions of ATAC (and CMA) would stop execution if the surface layer were removed
  - Moving grid used in surface layer
  - Different surface thermochemistry
  - Particularly troublesome for ATAC because of number of surface points, i.e., ablate through at any one point stopped the calculation
- New capability has been implemented to continue execution with subsurface material

Burn Through Capability

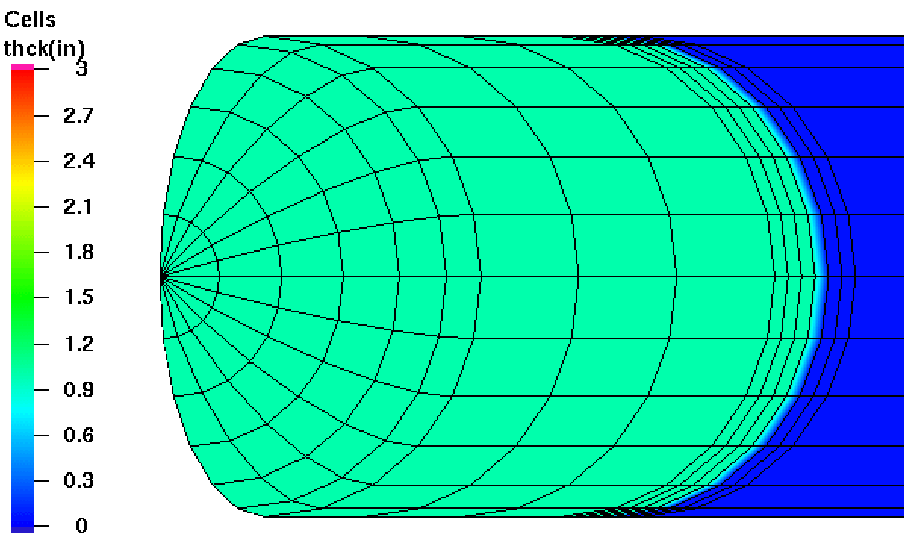
- Test case with silica phenolic covering carbon/carbon and aluminum
- Silica phenolic provides insulative layer for about 560 seconds.
- Carbon/carbon can provide adequate protection for a some period of time, depending on structural material used



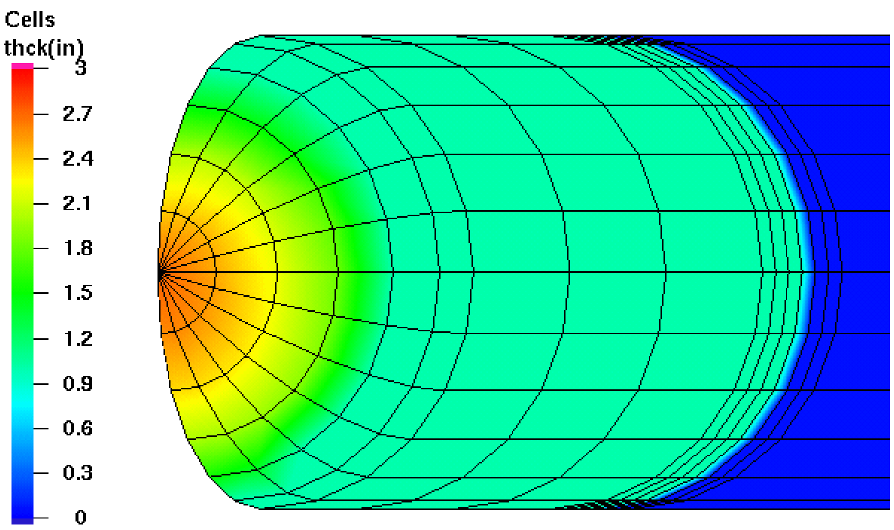
TPS Optimization

• New ATAC capability allows for optimization of the TPS layer based on thickness requirement (recession) or specified substrate temperature
• Capability is most useful for non axisymmetric shapes

Initial Thickness

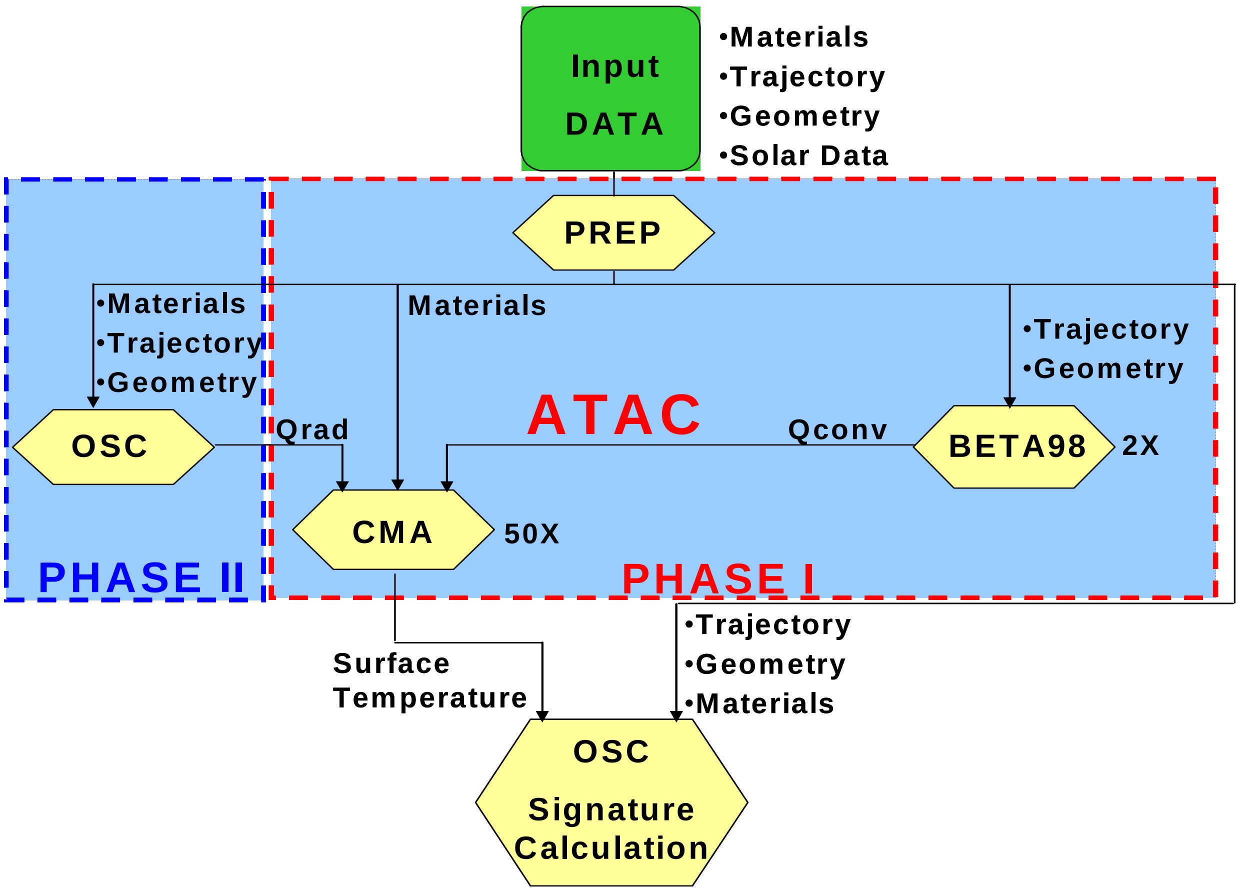


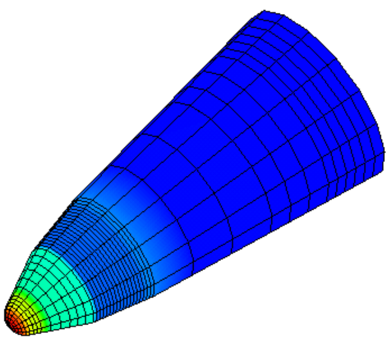
Final Thickness



Complete Trajectory Analysis

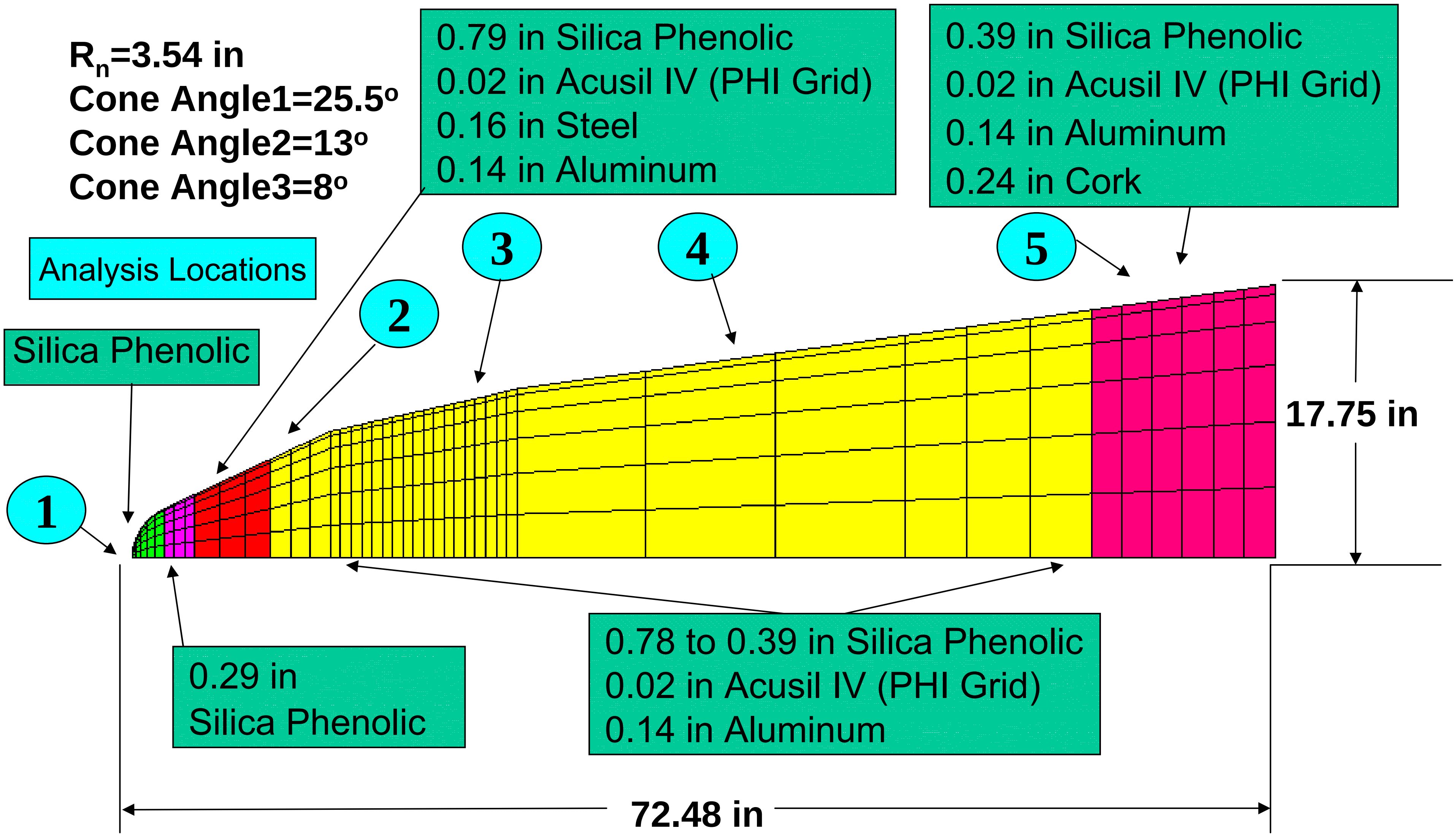
- Supports IR Signature Analysis
- Optical Signature Code (OSC) routines used to calculate radiant heating (exo flight) were incorporated into ATAC





ATAC RV Model

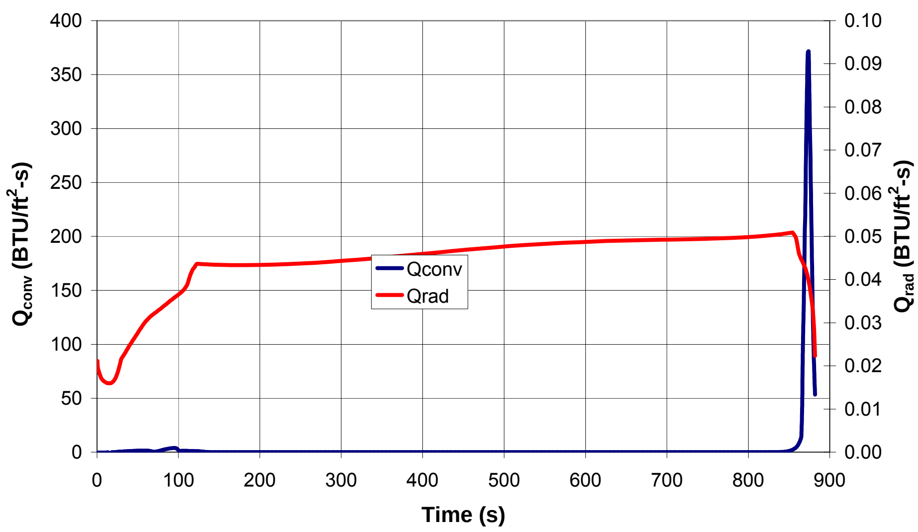
Complete Trajectory Test Case



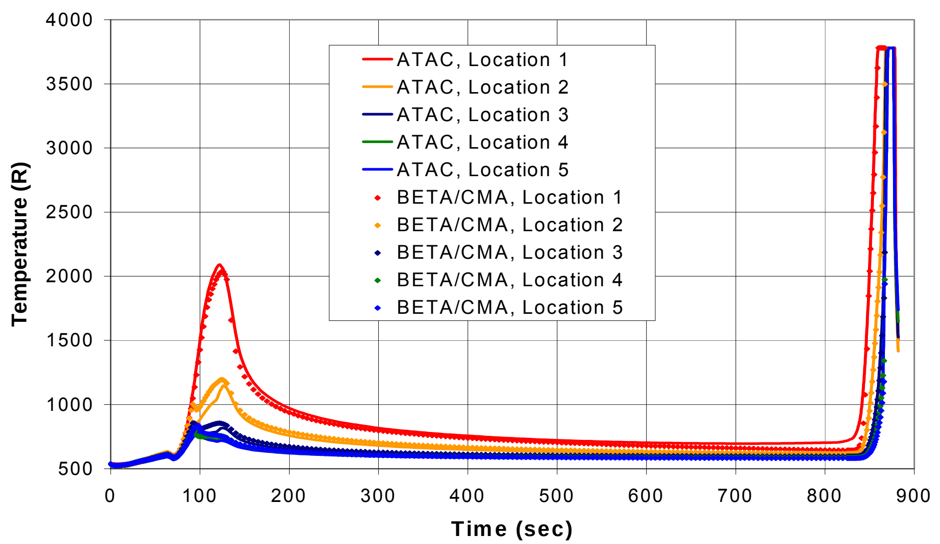
Complete Trajectory Analysis - Results

- Exoatmospheric at 148 seconds
- Reenters at 830 seconds
- Heating conditions are roll averaged

Heating Environments



Surface Temperatures



Particle Erosion Analysis G-Law

- ATAC uses a “G-Law” relationship to determine the amount of material removed by particle impact. “G” is a nondimensional parameter, where

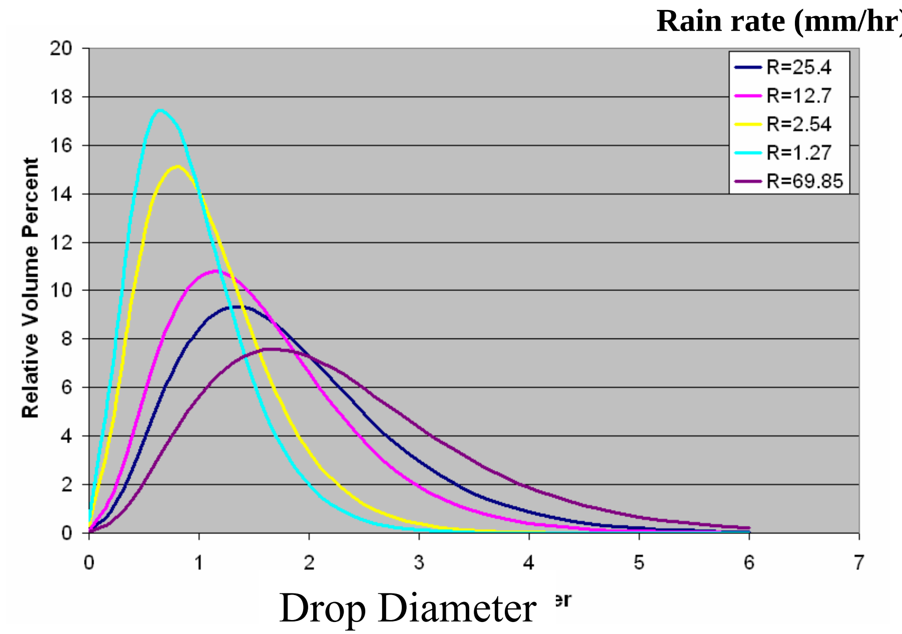
  G = Mass of material removed/ Incident mass flux

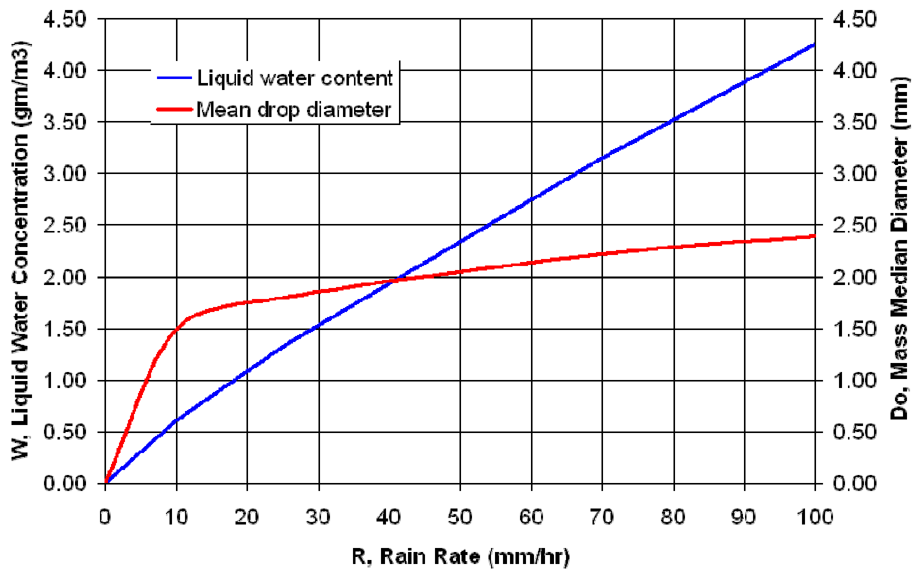
- The amount of mass removed is proportional to the impact parameters, particle diameter (D), velocity (V) and incidence angle (α)

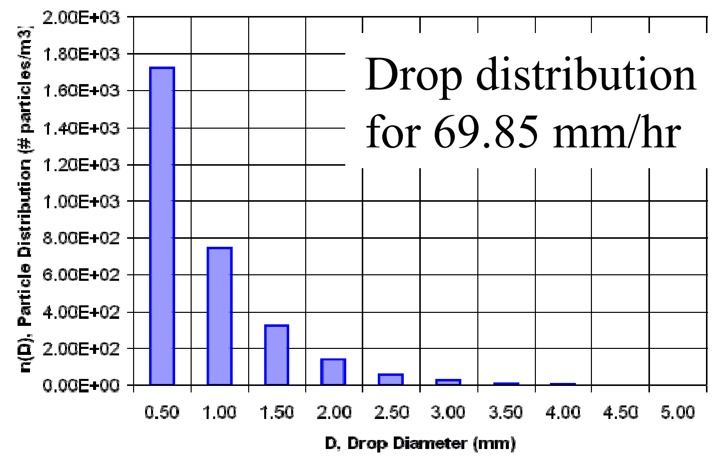
$$G_{mech} = a\, D^{b} V^{c} (\sin a)^{d}$$

Particle Environment

- ATAC models the environment in terms of liquid water content.
- Liquid water content is converted to drop size distribution – various distributions are available
- Drop size effects are very nonlinear

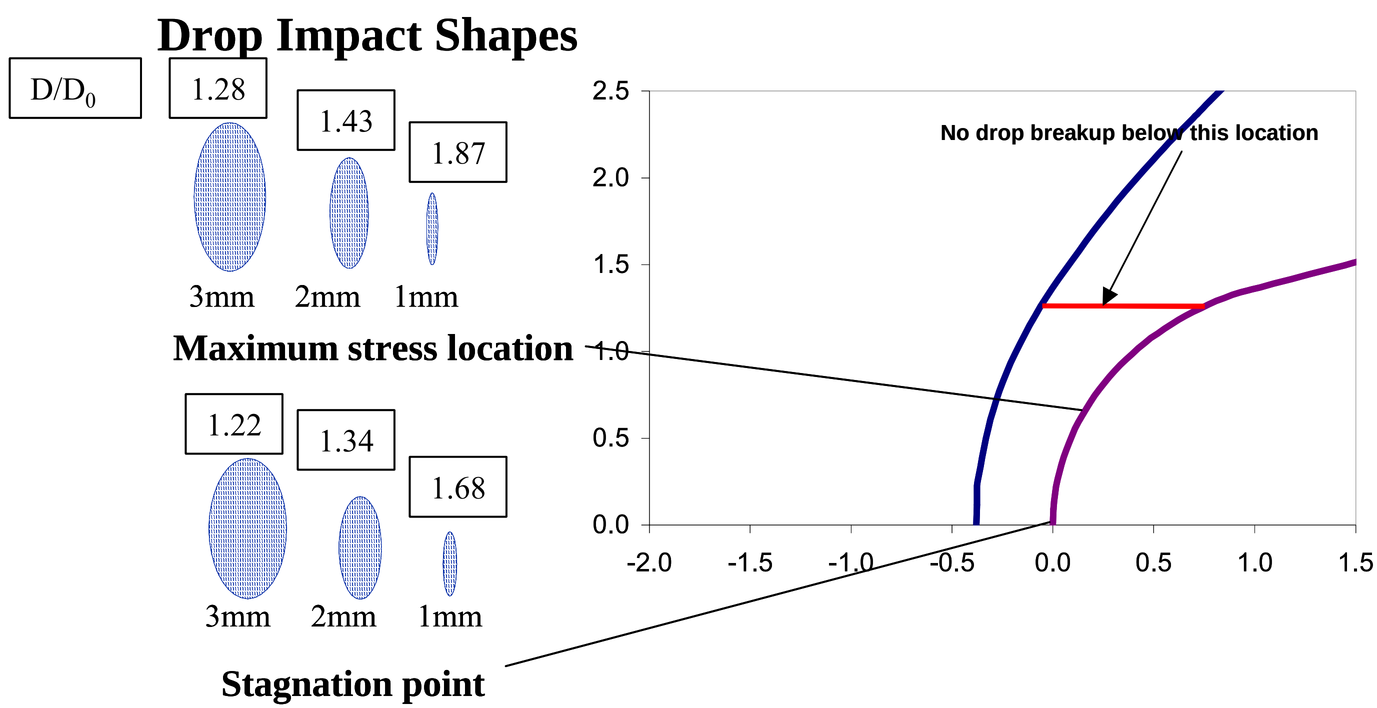






Drop Trajectory Calculations

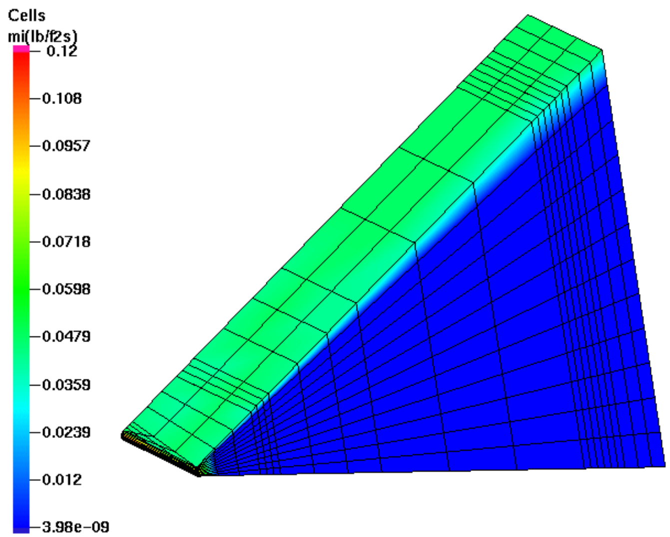
- Drops can break-up and distort as they cross the shock
- Drop distortion is more significant for smaller drop sizes
- Distortion is greatest aft of the stagnation region
- Drops slow down slightly after crossing the shock

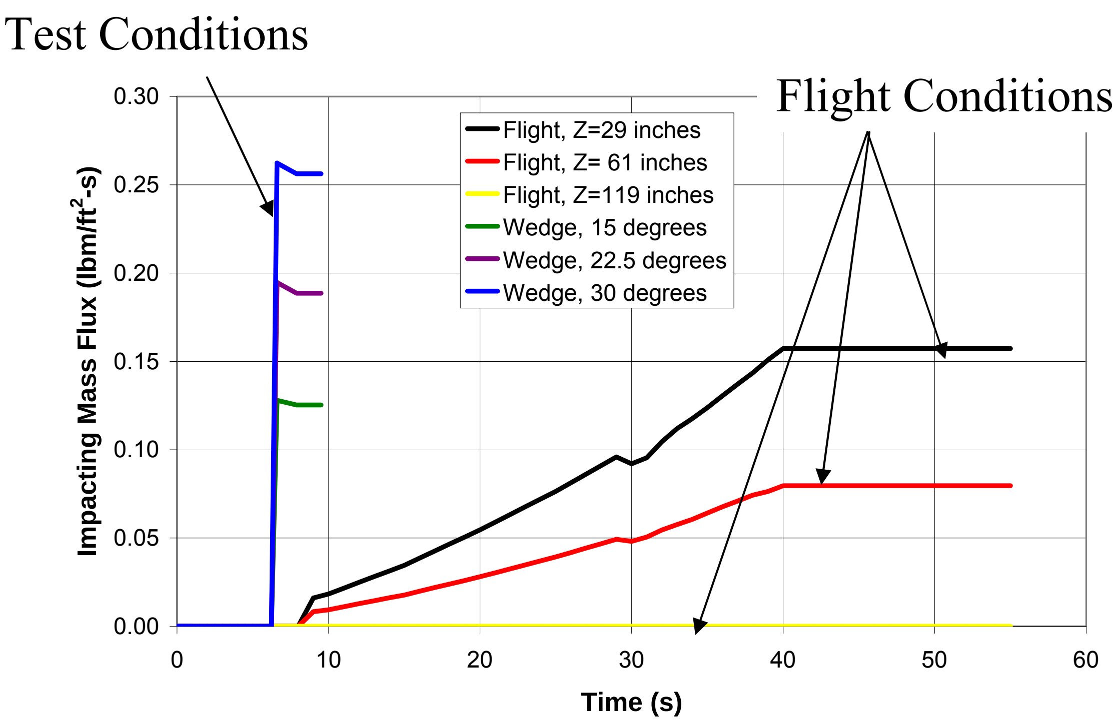


Impact Environment

• Analysis tool is also used to predict incident mass flux, particle sizes, and incident angle. Extensive ground testing is required to develop material models.

Wedge Test Model





Summary

- The ATAC code is continuing to evolve in response to the analysis requirements of developing aerospace systems
- Additional improvements are currently in process
  – Working with C&R to couple with Sinda. This is part of an AF SBIR program. Will also include coupling to CFD results for improved inviscid flowfield solution.
  – Shock layer radiation
  – Improvements to boundary layer transition modeling