TFAWS Aerothermal Paper Session

THERMAL & FLUIDS ANALYSIS WORKSHOP
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Development of a Multi-Disciplinary Aerothermostructural Model Applicable to Hypersonic Flight

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Outline

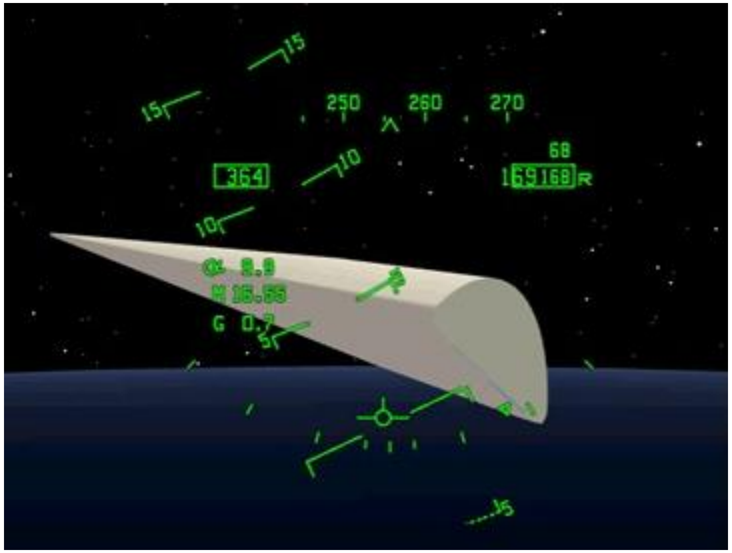
- Background
- Tool Requirements
- Tool Development
- Technical Approach
- Sample Problem
- Summary

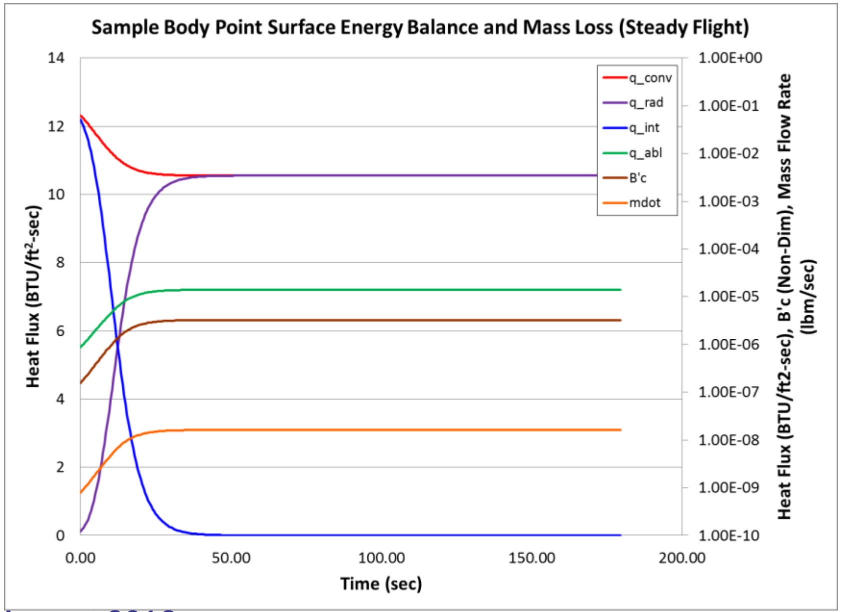
Background

- 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

Background (cont’d)

- Approx. 1 year later DFRC began pursuing incorporation of aerothermal, thermostructural into vehicle simulation
  - Enabled flight data reduction
  - GNC personnel seized opportunity to work on adaptive guidance algorithms based on aerothermal or thermostructural parameters
- First approach: obtain source code from one of several codes currently available that solve 1-D (in-depth) material response, not feasible nor desirable
- Second approach: “update” simplified aerothermal routines from DFRC NASP vehicle simulation

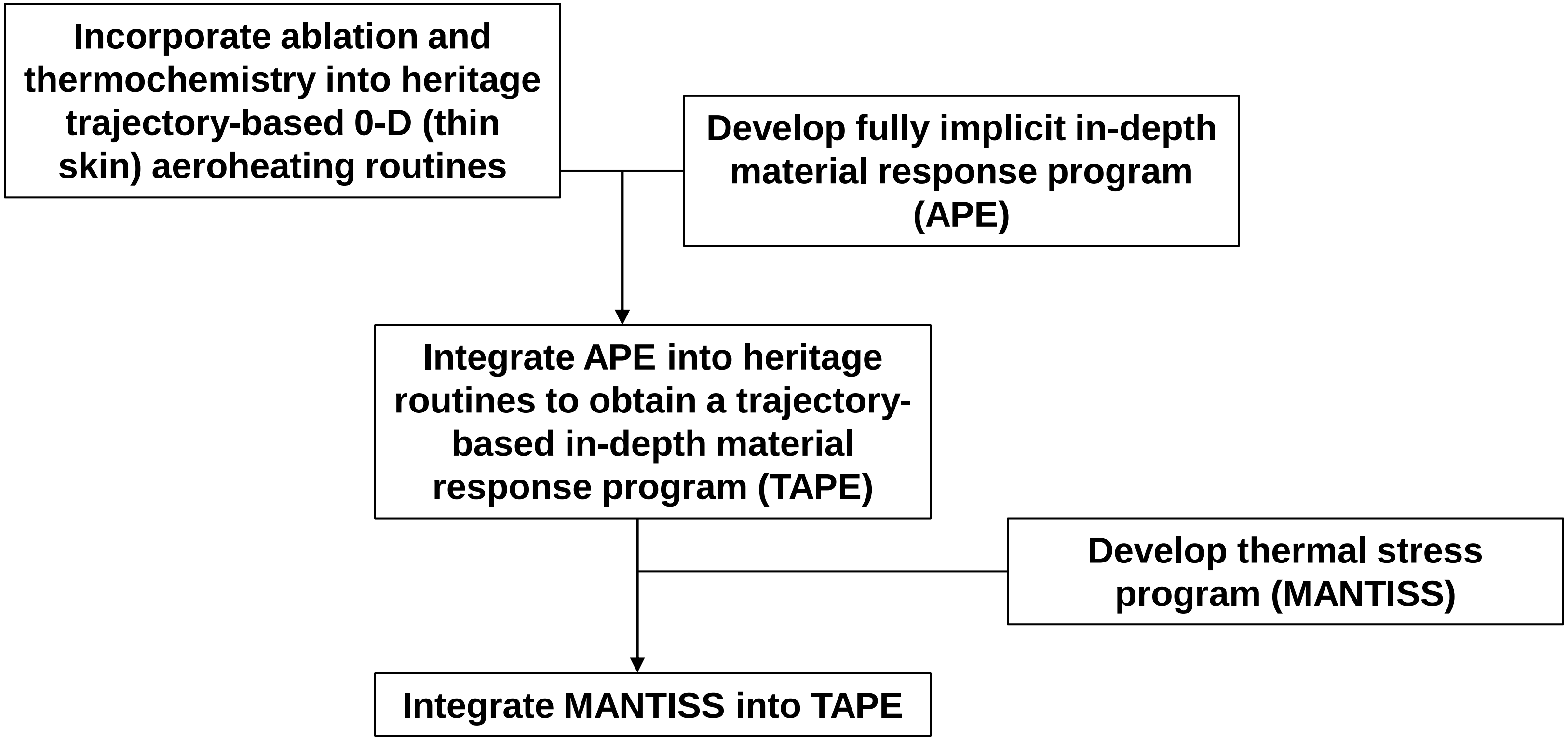




Tool Requirements

- 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



Incorporate ablation and thermochemistry into heritage trajectory-based 0-D (thin skin) aeroheating routines

Develop fully implicit in-depth material response program (APE)

Integrate APE into heritage routines to obtain a trajectory-based in-depth material response program (TAPE)

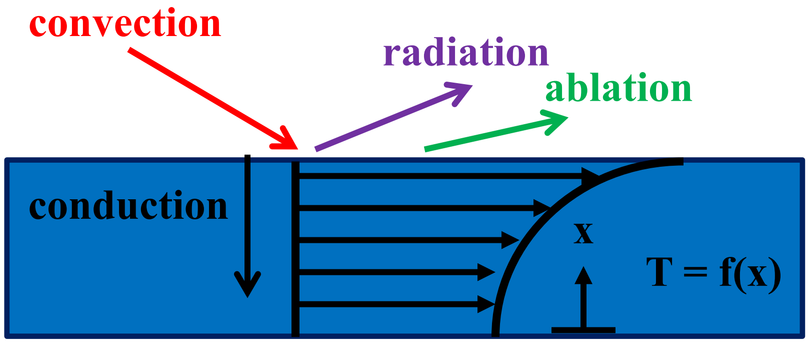
Develop thermal stress program (MANTISS)

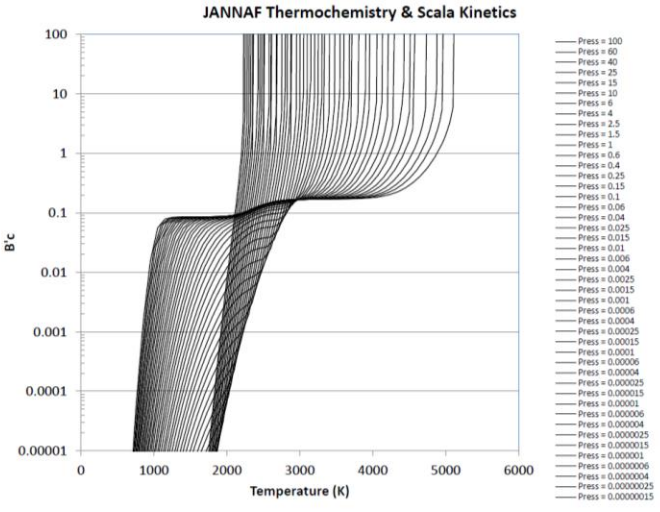
Integrate MANTISS into TAPE

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





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

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
  - α 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 ν is Poisson's ratio
- Thermal stress, fully restrained in 3 dimensions

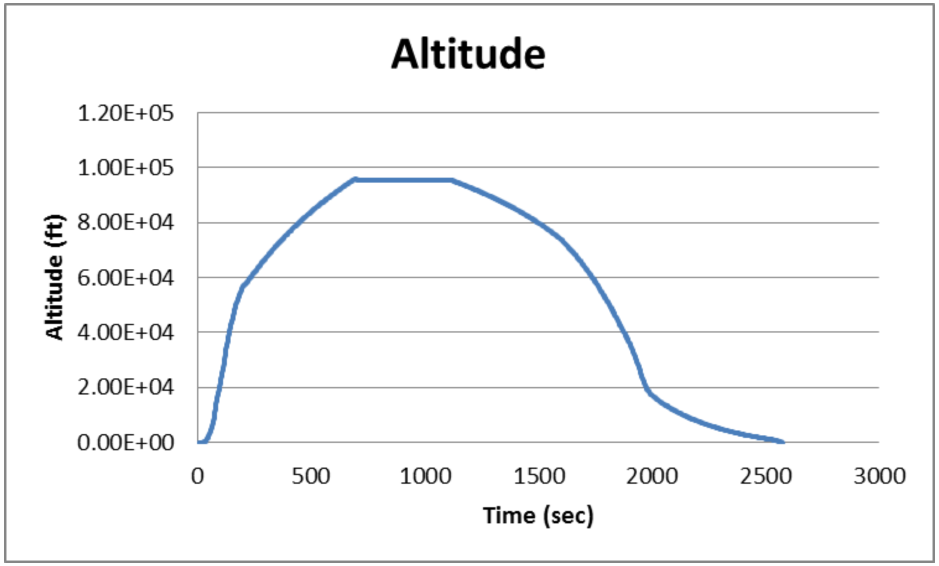
$$\sigma_{Th} = \frac{1}{1-2\nu}E(T)\alpha(T)(T - Tref) + \sigma_{ref}$$

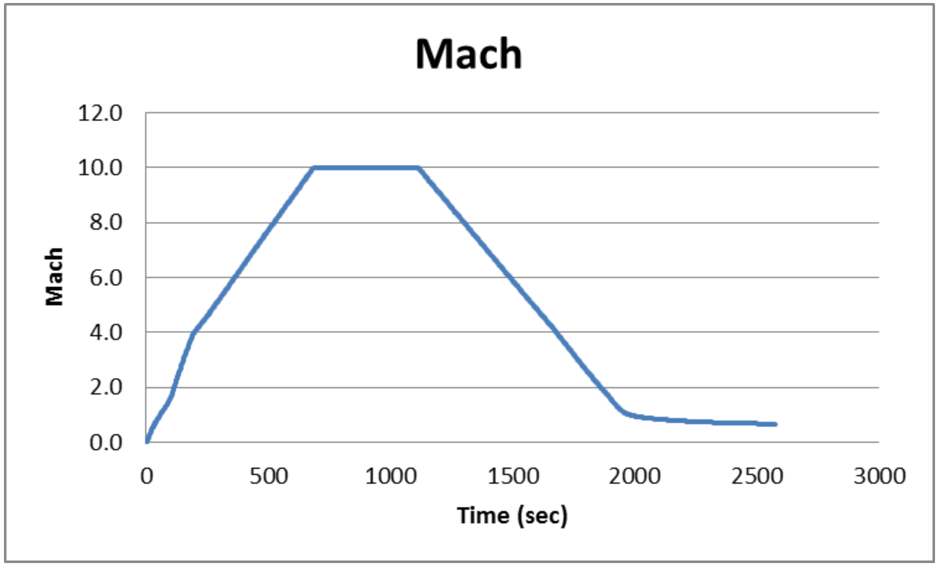
Sample Problem

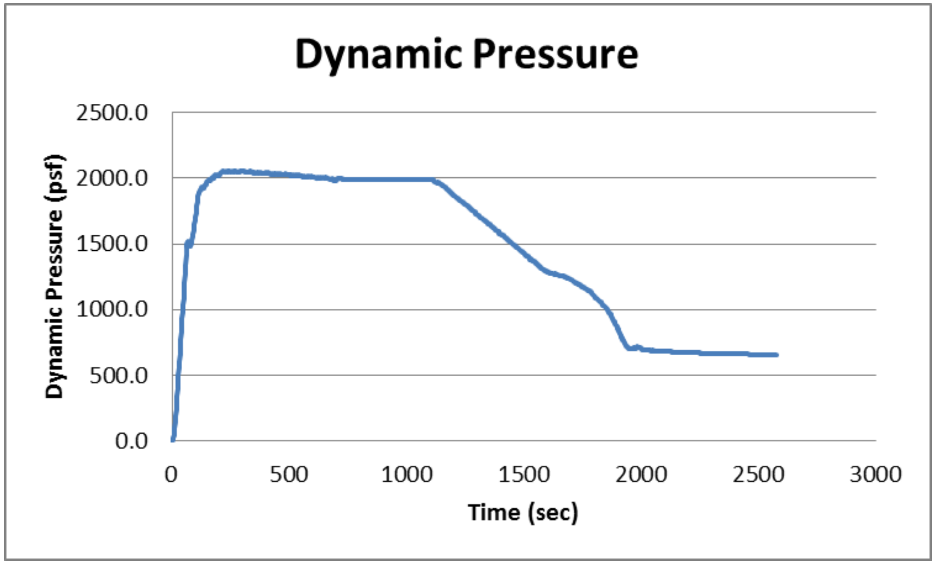
- NASA ARMD (Aeronautics Research Mission Directorate) developed publicly distributable generic hypersonic vehicle trajectory for coast-to-coast flight (NY-LA)
- Problem Definition:
  - Assume C-C panels (using publicly available properties*), 24-in flow length along conical nose
  - With and without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

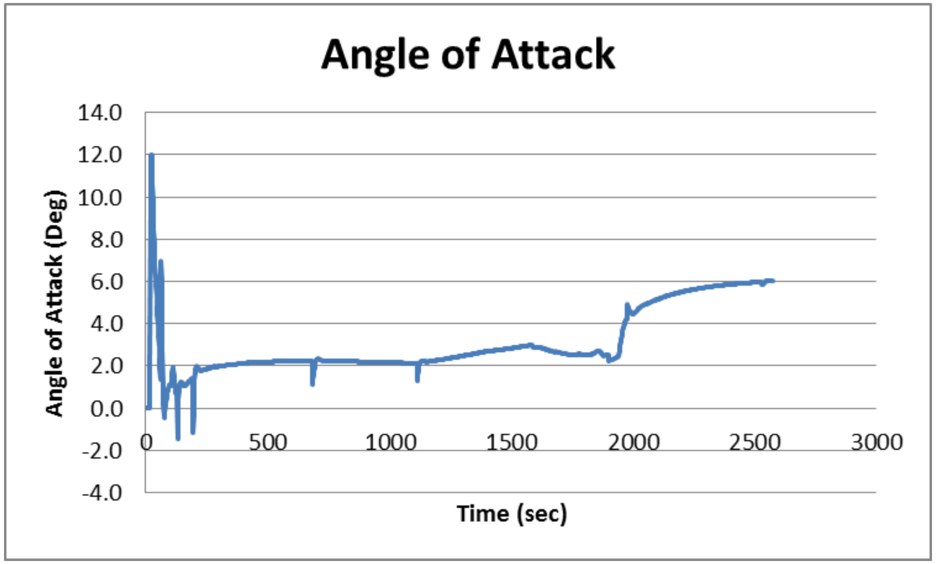
***Fitzer, E, and L. M. Manocha, *Carbon Reinforcements and Carbon/Carbon Composites*, Springer, Berlin, 1998**

Sample Problem - Trajectory


Altitude


Mach


Dynamic Pressure

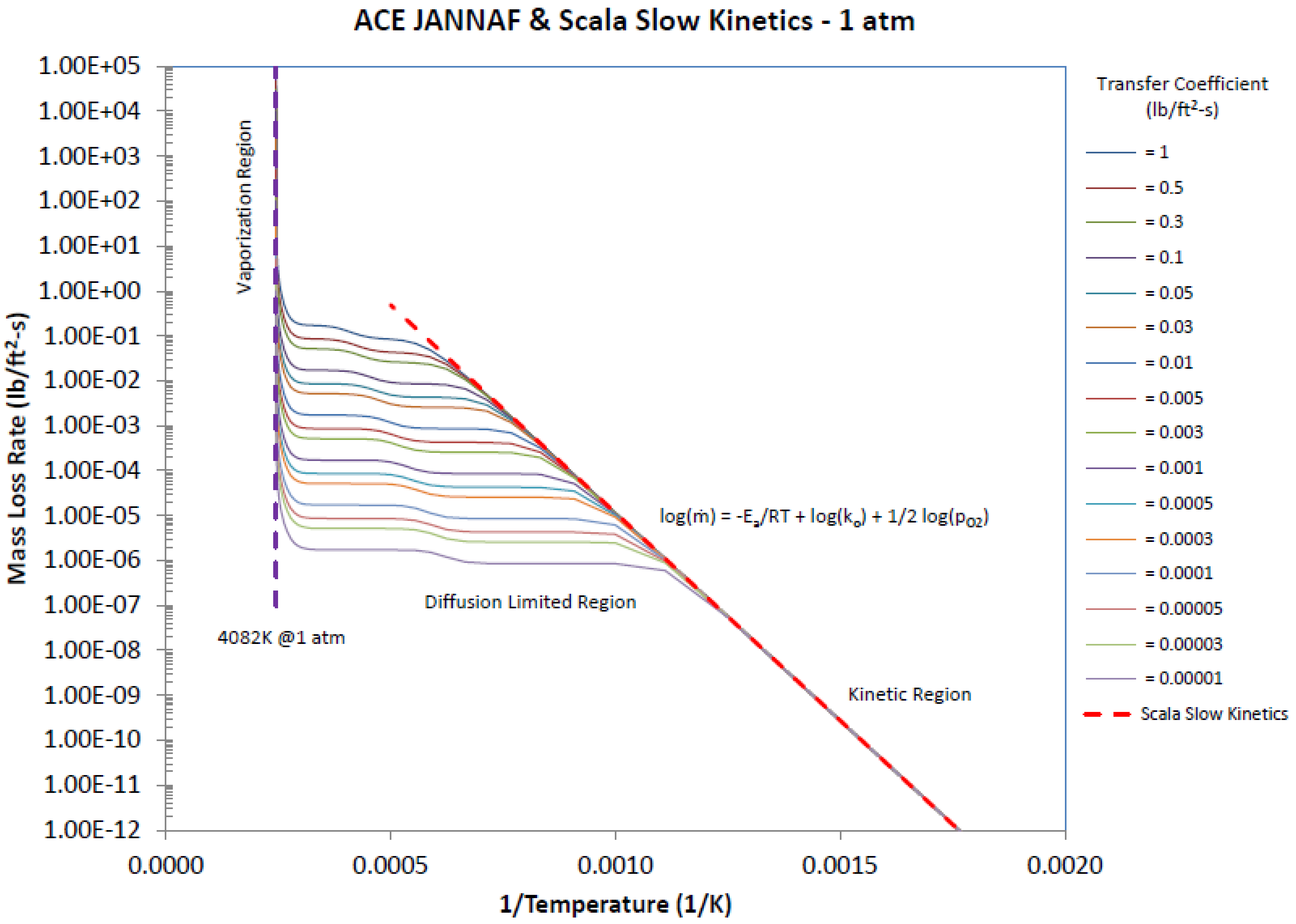

Angle of Attack

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



Sample Problem – Thermochemistry III

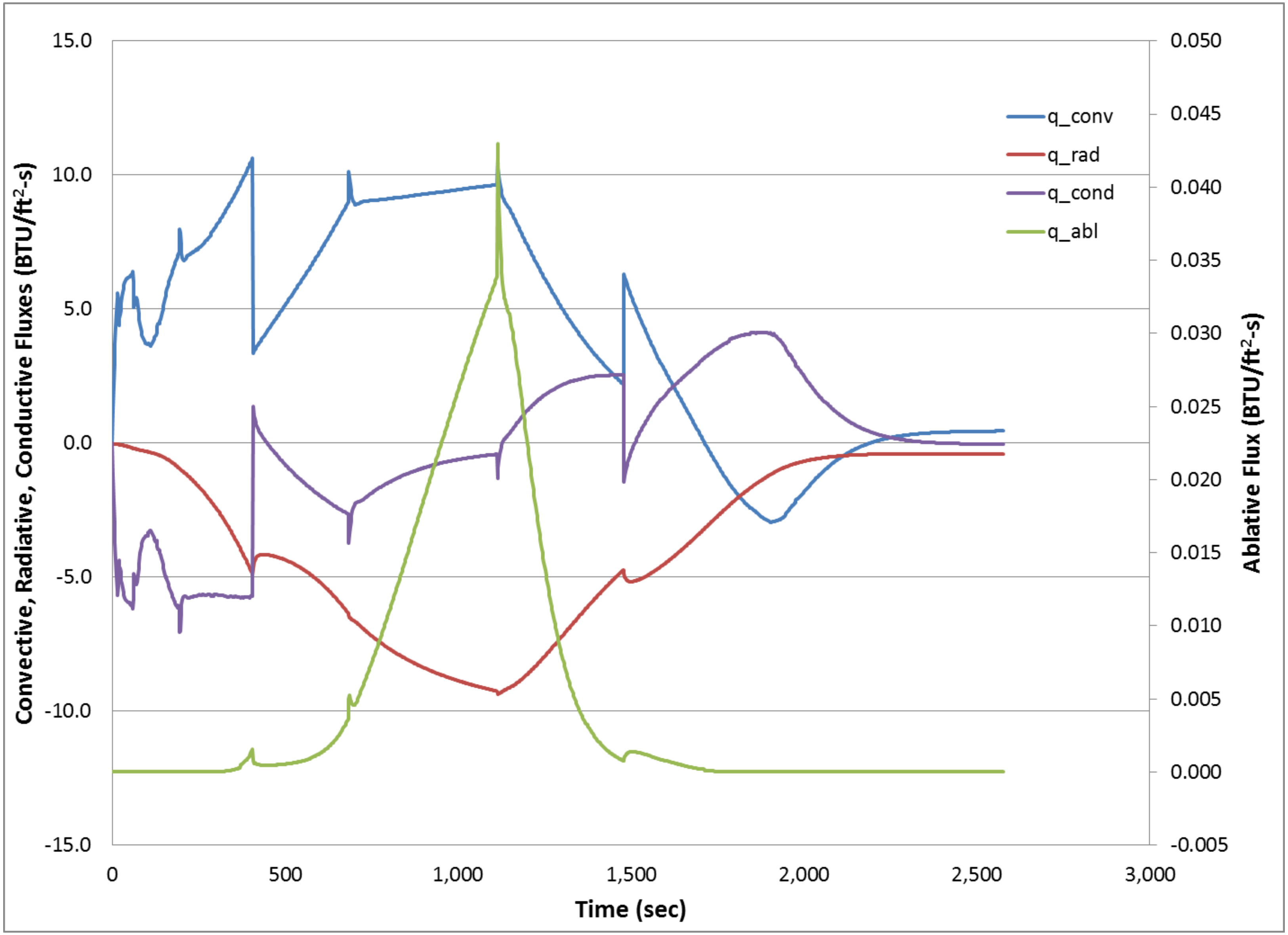
- At low temperatures, when reaction is not diffusion controlled, rate is only dependent on temperature and the partial pressure of oxygen at the surface

- Scala reported two bounding models for carbon kinetics, referred to as “slow and “fast”

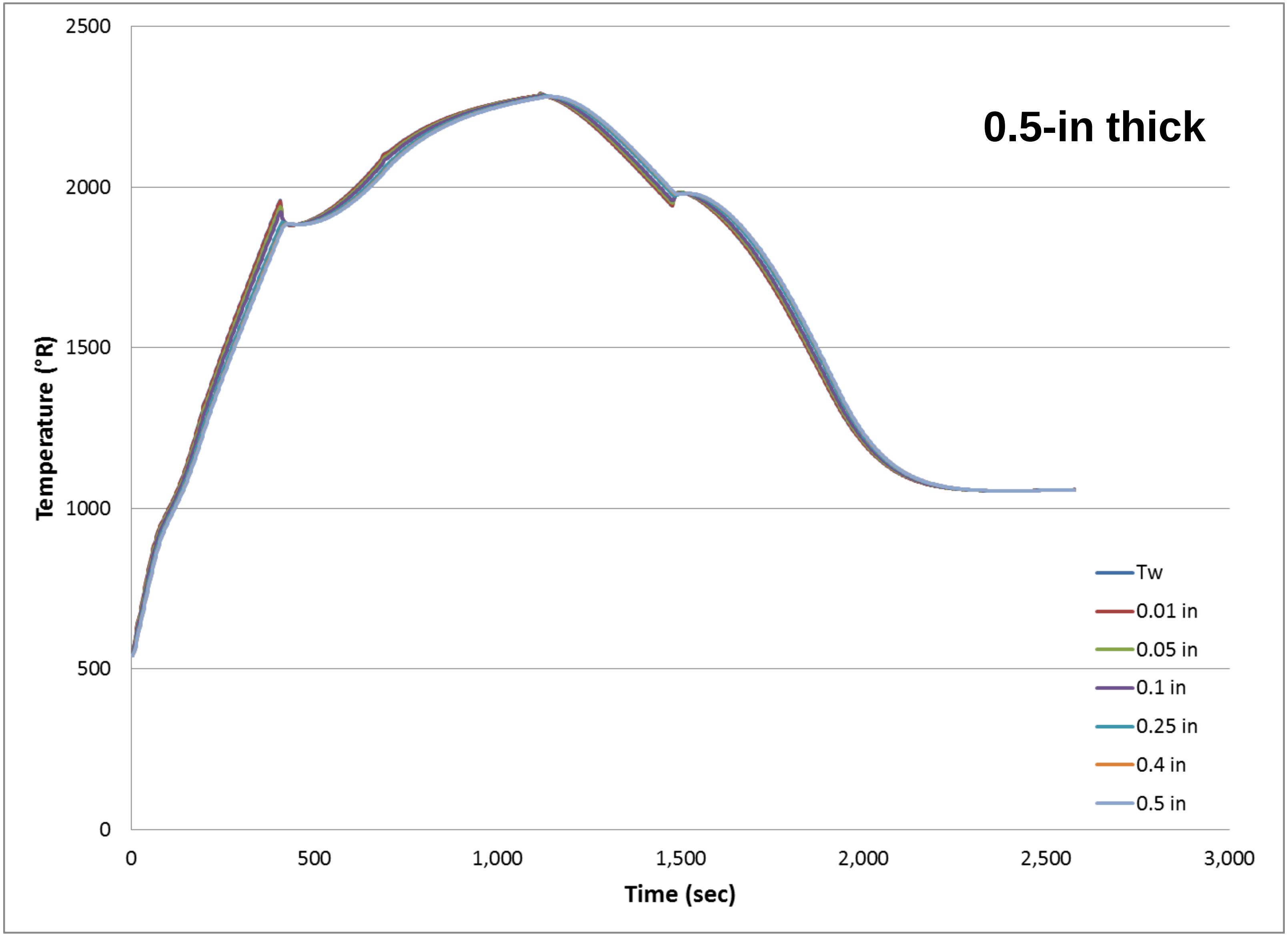
- Scala Slow Kinetics
  - $C + ½ O_2 \rightarrow CO$
  - $\dot{m} = k_o (p_{O_2})^{1/2} e^{-E_a/RT}$ (absolute surface mass loss rate)
  - k_o= 44,730 lb/ft^2-s-atm$^{1/2}$
  - E_a= 42,300 cal/mol-K

- Scala Fast Kinetics
  - $C + ½ O_2 \rightarrow CO$
  - $\dot{m} = k_o (p_{O_2})^{1/2} e^{-E_a/RT}$ (absolute surface mass loss rate)
  - k_o= 672,900,000 lb/ft^2-s-atm$^{1/2}$
  - E_a= 44,000 cal/mol-K

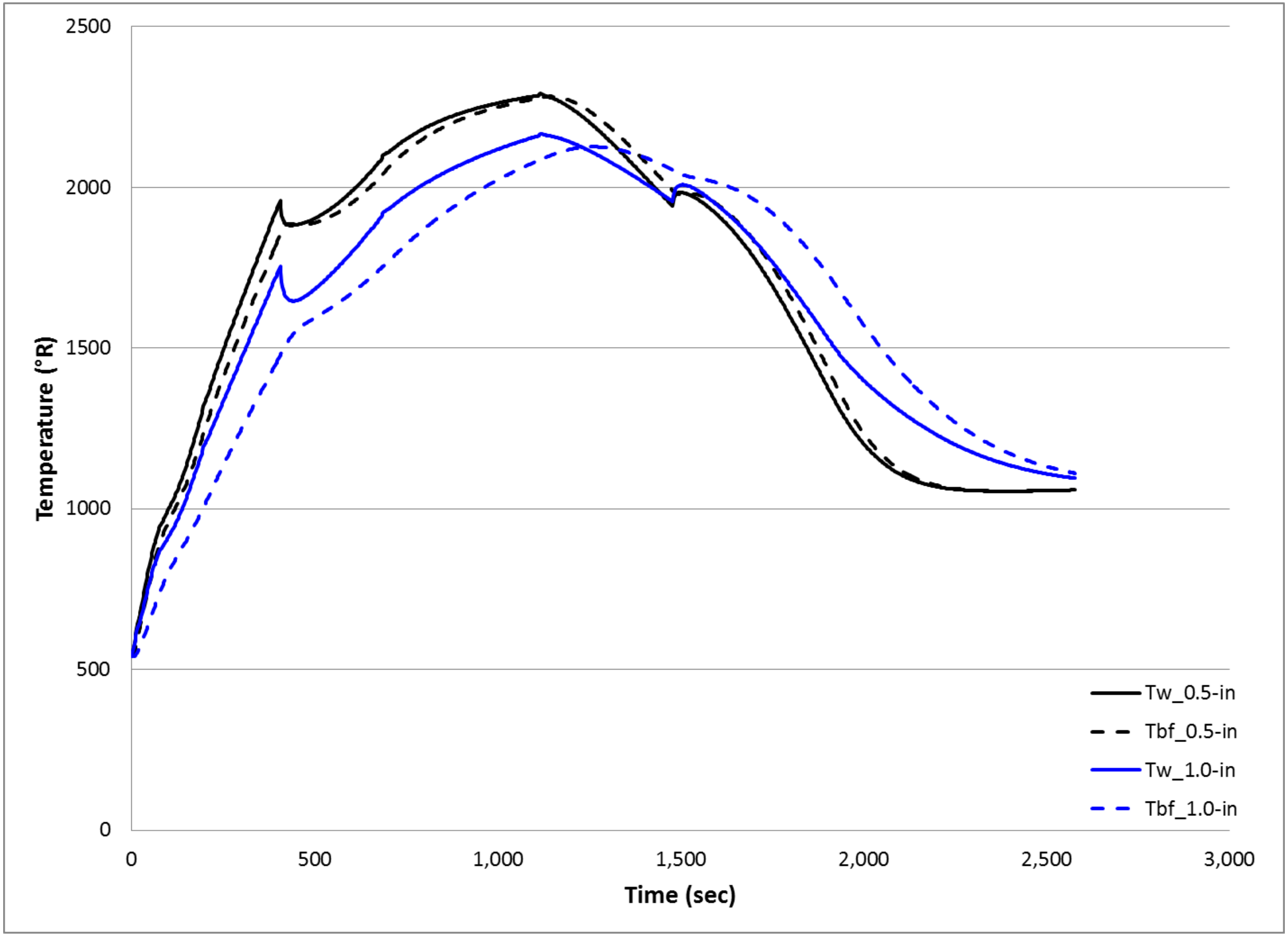
Surface Energy Balance Time History



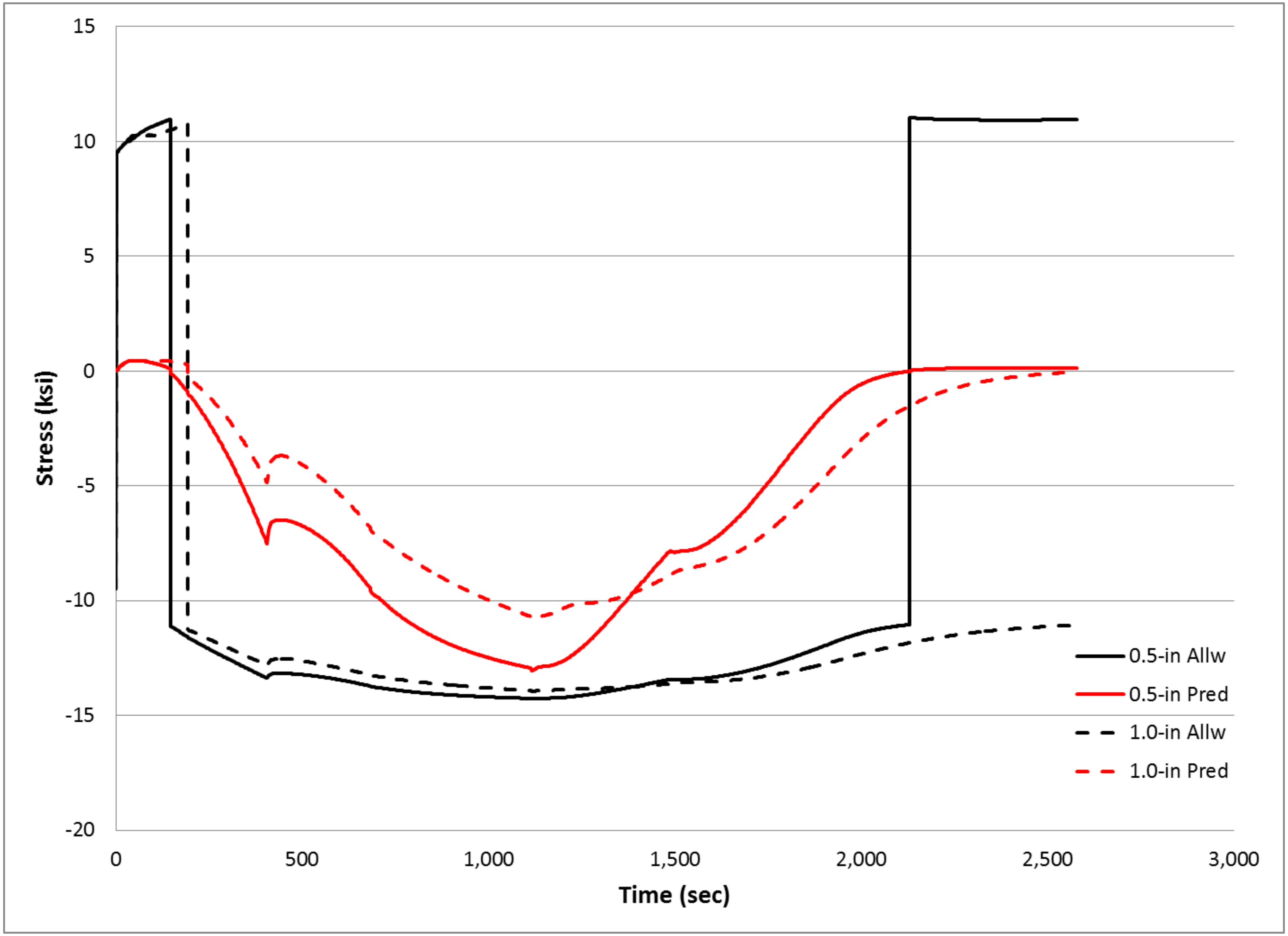
Thermocouple Time History



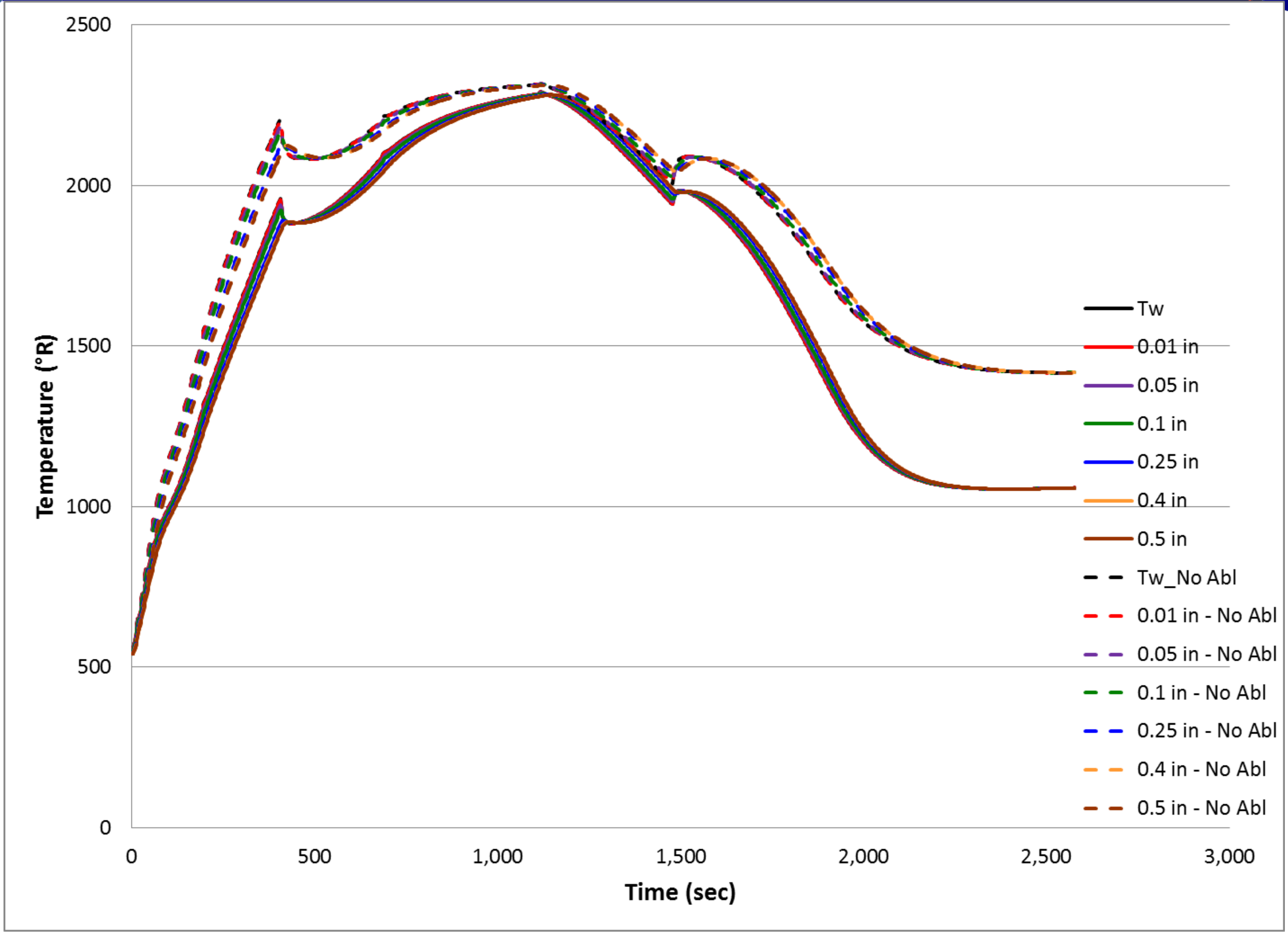
Thickness Comparison – Thermocouples



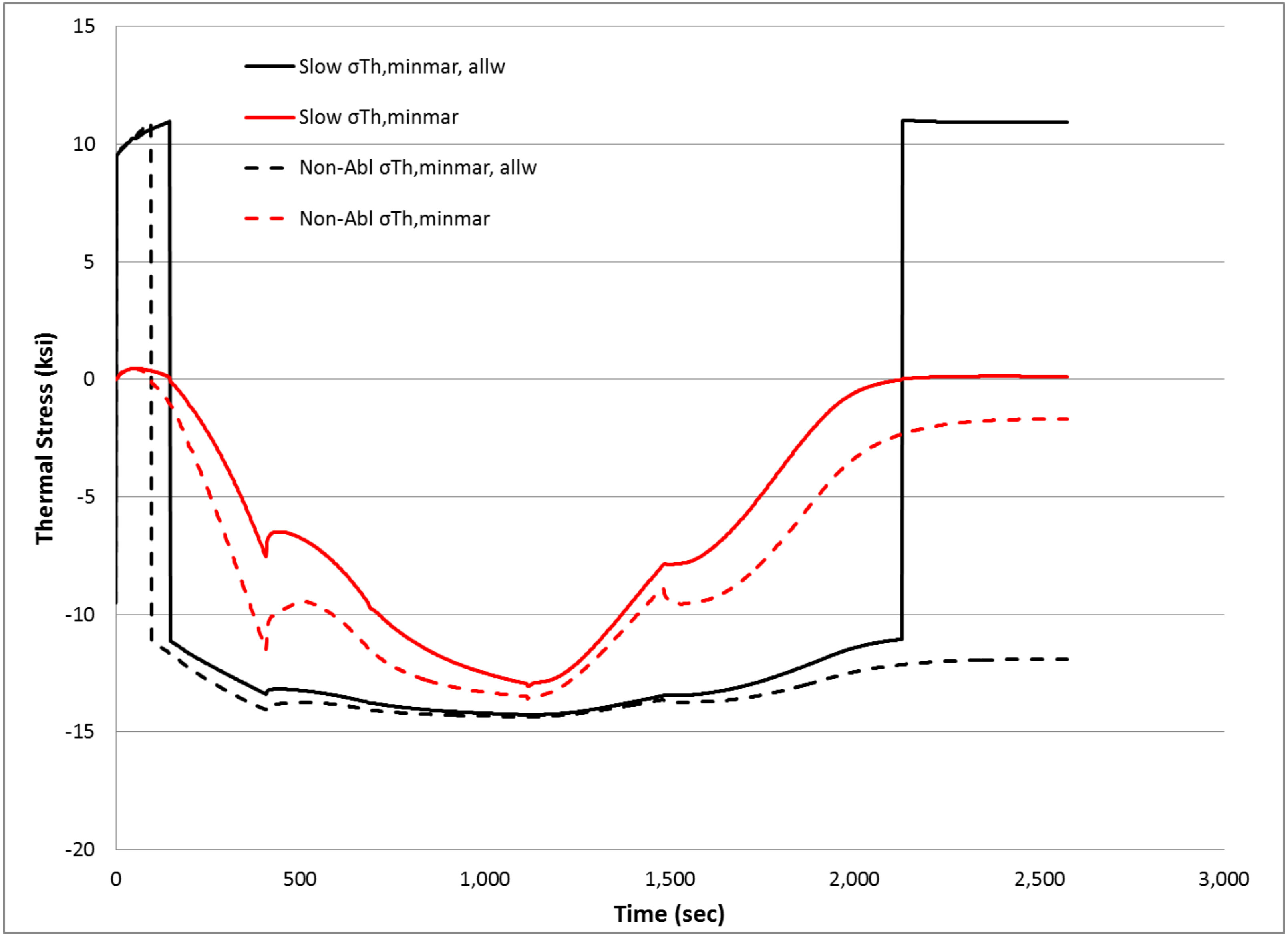
Thickness Comparison – Thermal Stress



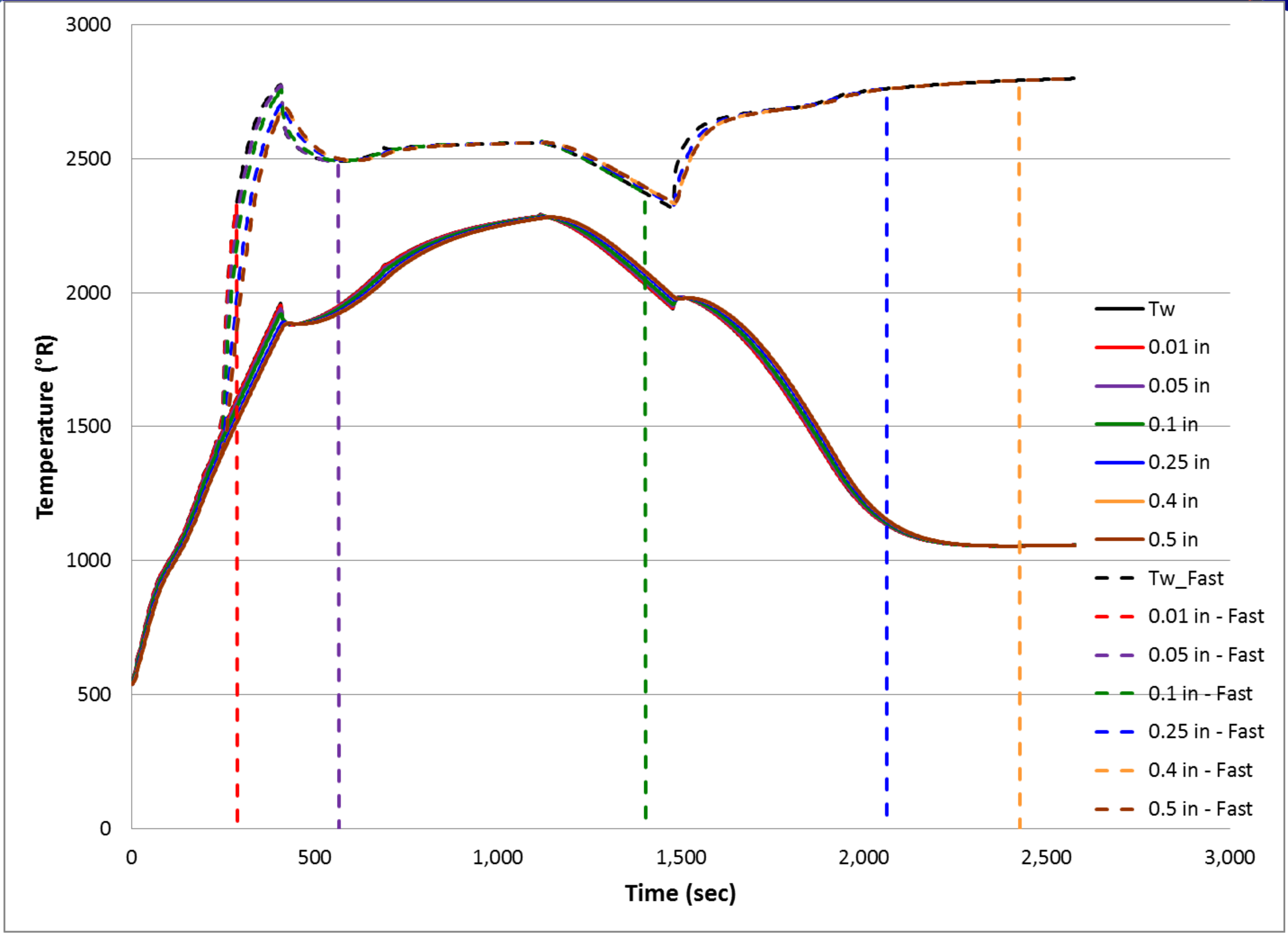
Ablation vs Non-ablating



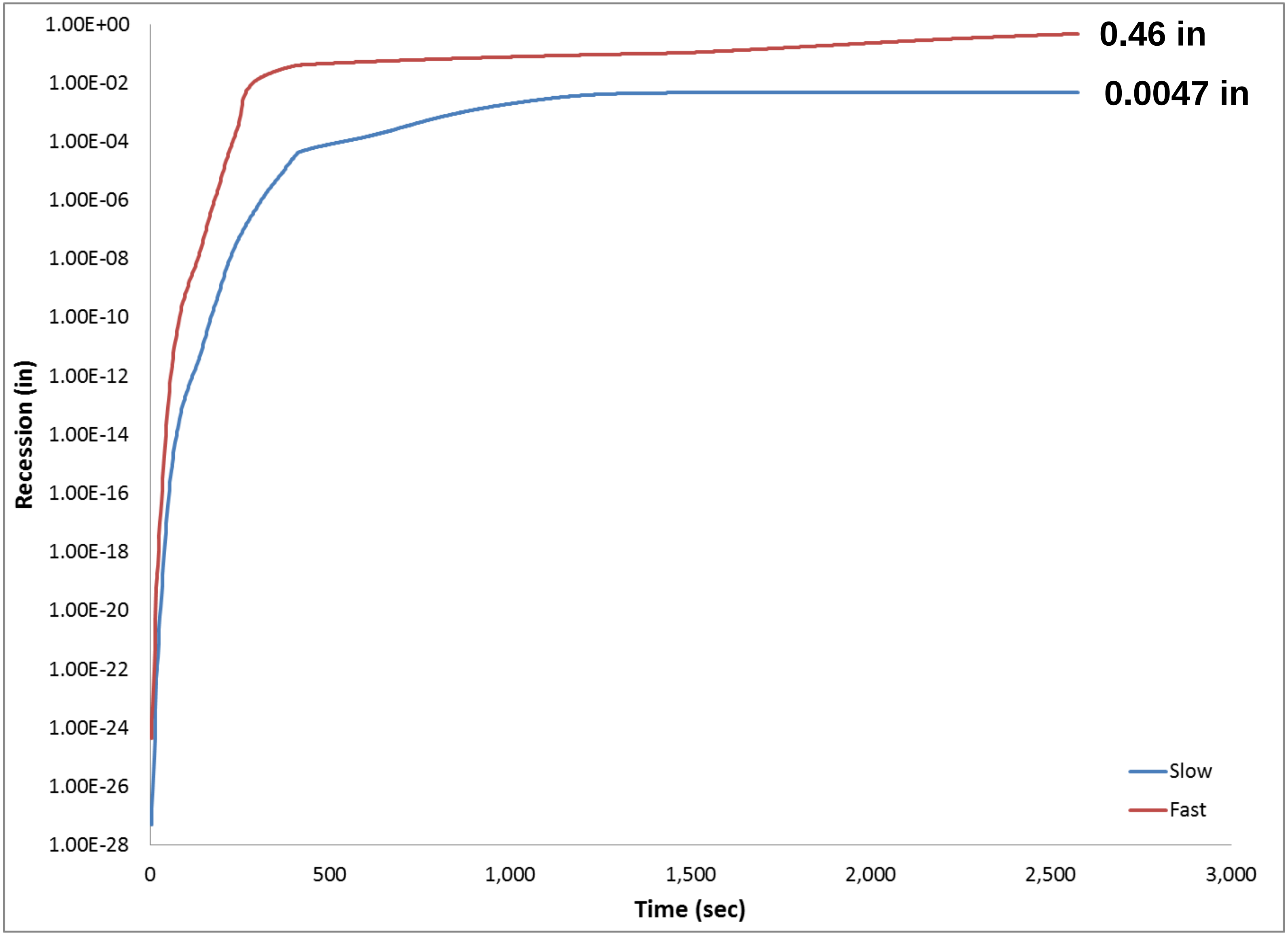
Ablation Impact on Thermal Stress



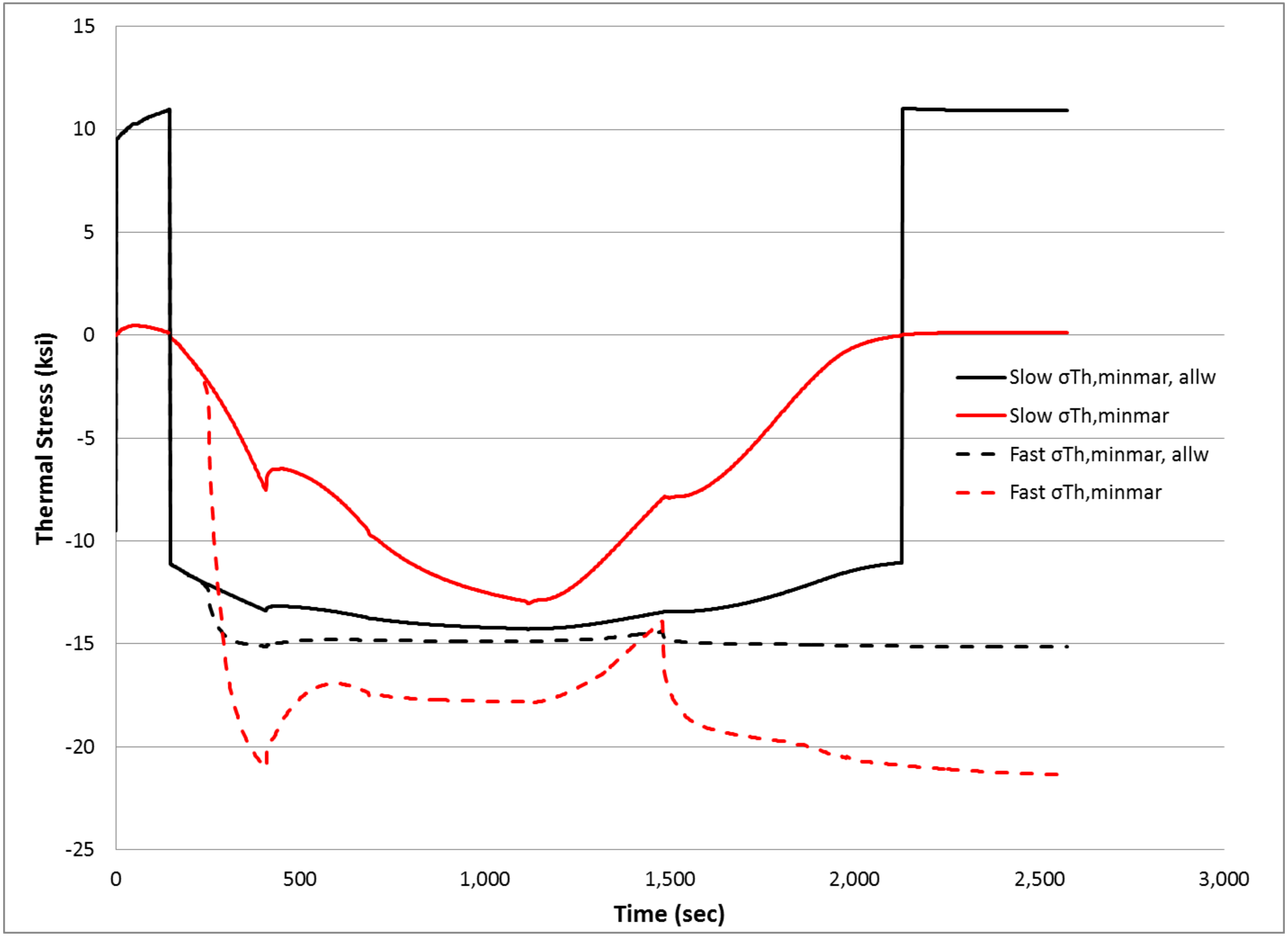
Slow vs Fast Scala Kinetics



Slow vs Fast Scala Kinetics Recession

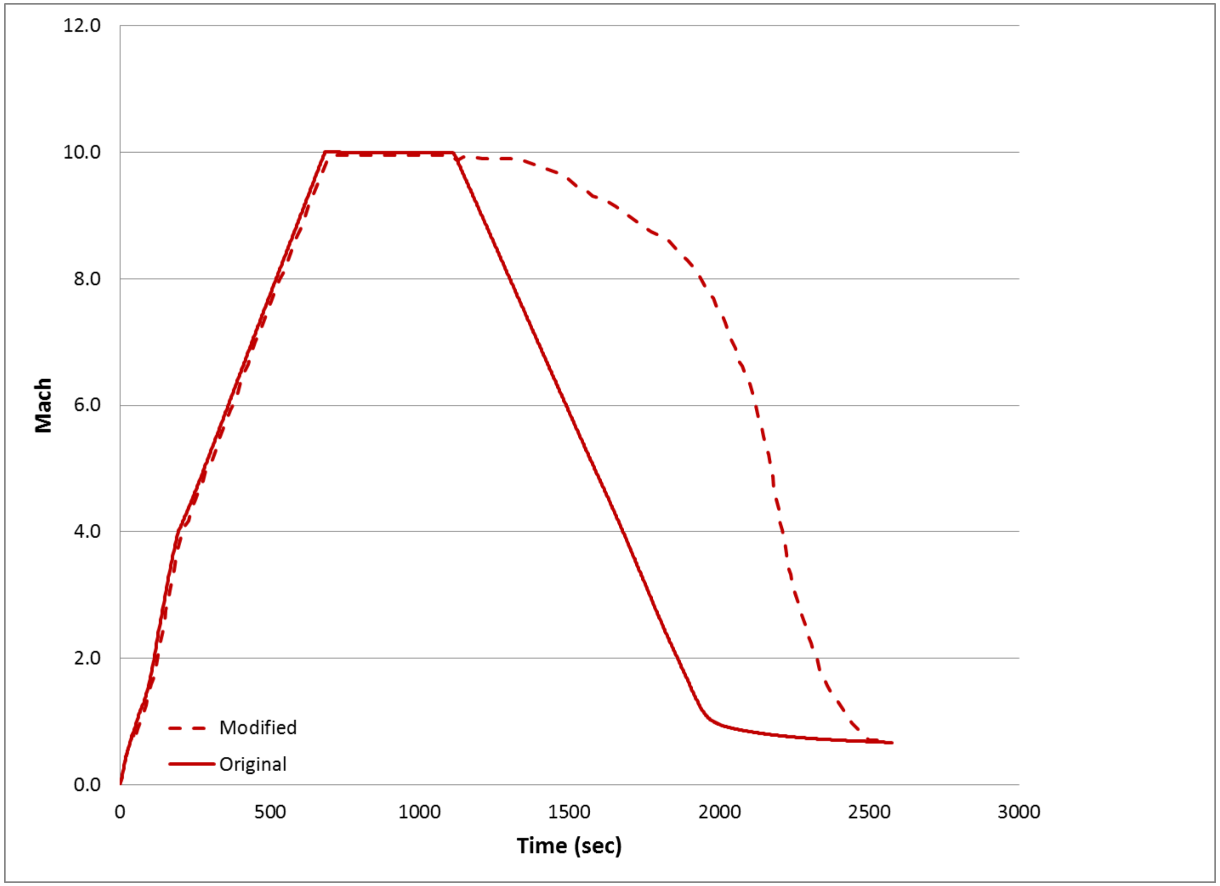


Slow vs Fast Scala Kinetics Impact on Predicted Thermal Stress

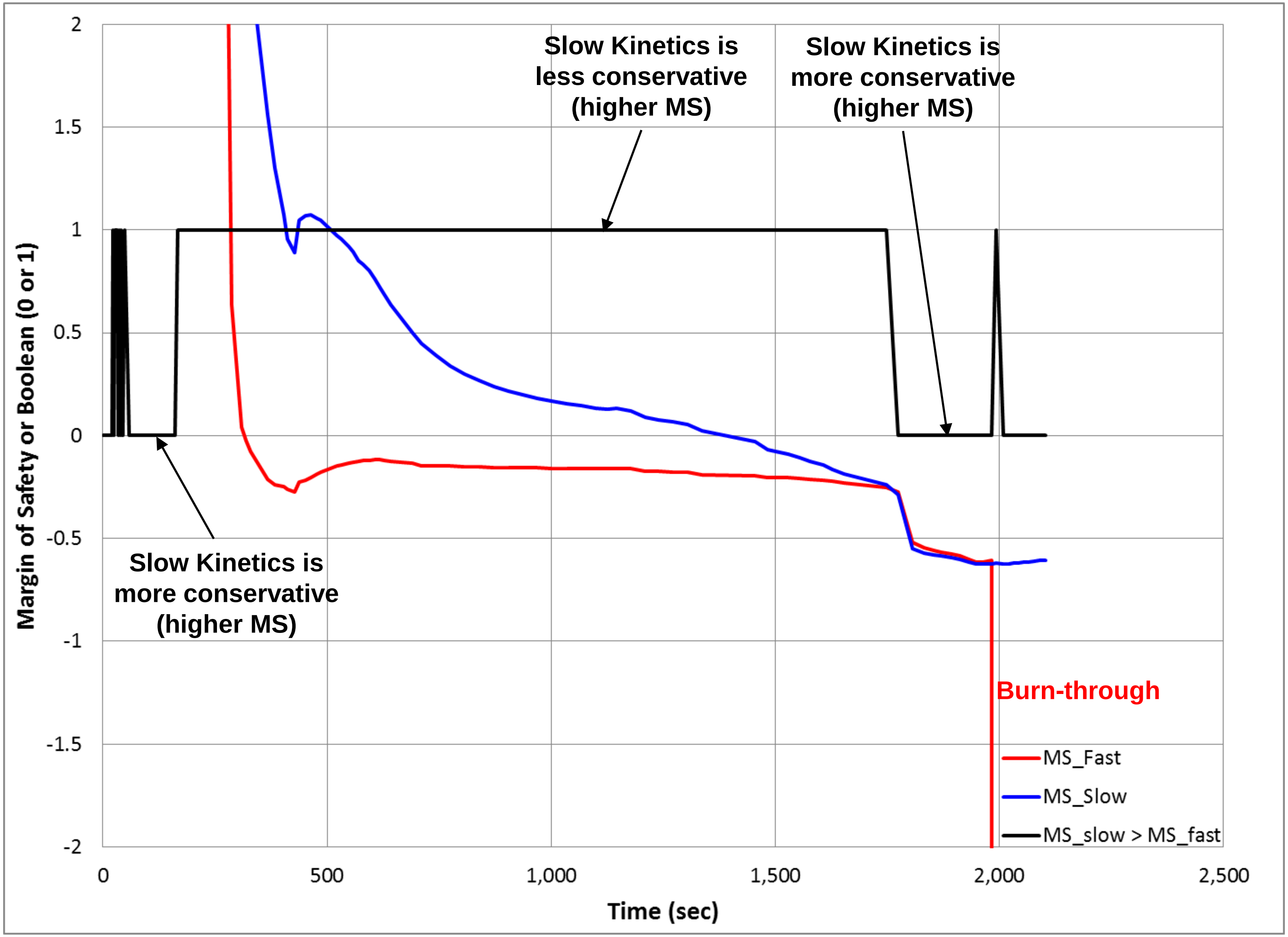


Sample Problem Modification

- 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



Slow Kinetics is less conservative (higher MS)

Slow Kinetics is more conservative (higher MS)

Slow Kinetics is more conservative (higher MS)

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

Back-up