

## Development of a Multi-Disciplinary Aerothermostructural Model Applicable to Hypersonic Flight

Chris Kostyk/NASA-DFRC

Tim Risch/NASA-DFRC

Presented By

Chris Kostyk & Tim Risch

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# Outline



- Background
- Tool Requirements
- Tool Development
- Technical Approach
- Sample Problem
- Summary



# Background



- US and other countries continue to pursue hypersonic vehicles for a variety of applications
  - Single or Two Stage to Orbit (SSTO or TSTO)
  - Long-duration endo-atmospheric flight (transport or weapon delivery)
- Hypersonic flight is a very coupled environment (“aero-thermo-servo-propo-elasto”) which drives requirements for weakly coupled or strongly coupled analysis
- Mid CY2008 DFRC GNC personnel initiated development of a non-linear, coupled, full vehicle dynamics, 6-DOF simulation







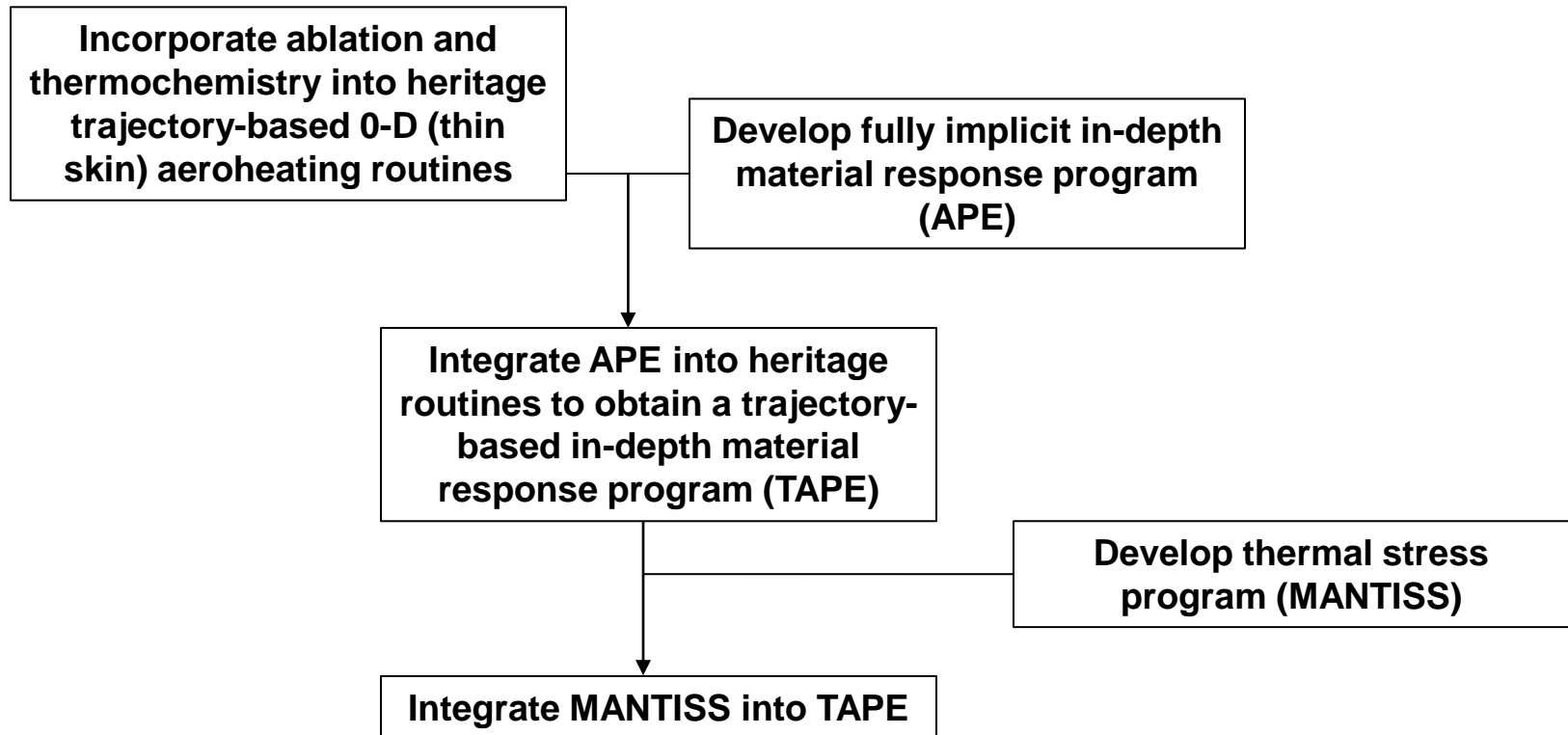
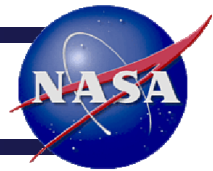
# Tool Requirements



- Heritage simplified aerodynamic heating routines for NASP vehicle simulation were insufficient
  - Free-stream Approximate Method: Computationally efficient method of determining stagnation point or body point heating using engineering methods (NASA TM-4222)
  - Verified and validated against real-gas shock solution program up to Mach 17
  - Limited to thin-skin (lumped-mass, 0-D) with explicit numerics, and no surface thermochemistry (no ablation)
- Simulation Requirements
  - Requirements driven by quantities of interest for supporting flight test, and parameters of use to GNC R&D (in-depth temperature profiles and recession)
  - In-depth material response, including surface thermochemistry
    - Multiple materials, including contact resistances, radiation or convection gaps, thermally varying material properties
  - Thermal stress estimate given in-depth thermal response and axial/bending/combined constraint in 1, 2, and 3 dimensions
  - Minimize computational time required to maintain real-time or near real-time run capability



# Tool Development



Verification and validation efforts utilized analytical and manufactured solutions, and comparisons with similar programs.

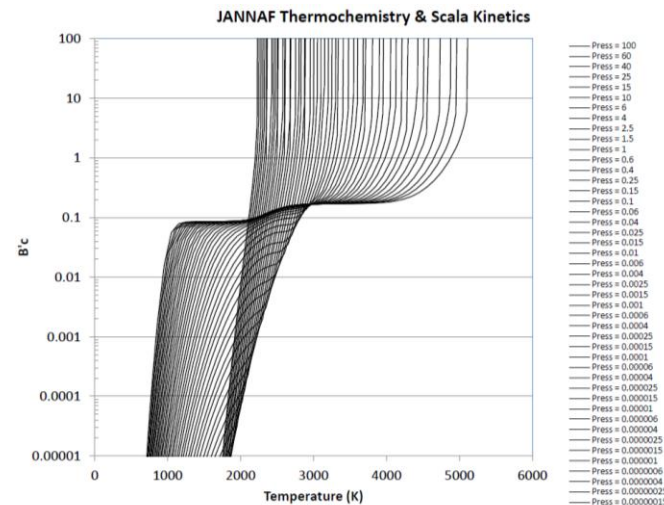
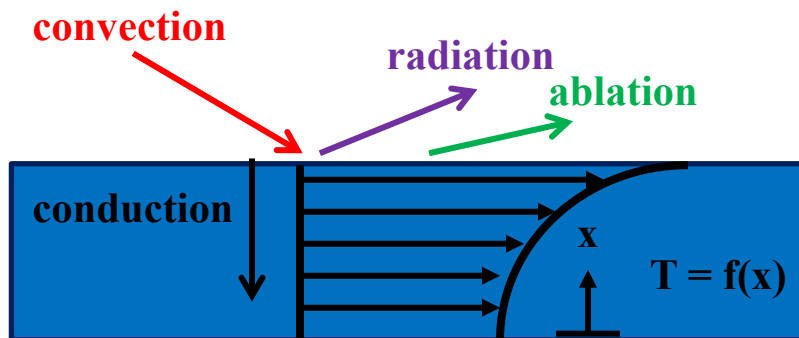




# Technical Approach – Thermal



- Technical Approach: two main aspects to the problem
  - Surface energy balance: accounting for effects from convection, ablation, radiation, stored or conducted away from surface
  - In-depth solution:
    - 0-D: lumped parameter, temperature response dependent upon thickness and heat capacity
    - 1-D: conduction between multiple material layers
- Solution Methodology
  - 0-D: implicit single equation solution
  - 1-D: implicit finite-difference solution to system of equations coupling surface energy balance and in-depth material response



$$q_{convection} - q_{radiation} - q_{ablation} - q_{stored(0-D)/conducted(1-D)} = 0$$



# Technical Approach – Thermostructural



- Thermal stress
  - Thermal stress is caused when expansion or contraction is inhibited by mechanical constraint(s)
  - Mechanical constraints can be classified as: free, axial, bending, or fully constrained
- Thermal stress away from ends for 1-D temperature distribution in a bar, fully constrained:

$$\sigma_{Th,x}(y) = -E(T)\alpha(T) \left( T(y) - T_{ref}(y) \right) + A \frac{1}{2c} \int_{-c}^c E(T)\alpha(T) \left( T(y) - T_{ref}(y) \right) dy \\ + B \frac{3y}{2c^3} \int_{-c}^c E(T)\alpha(T) \left( T(y) - T_{ref}(y) \right) y dy + \sigma_{ref}(y)$$

- $A = 0$  unless unrestrained axially ( $A = 1$ )
  - $B = 0$  unless unrestrained in bending ( $B = 1$ )
  - $E$  is the Modulus of Elasticity
  - $\alpha$  is the linear average coefficient of thermal expansion given by  $\alpha = \frac{\frac{L(T) - L_{ref}}{L_{ref}}}{T - T_{ref}}$
- Thermal stress away from ends for thick plate, 1-D temperature distribution, has same form but each term is multiplied by  $\frac{1}{1-\nu}$ , where  $\nu$  is Poisson's ratio
- Thermal stress, fully restrained in 3 dimensions

$$\sigma_{Th} = \frac{1}{1 - 2\nu} E(T)\alpha(T)(T - T_{ref}) + \sigma_{ref}$$





# Sample Problem

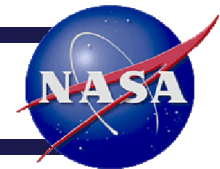


- NASA ARMD (Aeronautics Research Mission Directorate) developed publicly distributable generic hypersonic vehicle trajectory for coast-to-coast flight (NY-LA)
- Problem Definition:
  - Assume C-C panels (using publicly available properties\*), 24-in flow length along conical nose
  - With and without ablation
  - Scala slow and Scala fast kinetics models
  - 0.5 and 1.0-in thicknesses
- Compare structural margins resulting from ablation, kinetics models, thicknesses

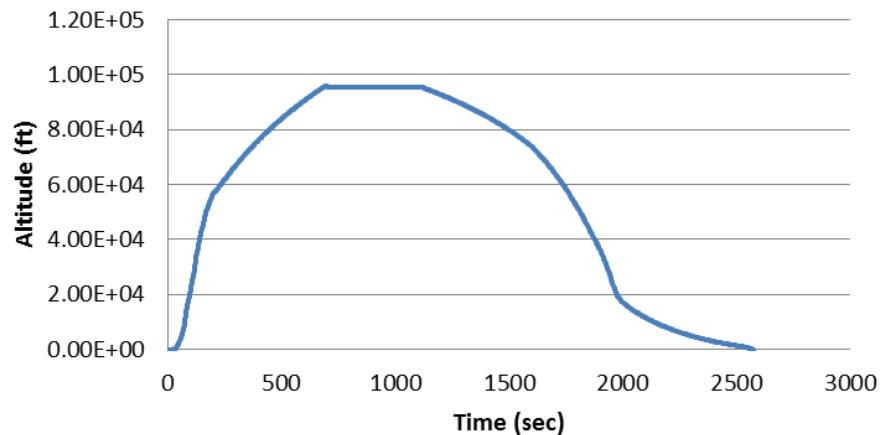
\*Fitzer, E, and L. M. Manocha, *Carbon Reinforcements and Carbon/Carbon Composites*, Springer, Berlin, 1998



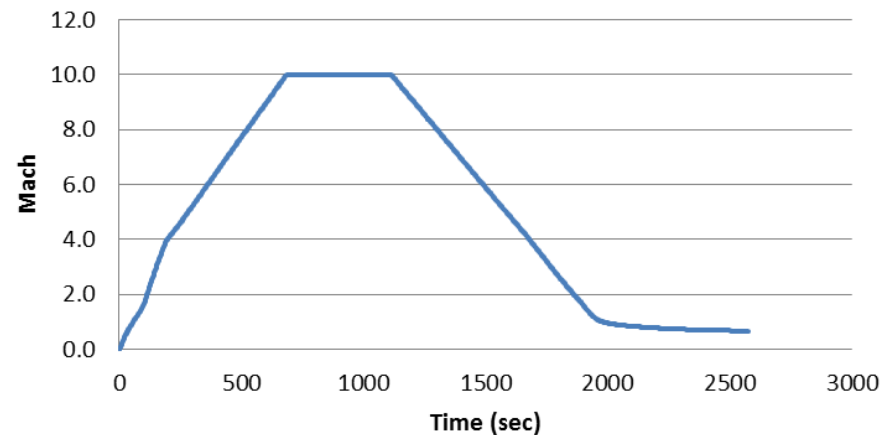
# Sample Problem - Trajectory



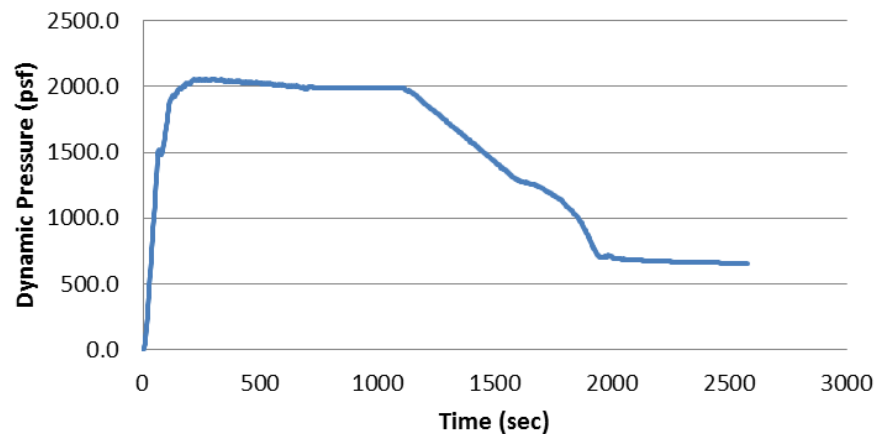
## Altitude



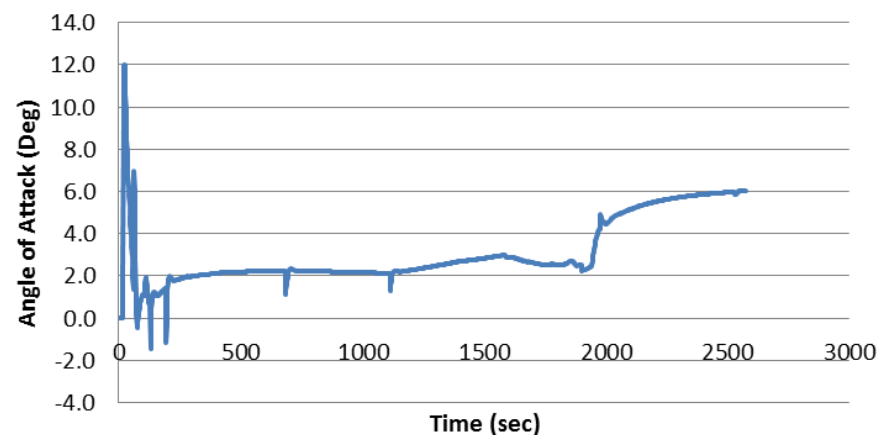
## Mach



## Dynamic Pressure



## Angle of Attack





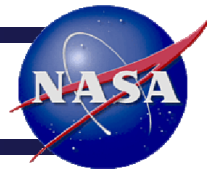
# Sample Problem – Thermochemistry I



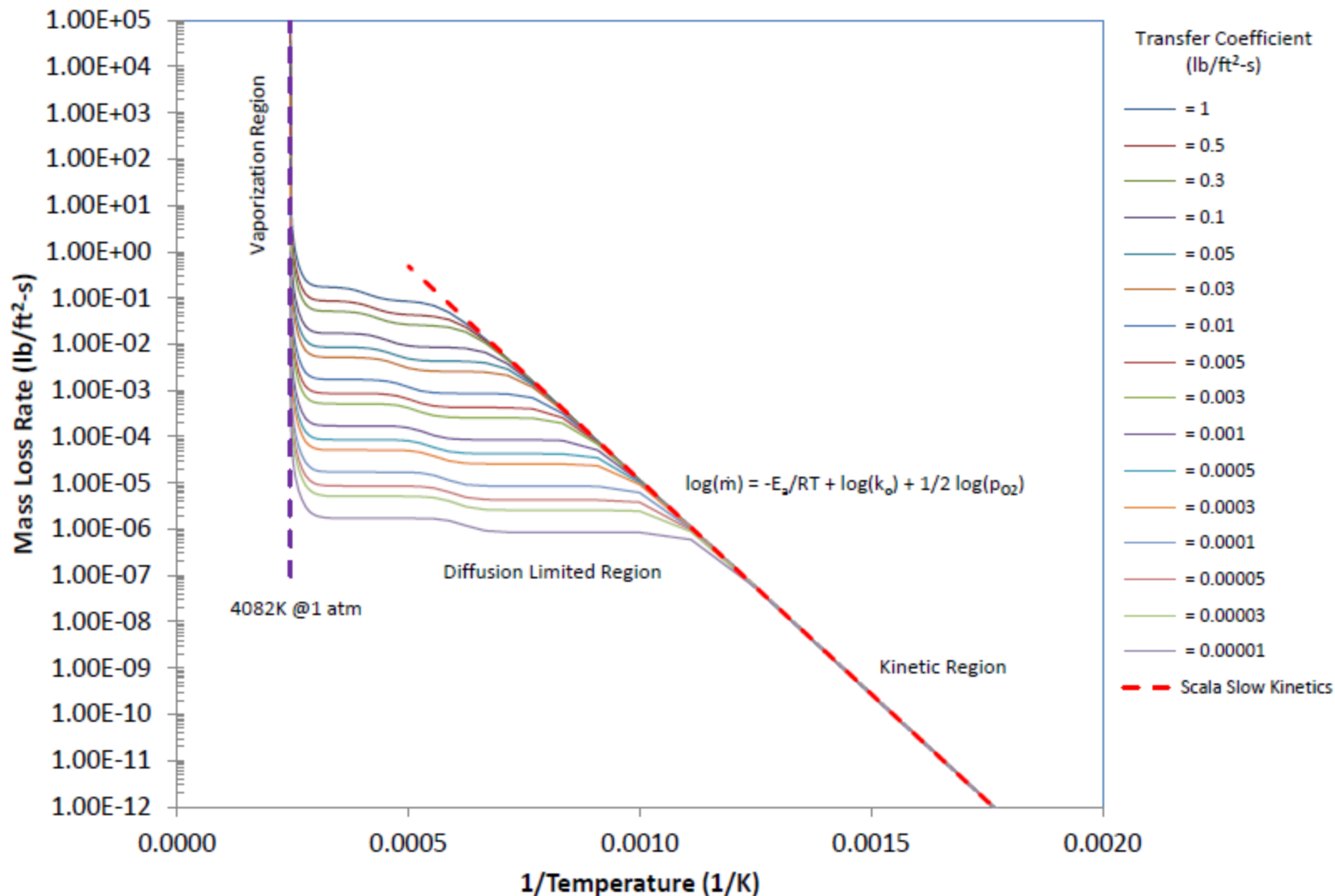
- There are three ablation regimes, characterized as follows:
- **Kinetic Rate Limited Regime**
  - Low temperatures
  - Ablation rate determined only by temperature and partial pressure of oxygen at surface
  - Rate is independent of mass transfer coefficient and follows Arrhenius relationship
- **Diffusion Limited Regime**
  - Intermediate temperatures
  - Ablation rate determined by the rate of oxygen transported to the surface
  - Rate is proportional to mass transfer coefficient
- **Vaporization Regime**
  - High temperatures
  - Ablation rate determined by the rate of carbon diffusing away from the surface
  - Rate is proportional to mass transfer coefficient
  - Surface approaches asymptotic temperature limit dependent on pressure at high mass transfer rates



# Sample Problem – Thermochemistry II



## ACE JANNAF & Scala Slow Kinetics - 1 atm





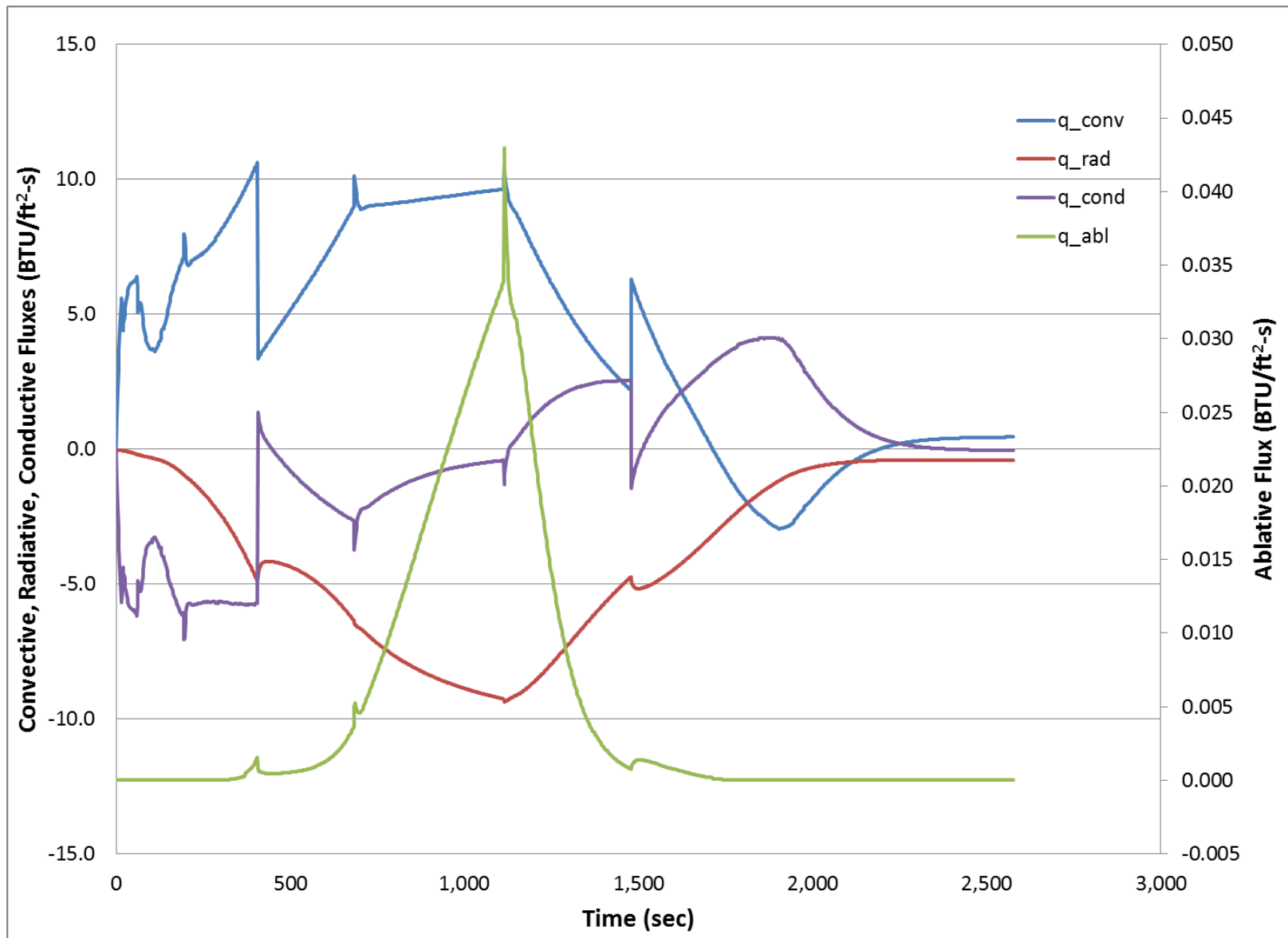
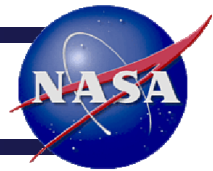
# Sample Problem – Thermochemistry III



- At low temperatures, when reaction is not diffusion controlled, rate is only dependent on temperature and the partial pressure of oxygen at the surface
- Scala reported two bounding models for carbon kinetics, referred to as “slow and “fast”
- Scala Slow Kinetics
  - $\text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}$
  - $\dot{m} = k_o (p_{\text{O}_2})^{1/2} e^{-E_a/RT}$  (absolute surface mass loss rate)
  - $k_o = 44,730 \text{ lb/ft}^2\text{-s-atm}^{1/2}$
  - $E_a = 42,300 \text{ cal/mol-K}$
- Scala Fast Kinetics
  - $\text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}$
  - $\dot{m} = k_o (p_{\text{O}_2})^{1/2} e^{-E_a/RT}$  (absolute surface mass loss rate)
  - $k_o = 672,900,000 \text{ lb/ft}^2\text{-s-atm}^{1/2}$
  - $E_a = 44,000 \text{ cal/mol-K}$

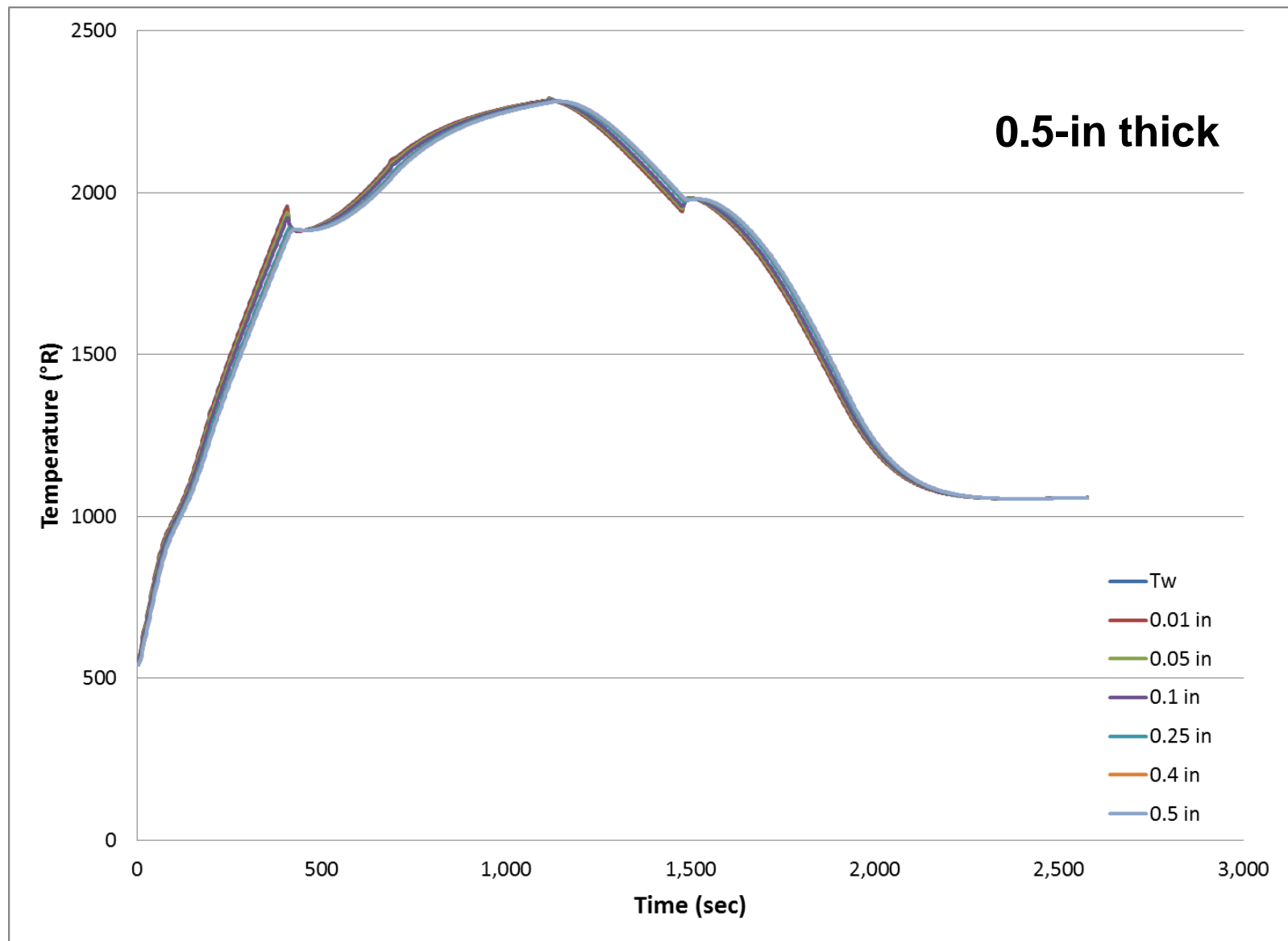
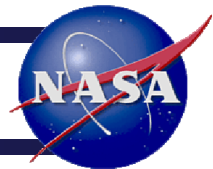


# Surface Energy Balance Time History





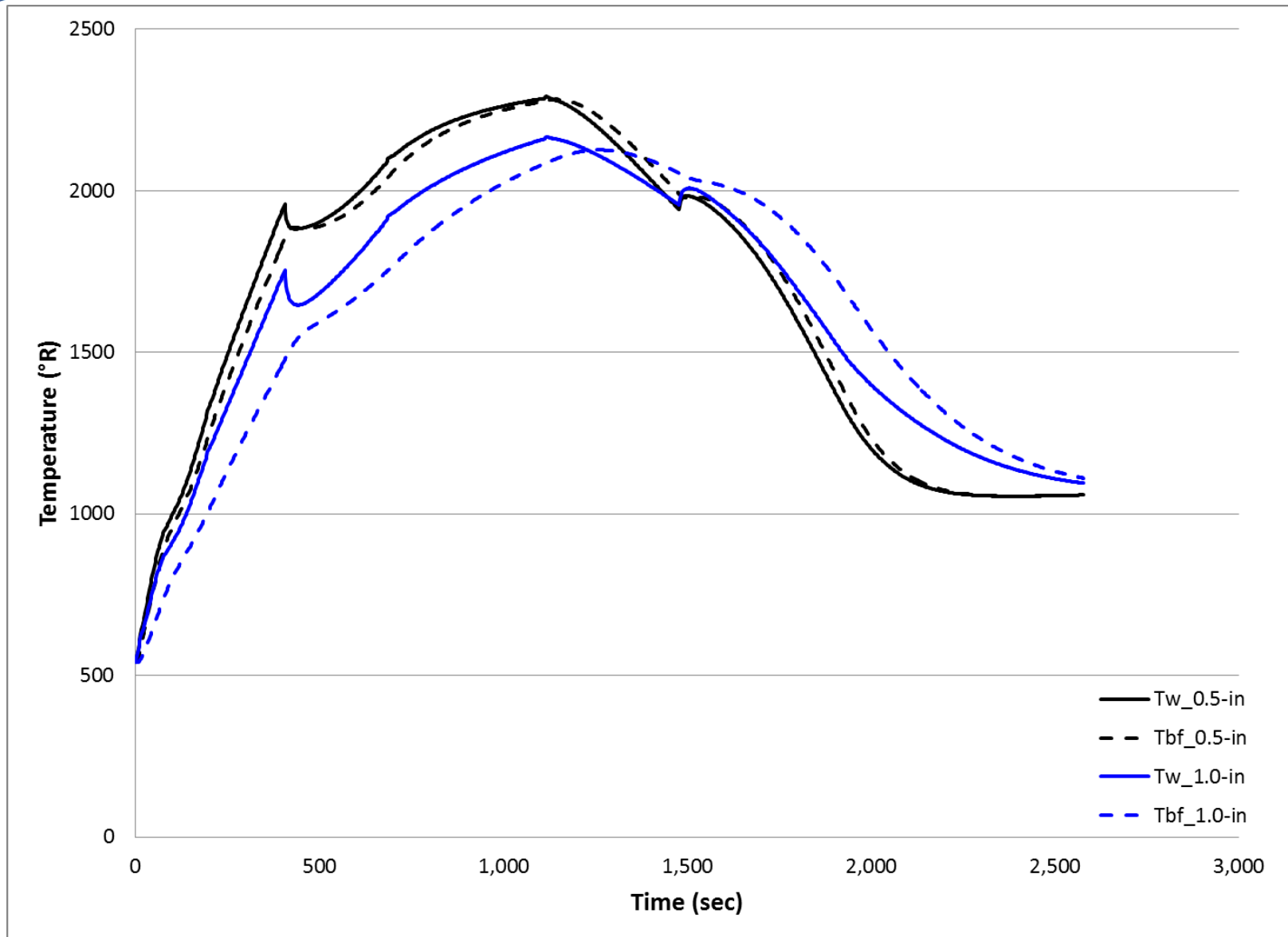
# Thermocouple Time History





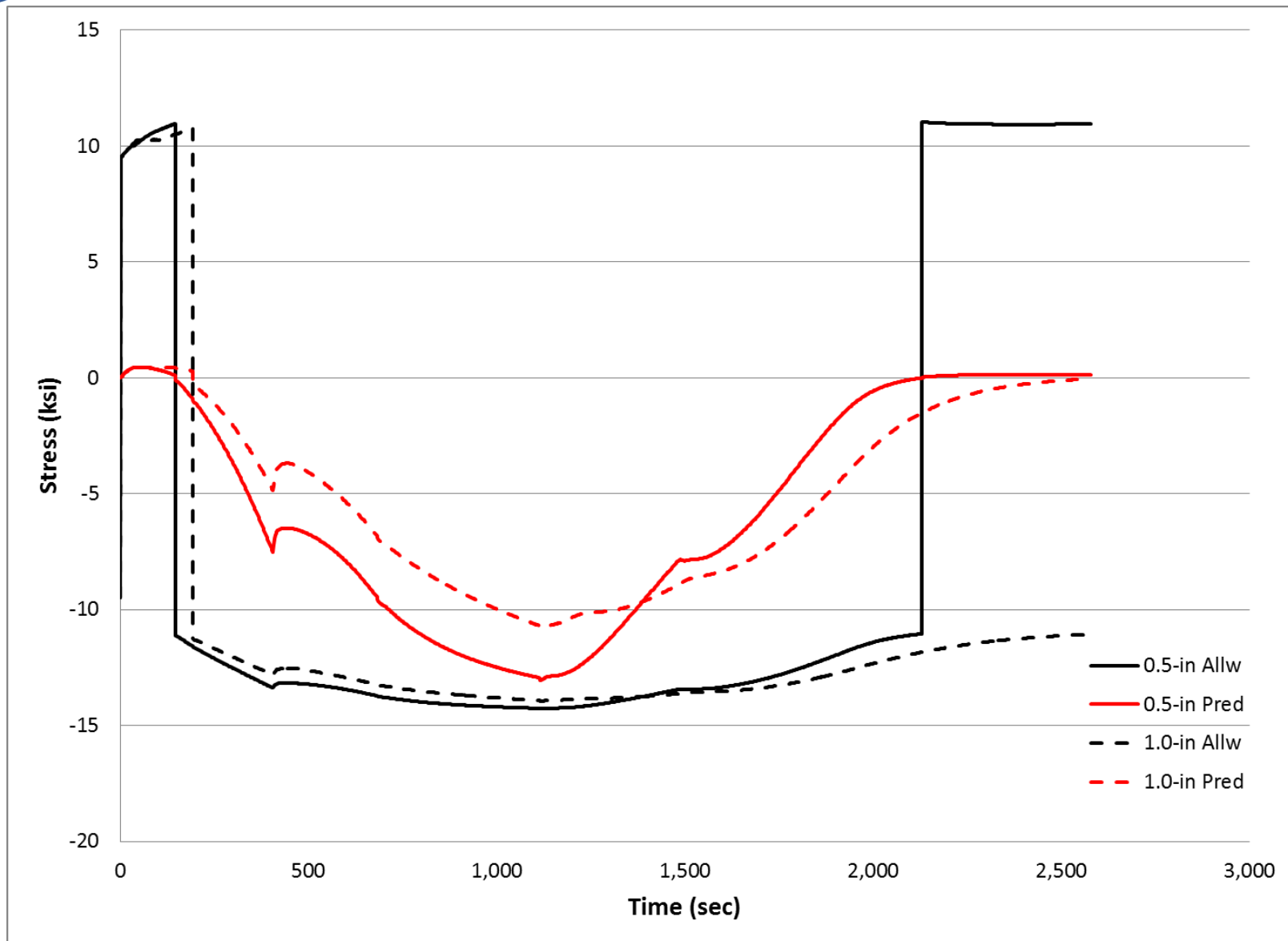
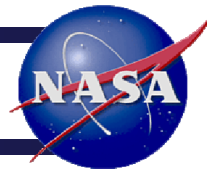


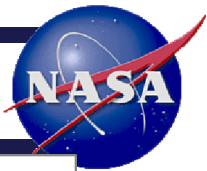
# Thickness Comparison – Thermocouples



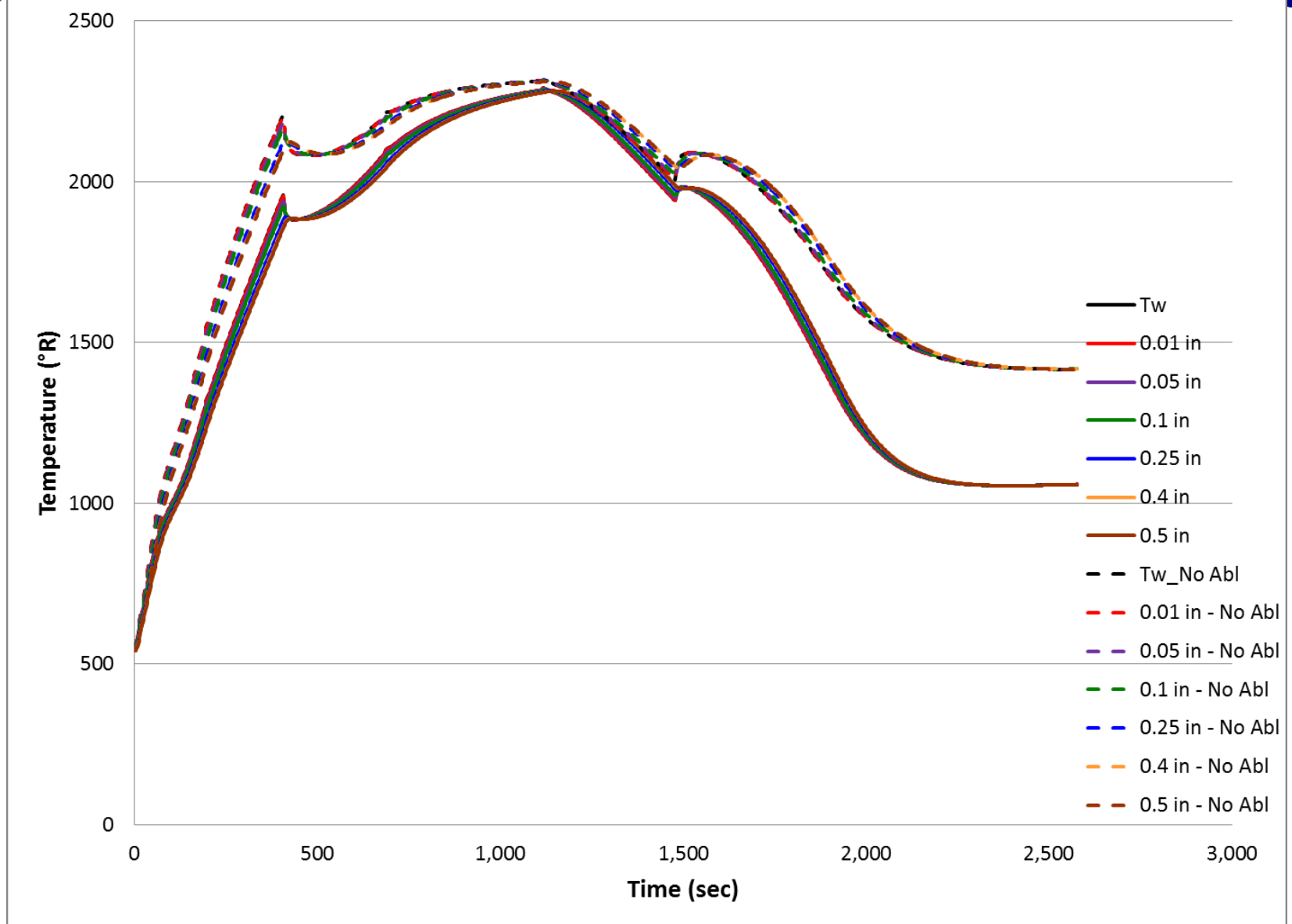


# Thickness Comparison – Thermal Stress



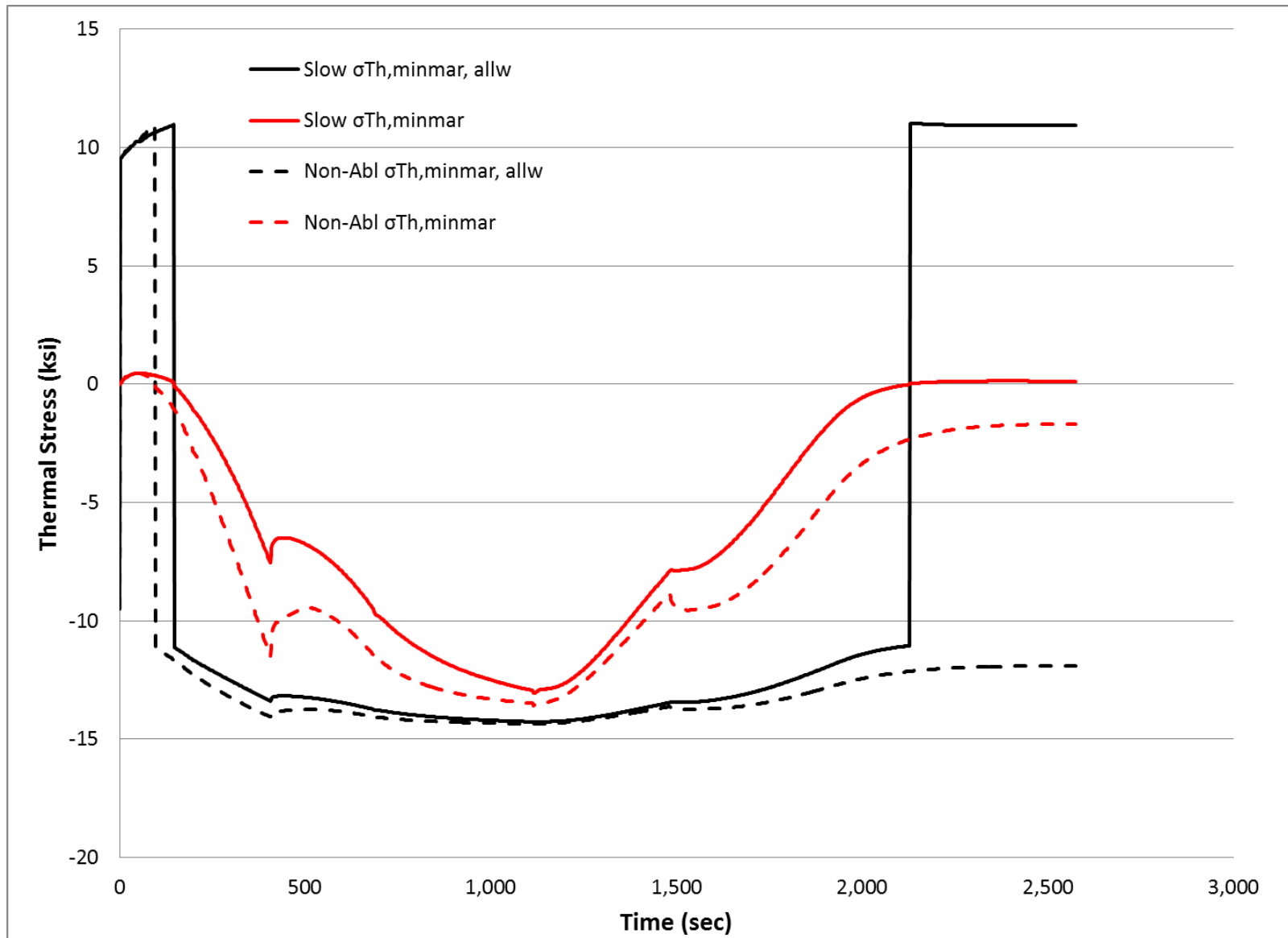
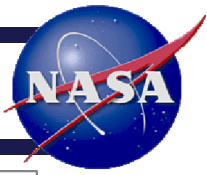


# Ablation vs Non-ablating



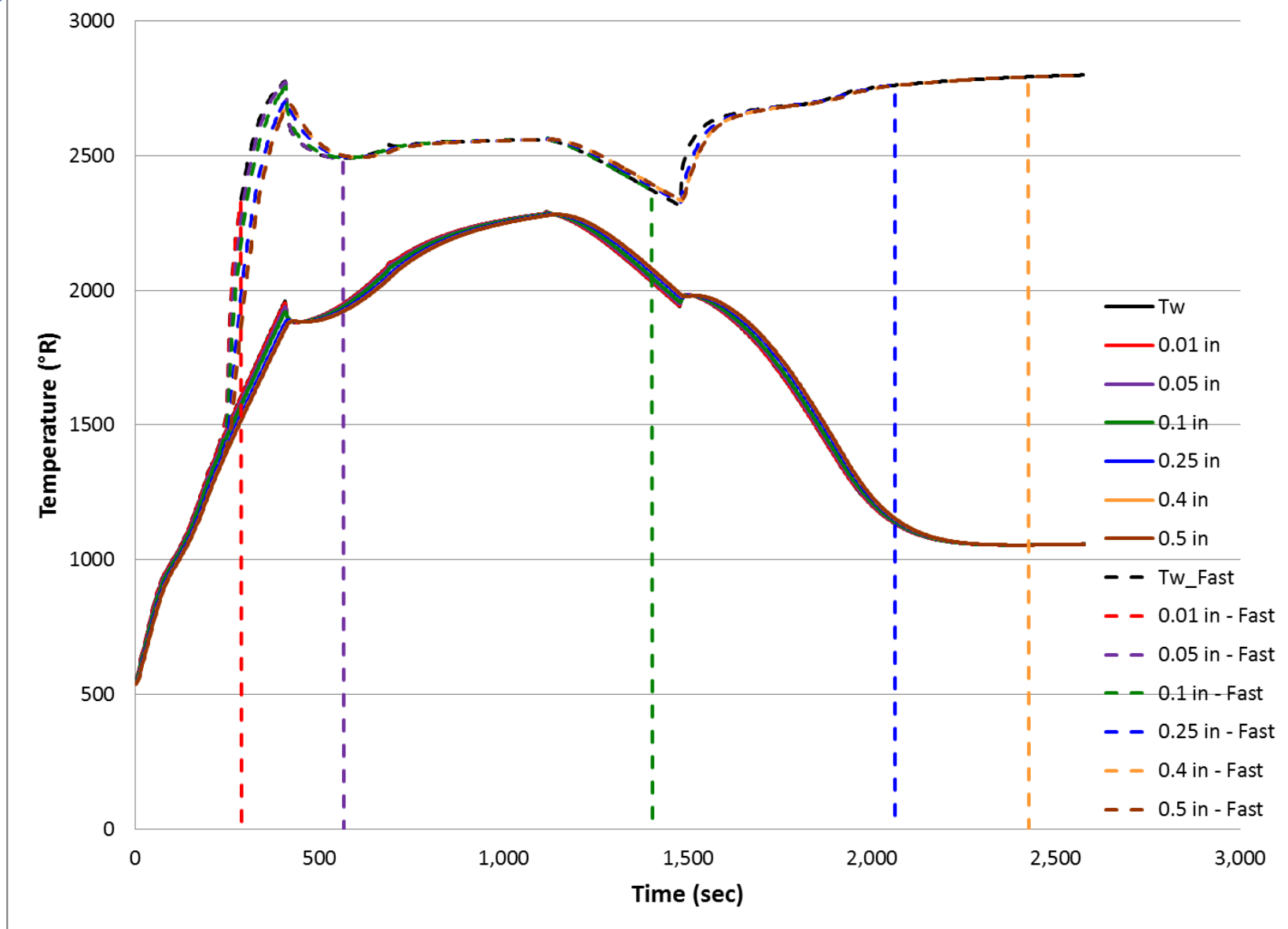
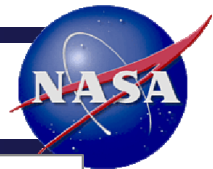


# Ablation Impact on Thermal Stress



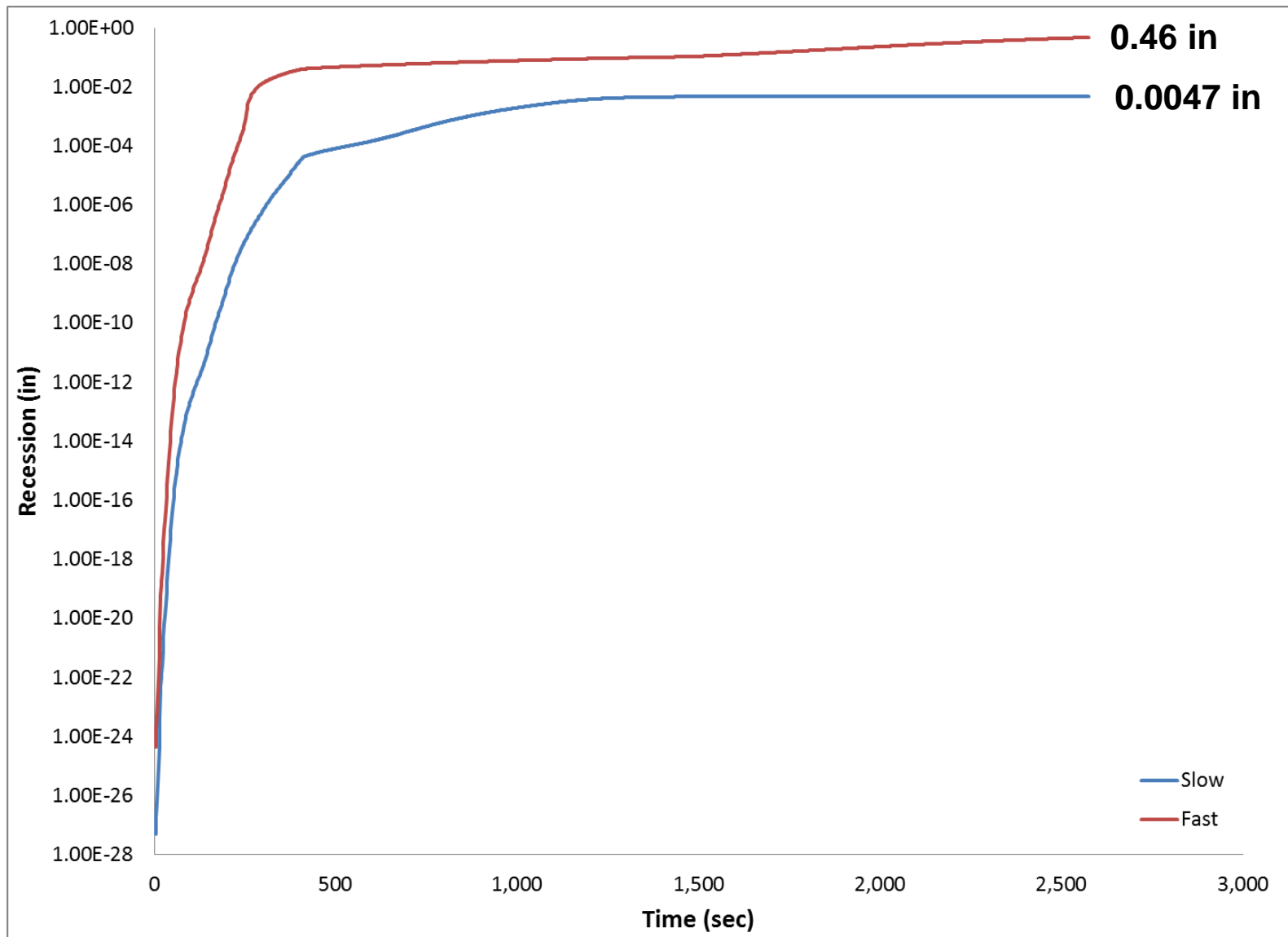


# Slow vs Fast Scala Kinetics



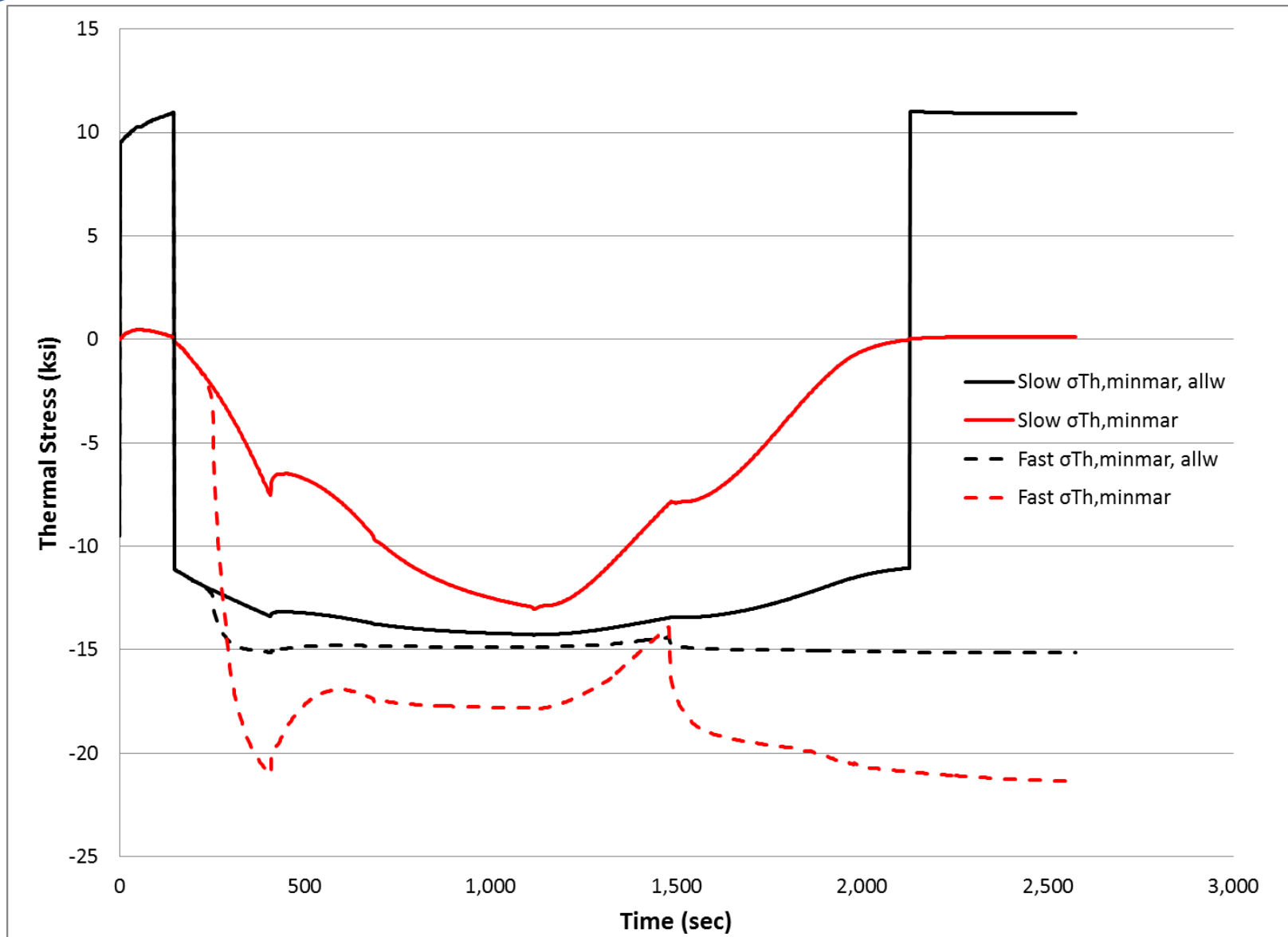
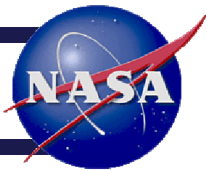


# Slow vs Fast Scala Kinetics Recession





# Slow vs Fast Scala Kinetics Impact on Predicted Thermal Stress



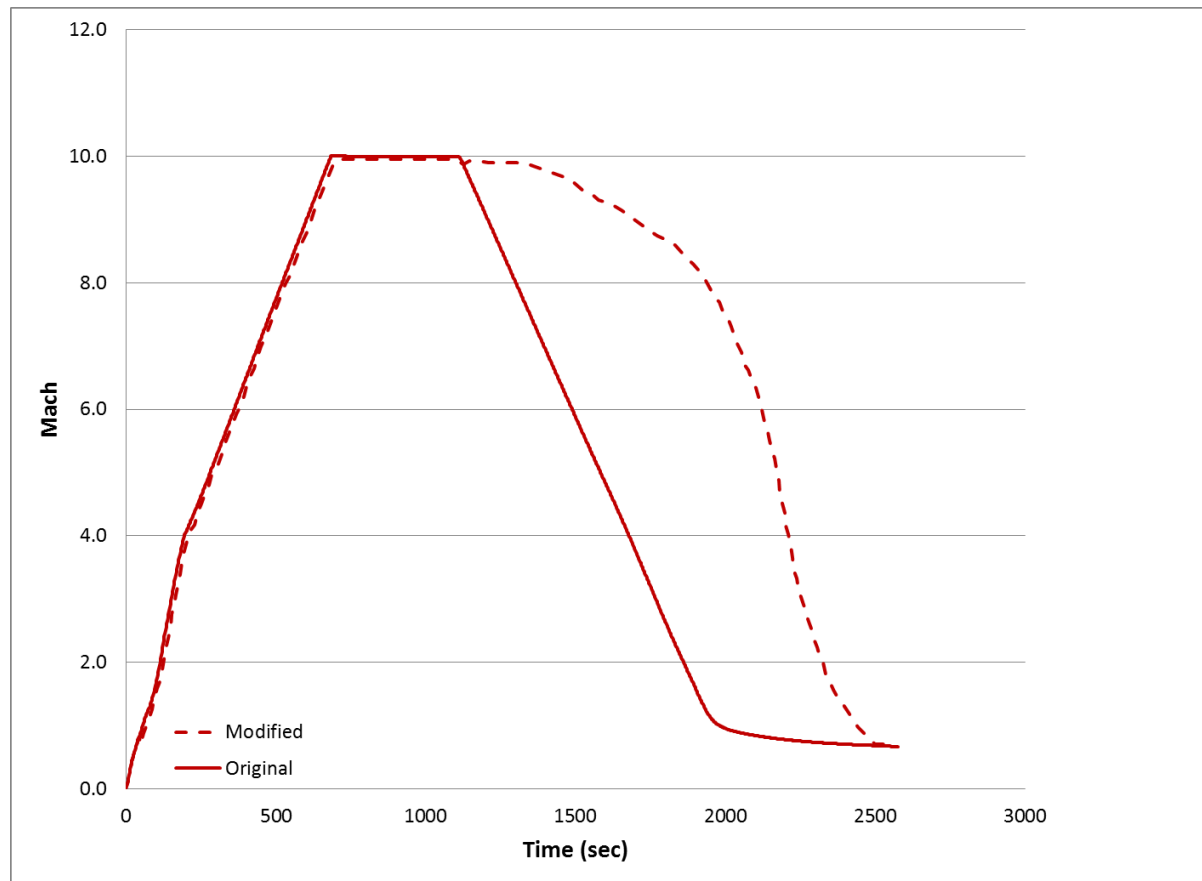




# Sample Problem Modification

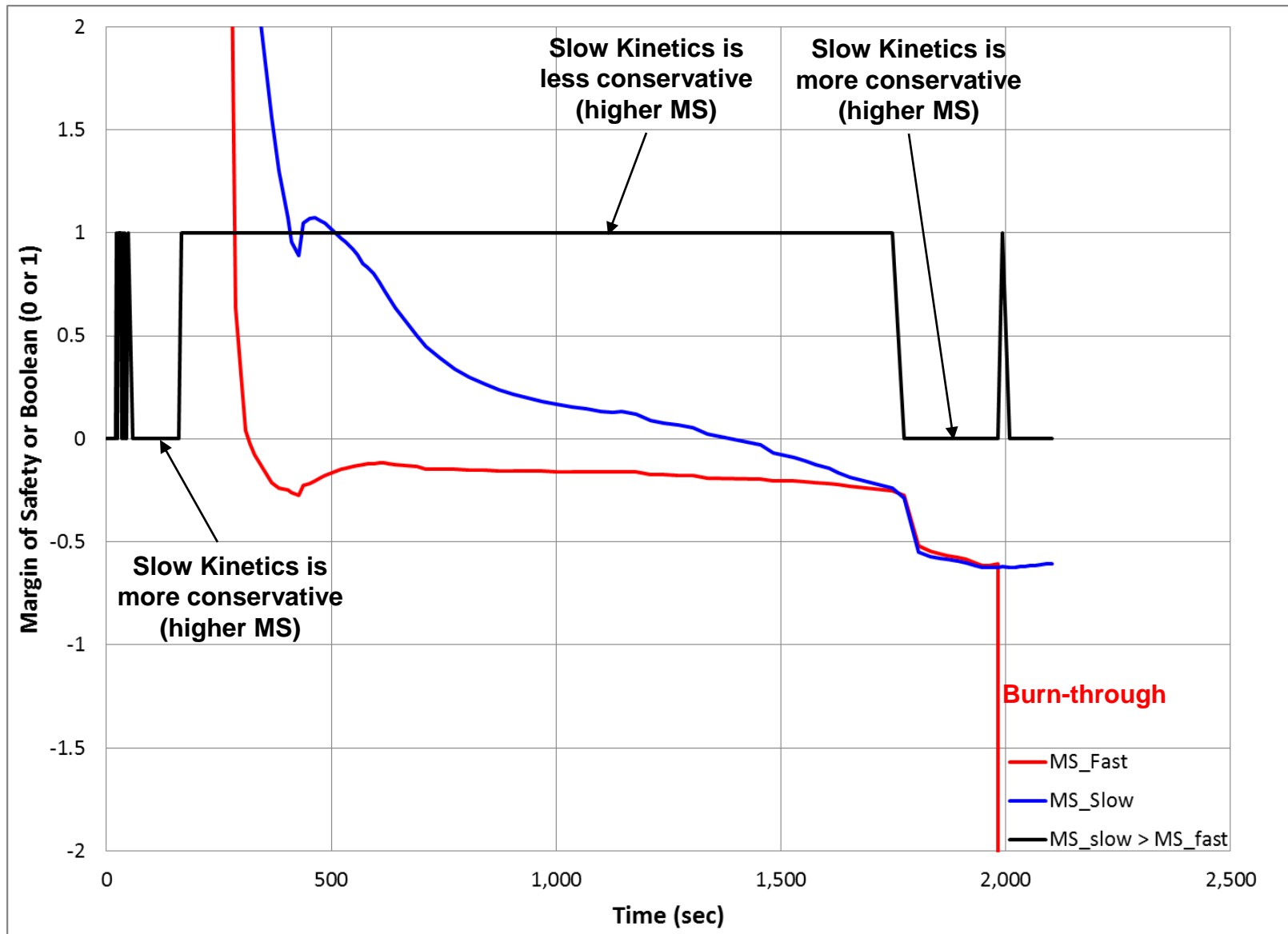


- Scala Fast Kinetics produced a uniformly more conservative margin of safety than Scala Slow Kinetics
- A modified trajectory that allows a deceleration curve with an inflection point (rather than simple ramp) was analyzed





# Modified Trajectory Margin of Safety Comparison Between Kinetics Models

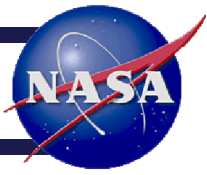




# Summary



- An engineering tool was developed to solve the thermal and stress response of a non-pyrolyzing, multi-material stack to a trajectory given a 1-D heat flow assumption, and 1, 2, and 3-D mechanical constraints (axial, bending, combined)
- The tool was shown to be useful for ascertaining the impact of ablation on the thermal response and stress state of the material
- The tool was shown to be useful for ascertaining the impact of various kinetics, or thermochemistry models on the thermal response and stress state of the material



# Questions