Thermal Stress Analysis of TPS using Marc

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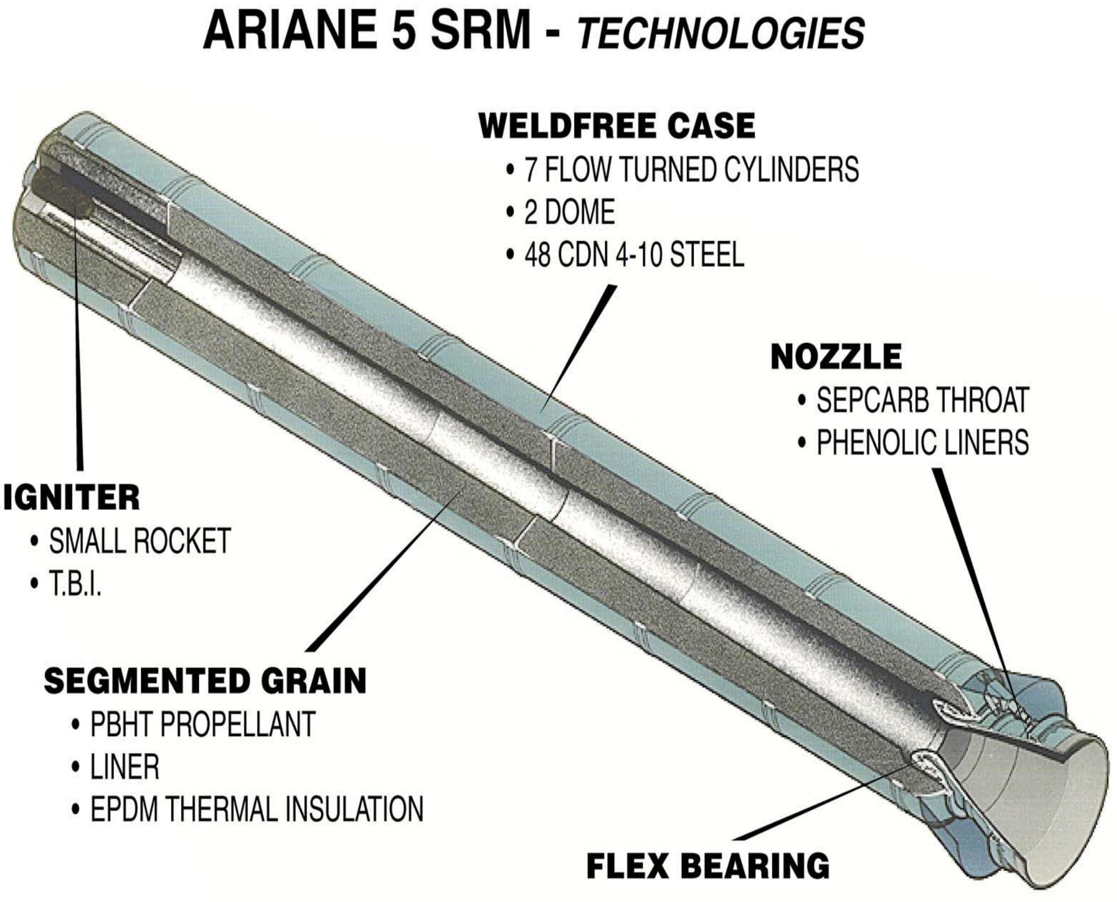
Overview

- Problem Statement
- Introduction of TPS Materials
- Thermal Modeling Methods
- Mechanical Simulation
- Material Models
- Contact
- Examples

Problem Statement



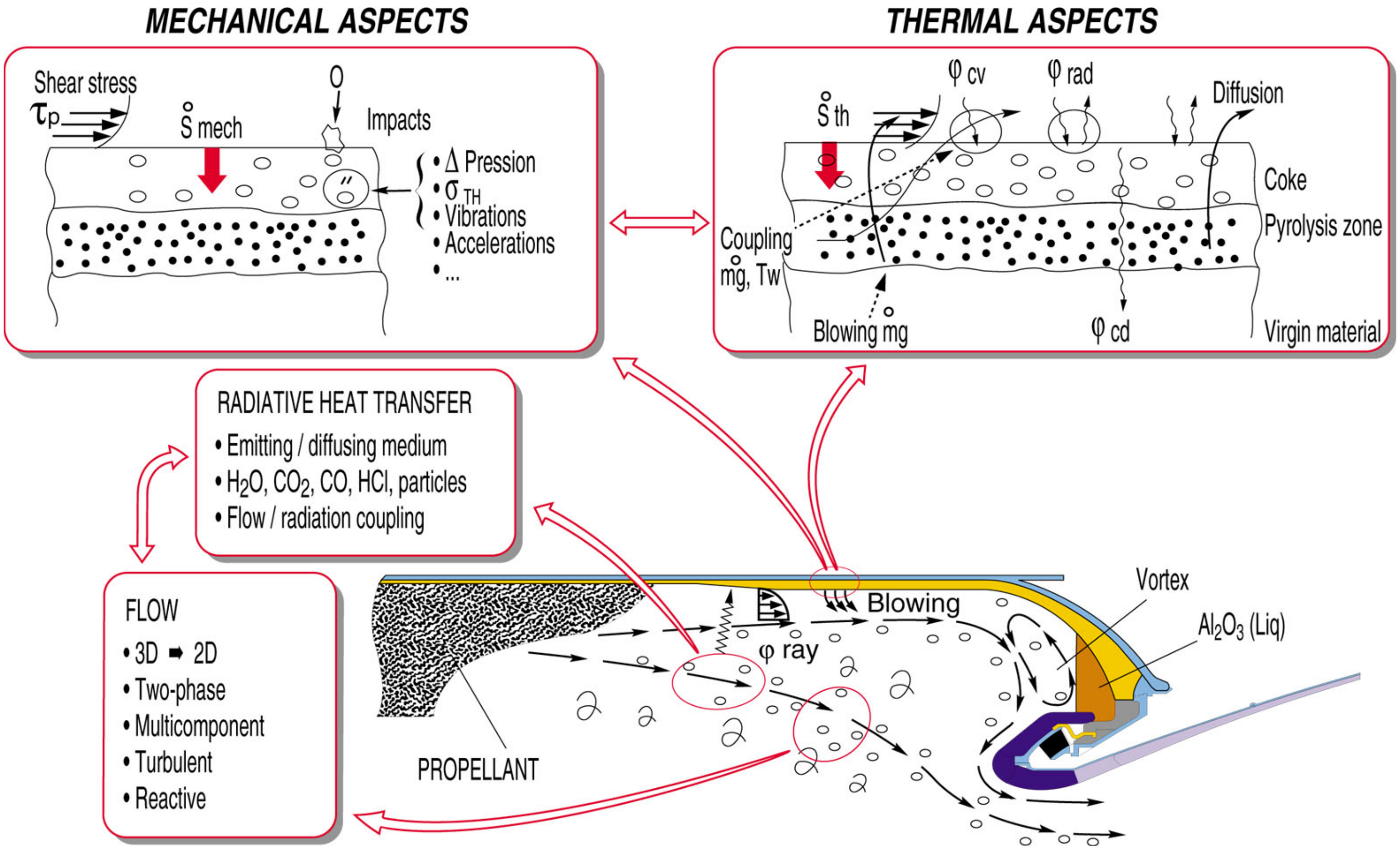
Problem Statement

- Extremely High Temperatures Achieved
- Extremely High Thermal Gradients
- Coefficient of Thermal Expansion Mismatch
- Stress Analysis Required
- Large Changes in Geometry
- Requirements for Coupled Analysis

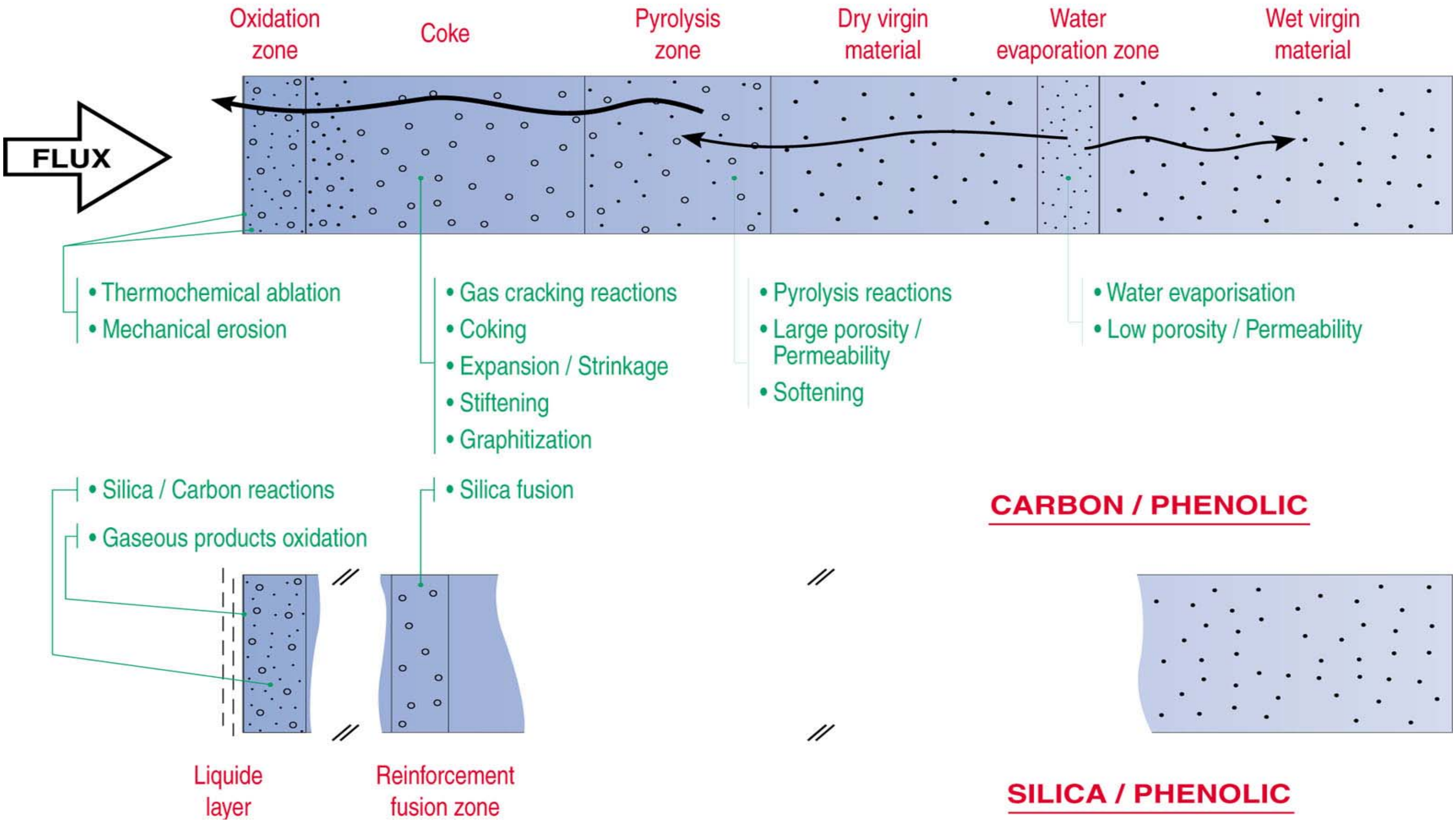
TPS Materials

- Carbon/Carbon
- Carbon/Phenolic
- Silica/Phenolic
- Ceramic Matrix composites
- Rubber and Reinforced Rubber
- Low Mass Thermal Insulators

Physics Overview

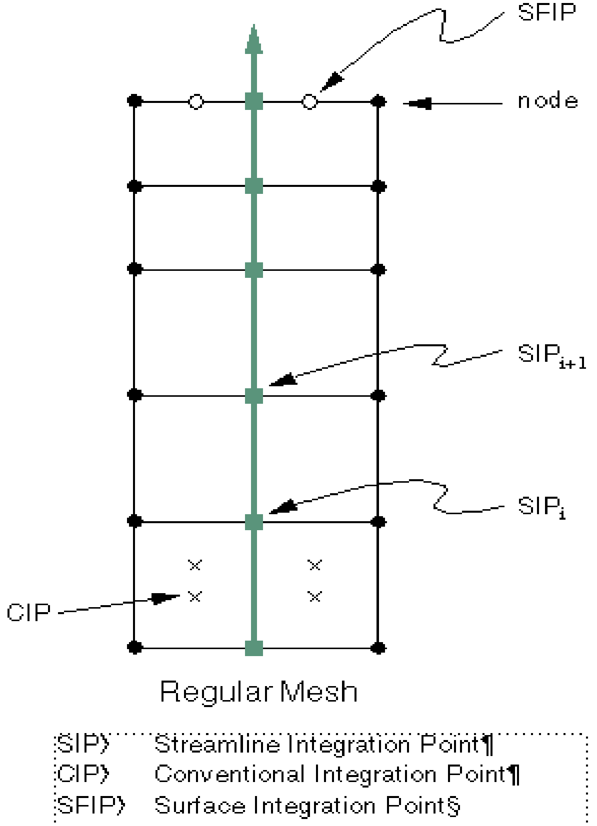


Thermo-Degradation Process



Thermal Modeling Methods

- Level 1 - One Dimensional Fluid Flow
- Level 2 - Three Dimensional Fluid Flow (Darcy Law)



Advanced Material Model

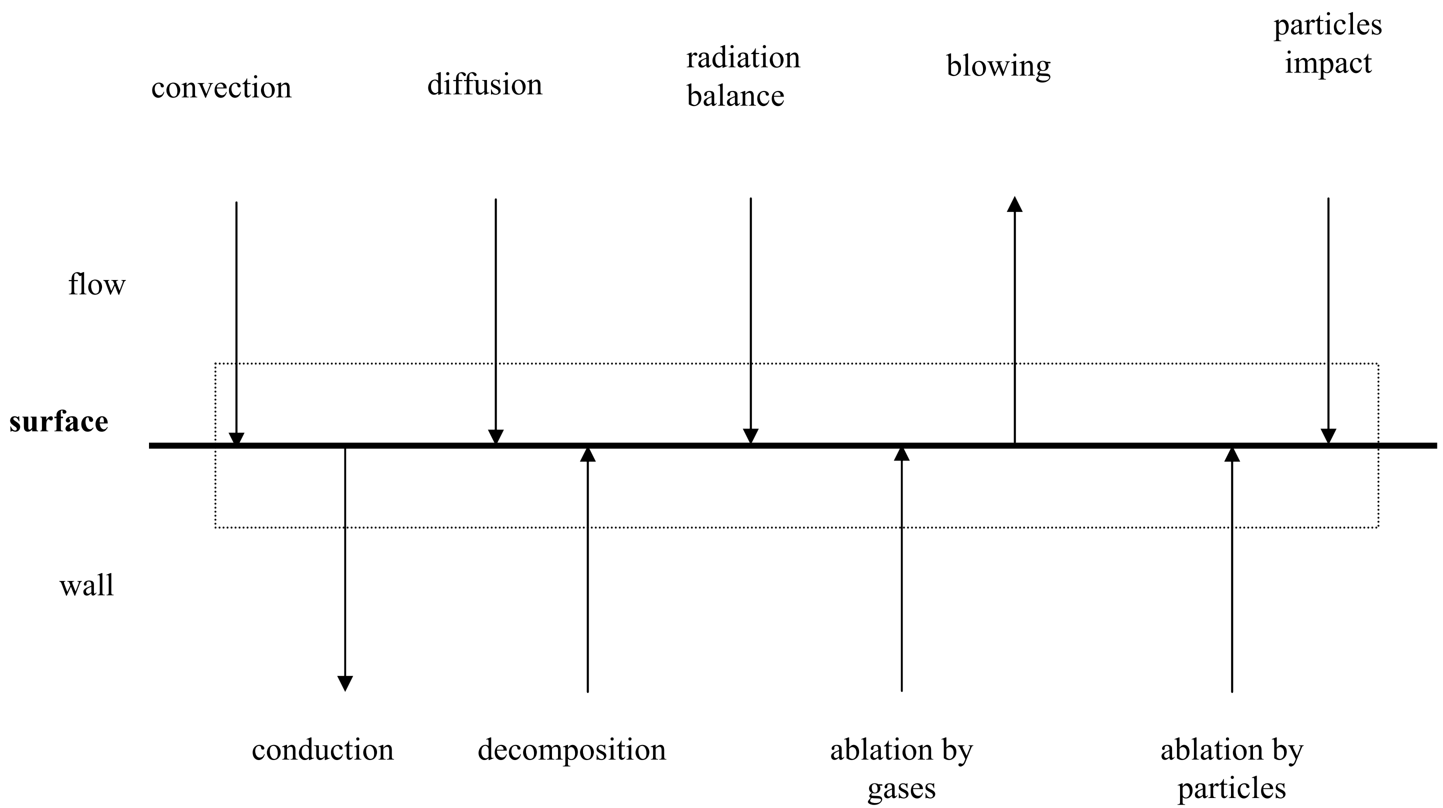
- Pyrolysis of Material
  - Mass Density Controlled by Arrhenius Law
  - Thermal Properties Change based upon a Kachanov Model between Virgin and Charred State
  - Energy absorption and internal convection
- Water Vapor Creation
- Coking
  - Carbon comes out of the Pyrolysis Gases and Deposits onto the Solid

Arrhenius Law for φ_j

- Dimensionless variable φ_j that goes from 1 to 0 during pyrolysis : calculated by Arrhenius law:

$$\frac{\partial \varphi_j}{\partial t} = -B_j \exp\left(\frac{-T_{a,j}}{T_s}\right)\varphi_j$$

Surface Energy Balance



Ablation

- Thermochemical Ablation (Gases, Particles)

$$\dot{S}_{th} = [\dot{m}_{s,th,g} + \dot{m}_{s,th,p}] / \hat{\rho}_s$$

- Mechanical Erosion
  - Due to impacts of particles
  - Due to other actions such as the shear stress of the flow and vibration of the part

Energy Equation

$$\left(\hat{\rho}_{s,i^*} c_{pi} + \hat{\rho}_{s,p^*} \overline{c}_{s,p^*}\right) \frac{\partial T}{\partial t} + c_{pg} \dot{m}_g . \nabla T =$$

$$\nabla . \left(\lambda^* \nabla T\right) + \frac{\partial \hat{\rho}_{s,p^*}}{\partial t} \left(H_{g,p} - \overline{H}_{s,p,vc}\right)$$

Mechanical Simulation

- Uncoupled Mechanical Analysis
  - Perform Thermo-Pore Simulation
  - Move Temperatures into Structural Analysis
  - Problems with Geometry
- Coupled Mechanical Analysis
  - Solver Thermo-Pore-Mechanical in Staggard Manner

Thermal-Mechanical Coupled Analysis

- Mechanical Dependence on Thermal Analysis
  - Temperature Dependent Structural Properties
  - Thermal Strains
  - Geometry Changes due to Ablation
- Thermal Dependence on Structural Analysis
  - Geometric Changes Influence Boundary Conditions
  - Contact
  - Heat Generated due to Inelastic Behavior
- Diffusion Dependence on Structural Analysis
  - Porosity dependent upon strain

Structural Material Models

- Linear Elastic
- Elastic-Plastic
  - Von Mises or Hill yield
  - Mohr – Coulomb
  - Cam Clay
  - Isotropic, Kinematic, Combined, Power Law, Kumar, Johnson-Cook Hardening Models
  - Powder Model
- Shape Memory
- Rubber Models
  - Mooney-Rivlin
  - Ogden
  - Arruda-Boyce
  - Gent
  - Foam

Structural Material Models

- Nonlinear Elasticity – Hyperelastic
- Gurson or User Defined Damage Model
- Chaboche
- Composites
  - Layered Shells – Note Ablation is not allowed on a Shell
  - Brick
  - Solid Shell
  - Failure Criteria – Progressive Failure
    - Maximum Stress or Strain
    - Tsai-Wu
    - Hoffman
    - Hill
    - Puck
    - Hashin

Structural Material Models

- Mixture Models
- Fixed Volume Fraction
  - Elastic
  - Elastic-Plastic
  - Simplified nonlinear elastic
- Variable Fraction
  - Phase transformations – future
  - Pyrolysis

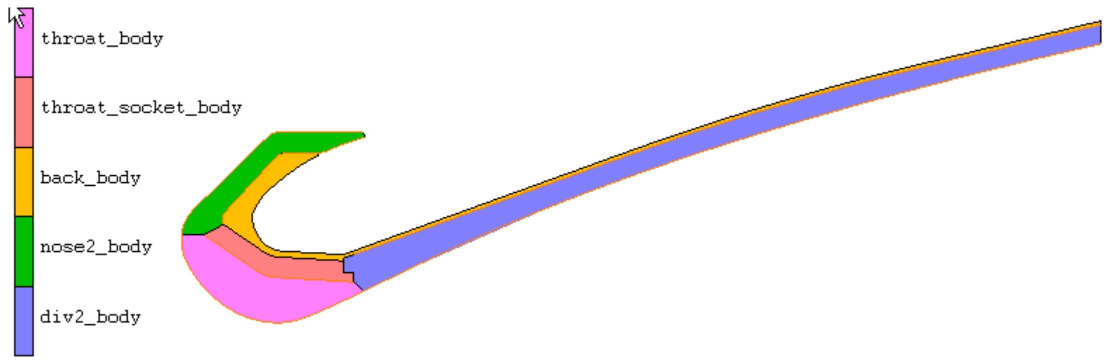
Structural Material Properties

- Pyrolysis
- Elastic Properties, Coefficient of thermal expansion
- $E^*(T)=(1-\xi_p)\,E_v\,(T)+\xi_p(1-\xi_c)E_c\,(T)+\xi_p\xi_c E_{ck}\,(T)$

- Combine the virgin properties, charred properties and coked properties
- For nonlinear Elasticity will use
- $\mathbf{D}^*=(1-\xi_p)\,\mathbf{D}_v\,(T)+\xi_p(1-\xi_c)\mathbf{D}_c\,(T)+\xi_p\xi_c\mathbf{D}_{\mathbf{ck}}\,(T)$
- Where D is the tangent stress-strain law $\Delta\sigma=\mathbf{D}\Delta\varepsilon$

Contact

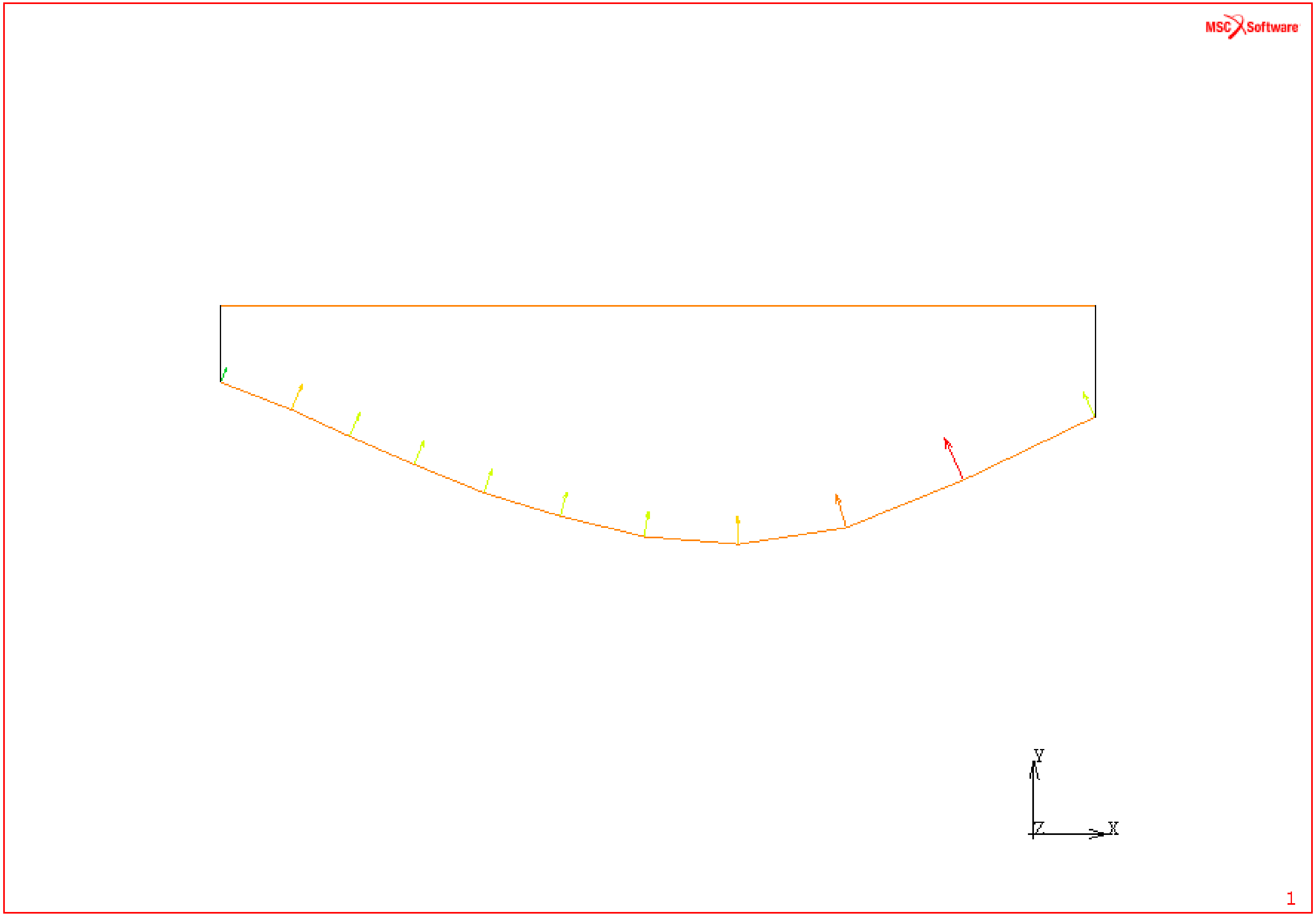
- Mechanical
  - No Penetration
  - Separation
  - Friction



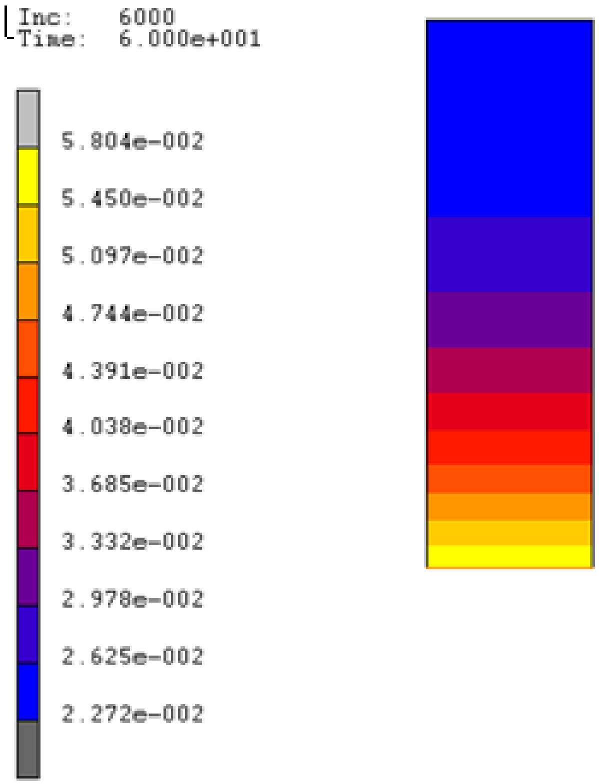
- Thermal
  - True Contact – User defined thermal contact coef.
  - Near Contact
  - To Environment
- Diffusion
- Contact Table
- Easy to use

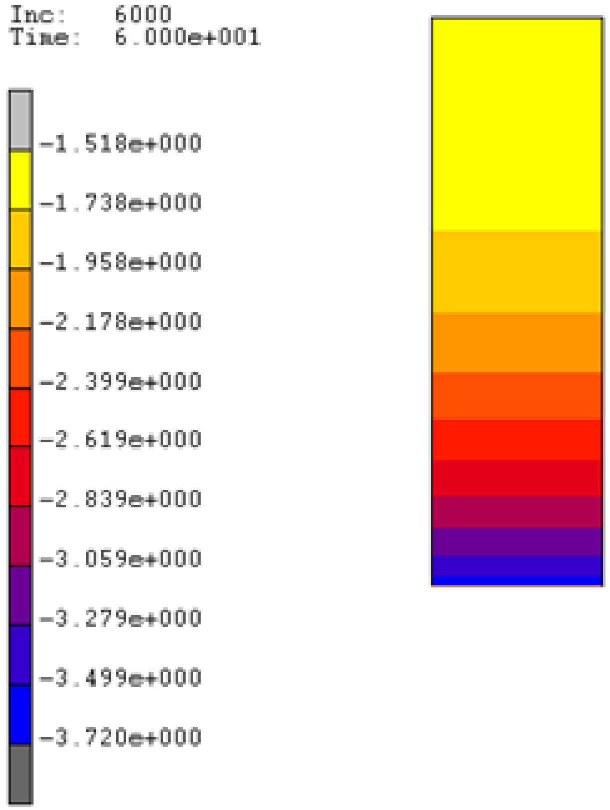
$$Q = h_{cv}*(T_2-T_1)+h_{nt}*(T_2-T_1)^{nt} + \sigma*\varepsilon*(T_2^4-T_1^4) + (h_{ct} - (h_{ct}-h_{bl})*gap/dqnear)*(T_2-T_1)$$

Follower Force Effects



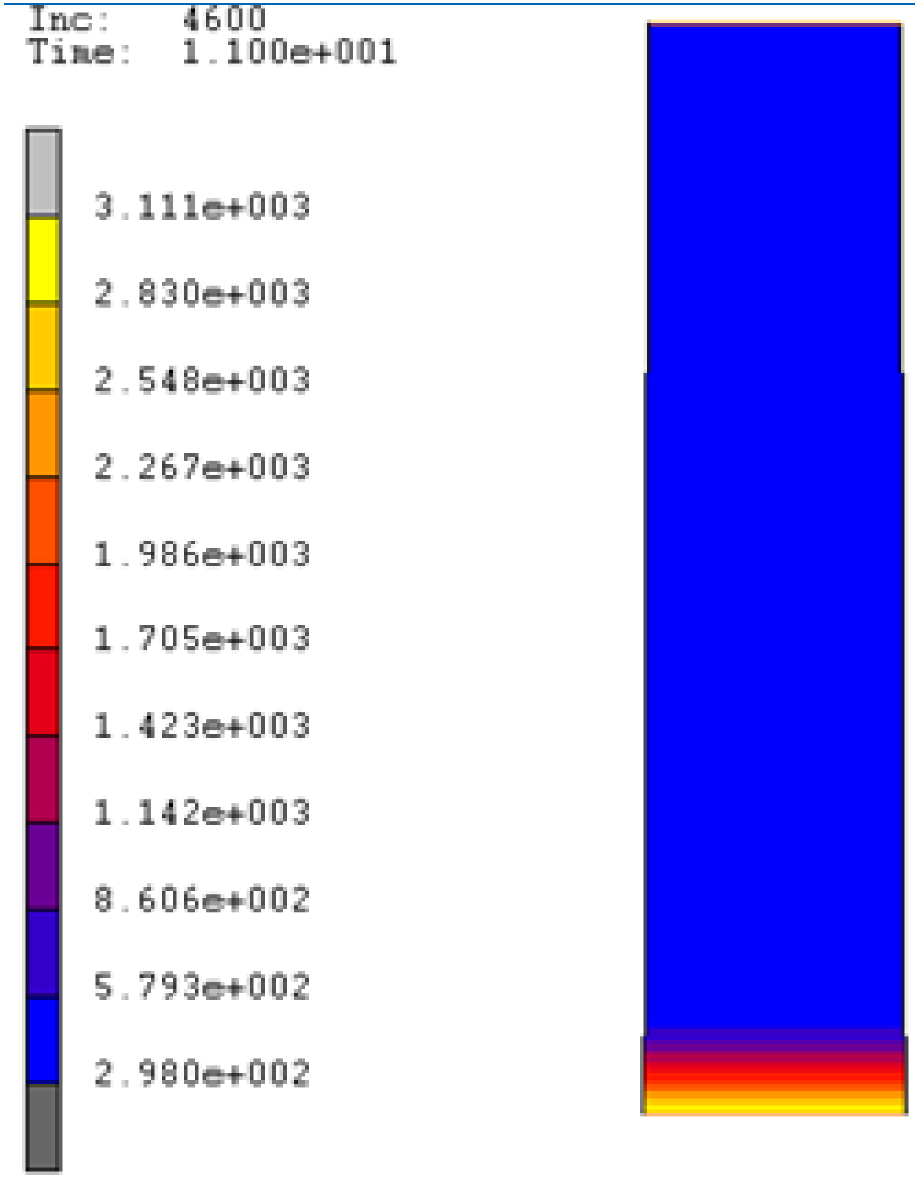
1-D Ablation and Thermal Strains



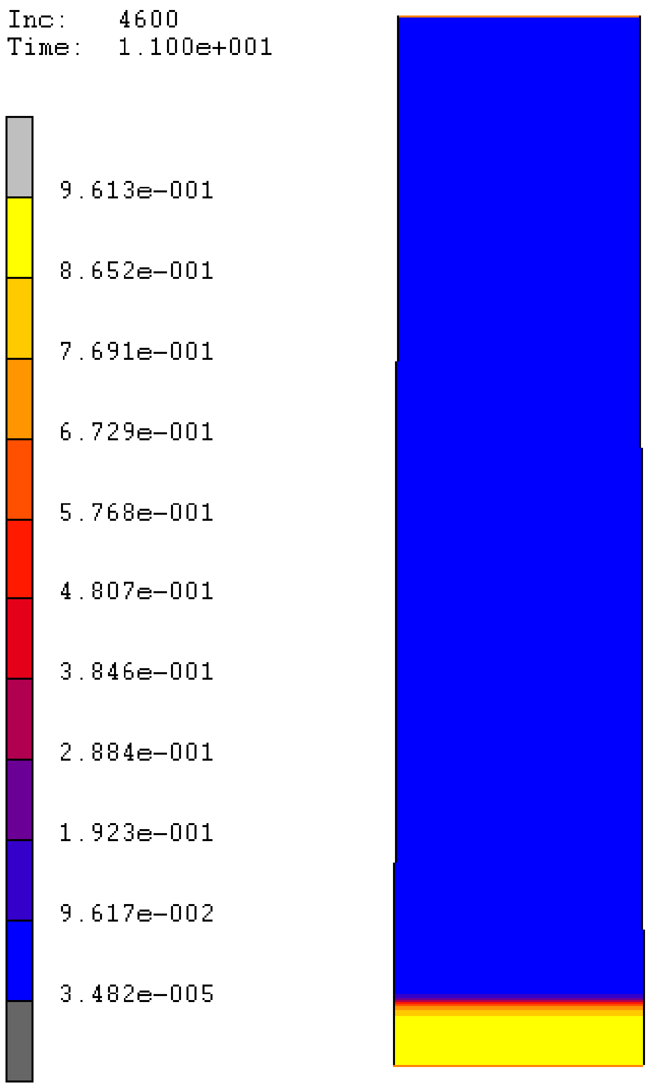


Max Thermal Strain
<6%

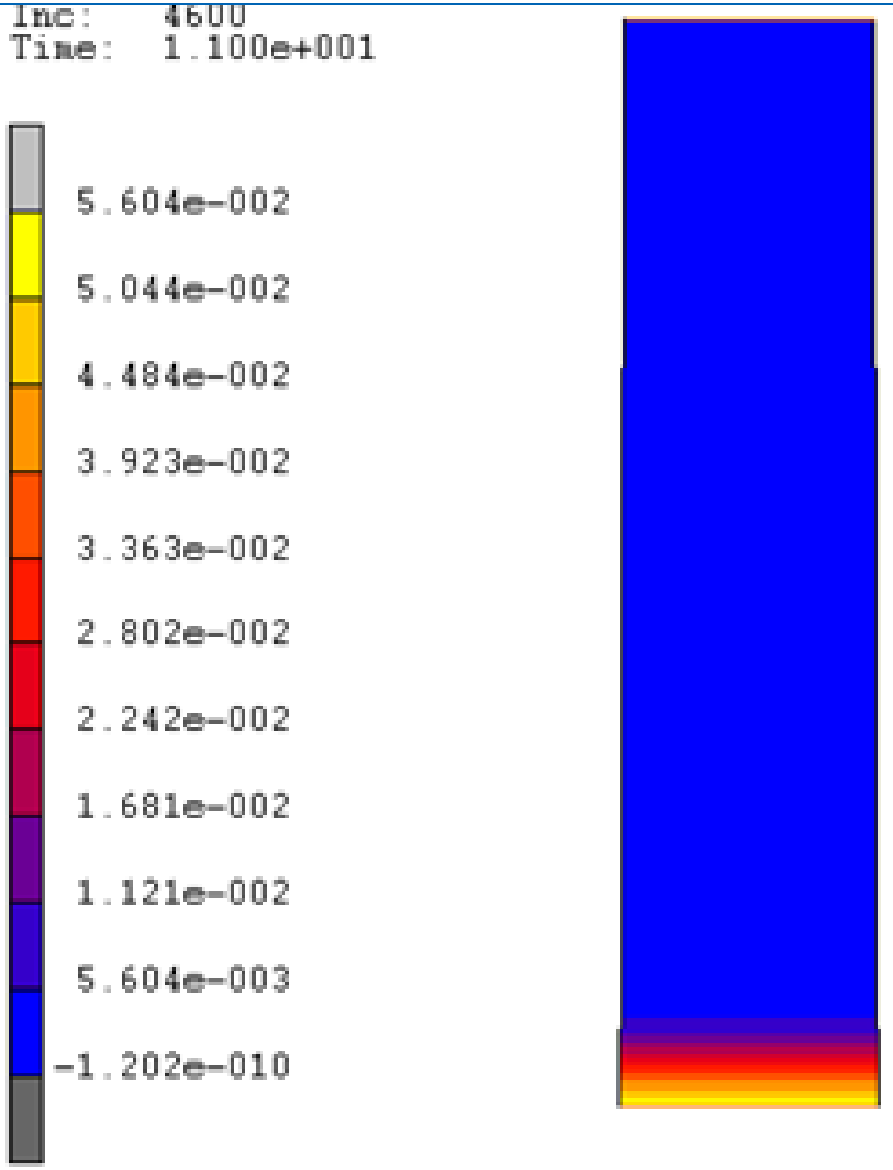
1-D Ablation and Pyrolysis - Temperature



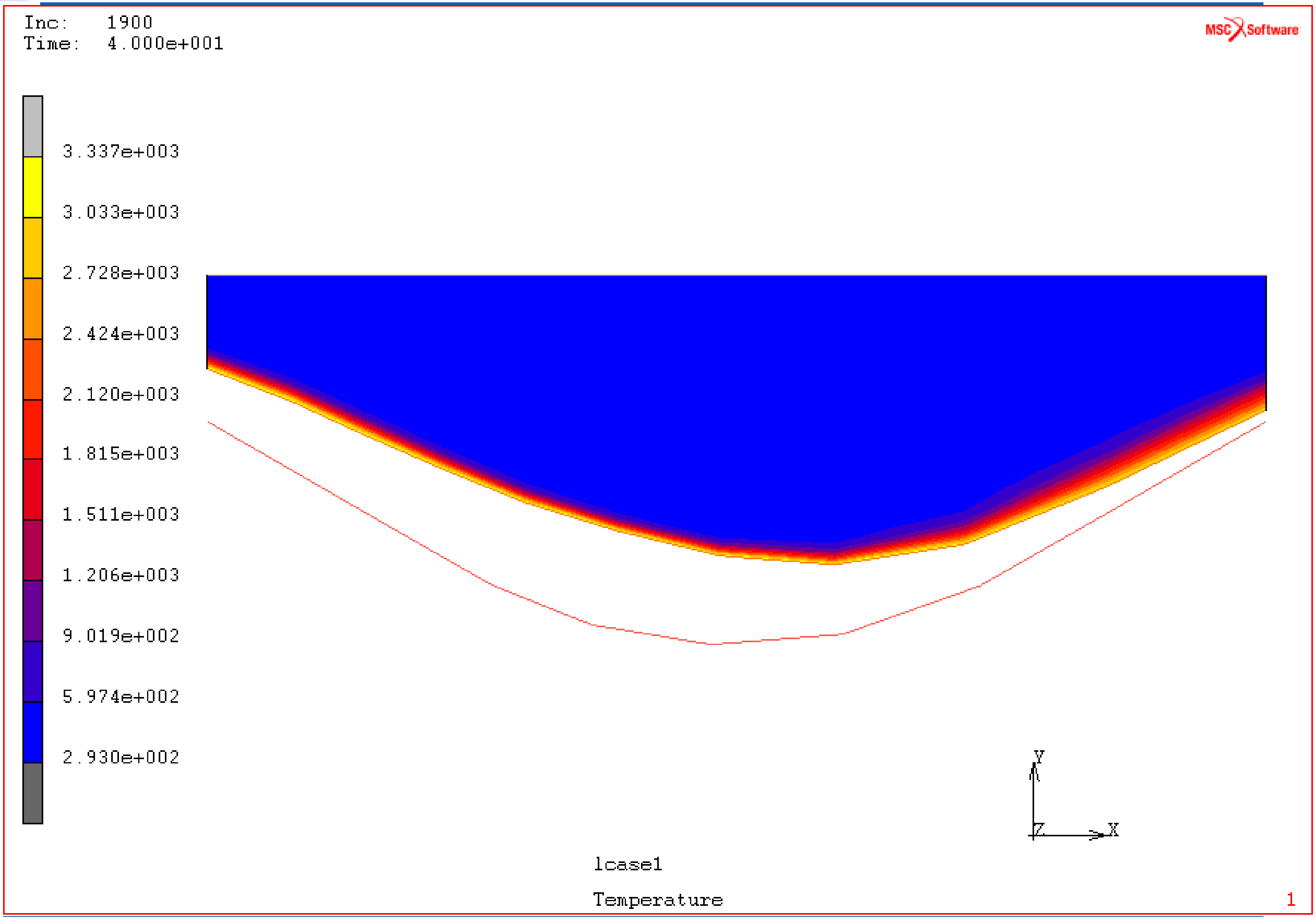
1-D Ablation and Pyrolysis – Char Fraction



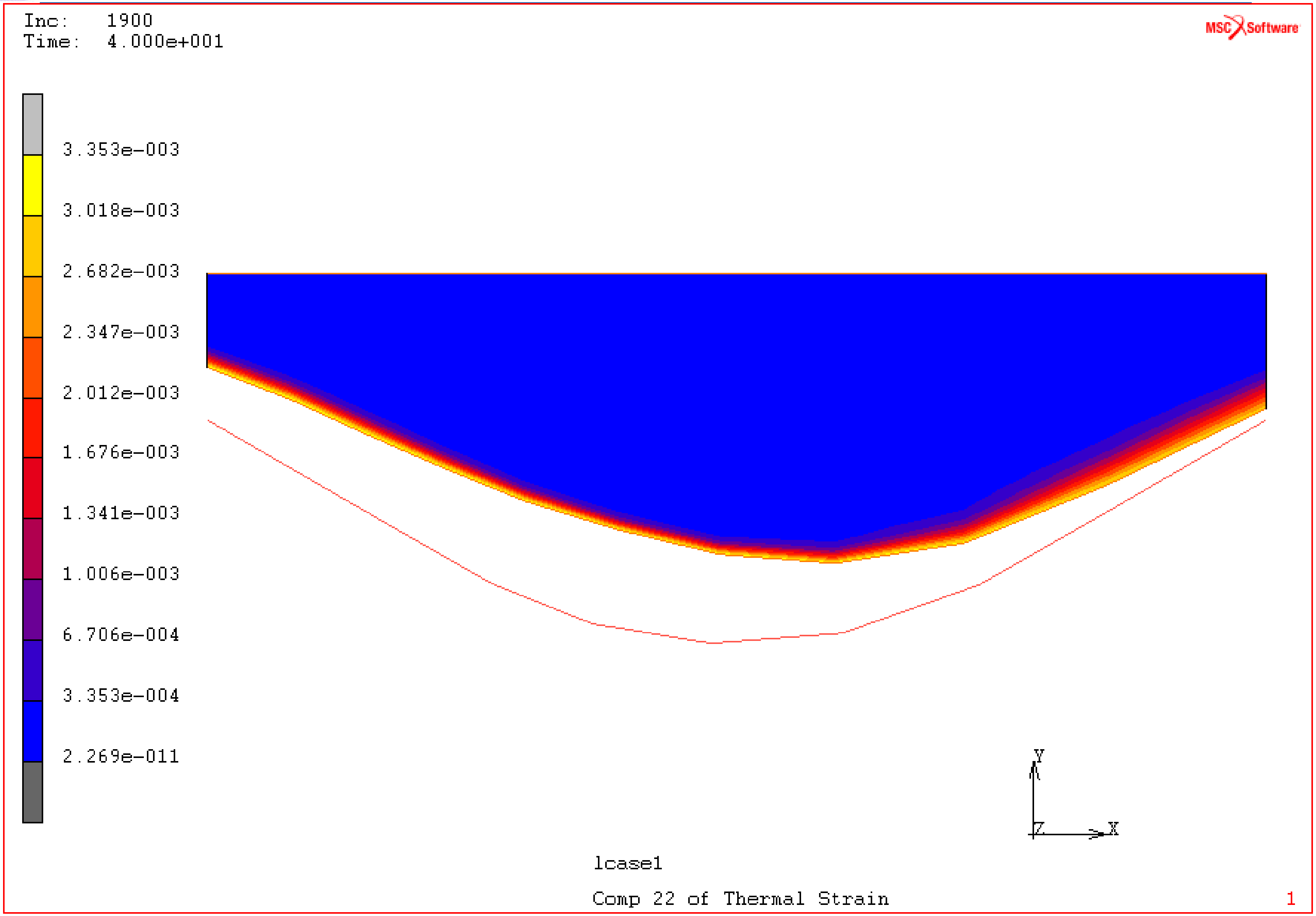
1-D Ablation and Pyrolysis – Thermal Strain



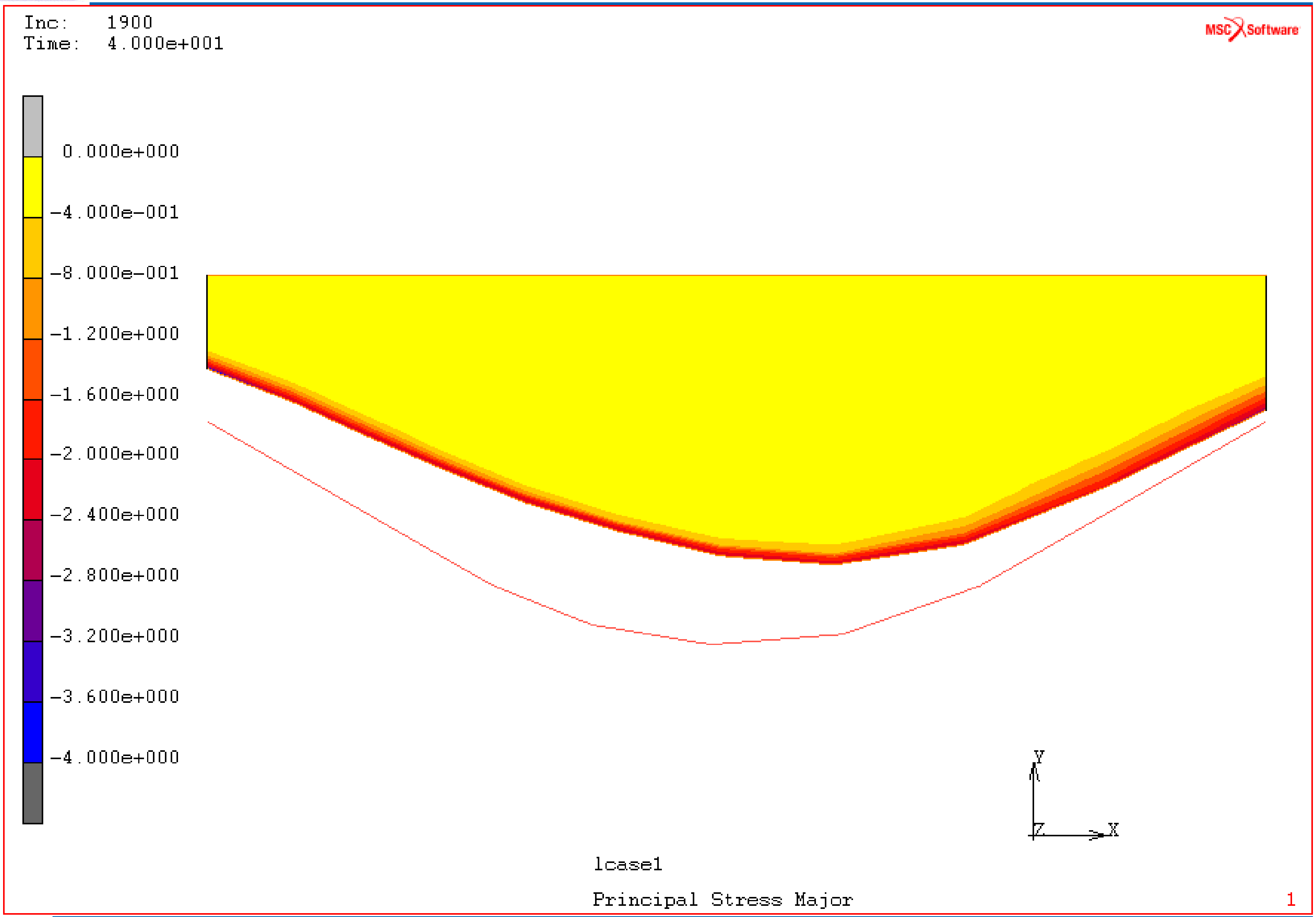
Simplified Throat Section- Temperatures



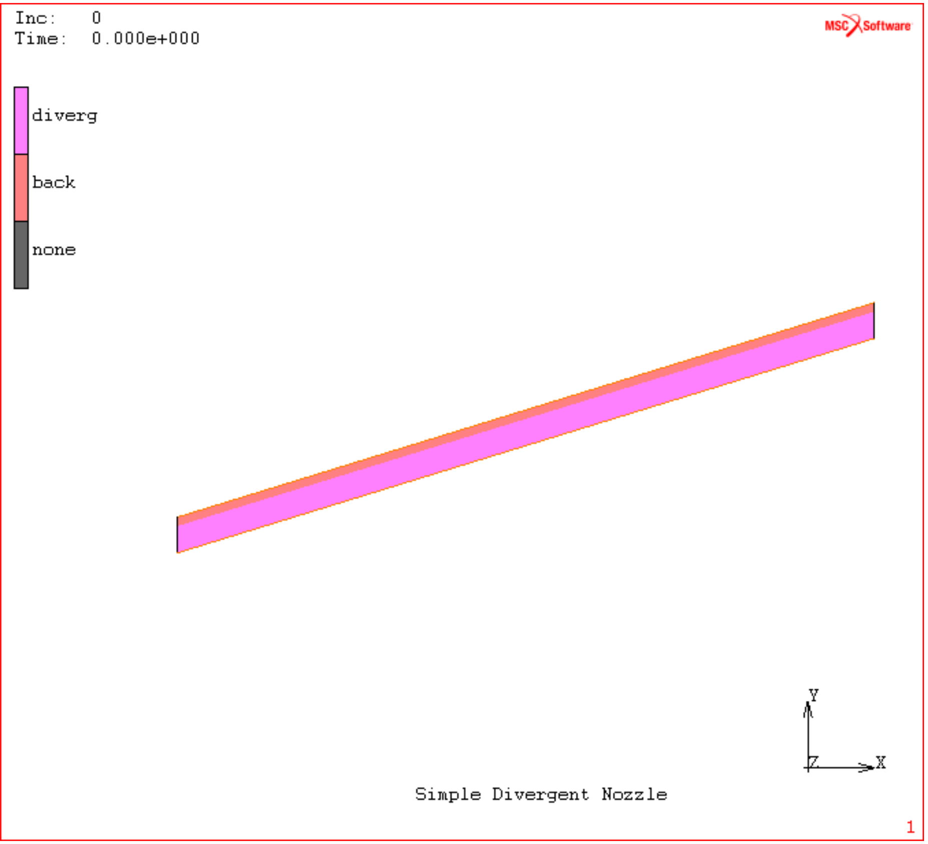
Simplified Throat Section – Thermal Strain

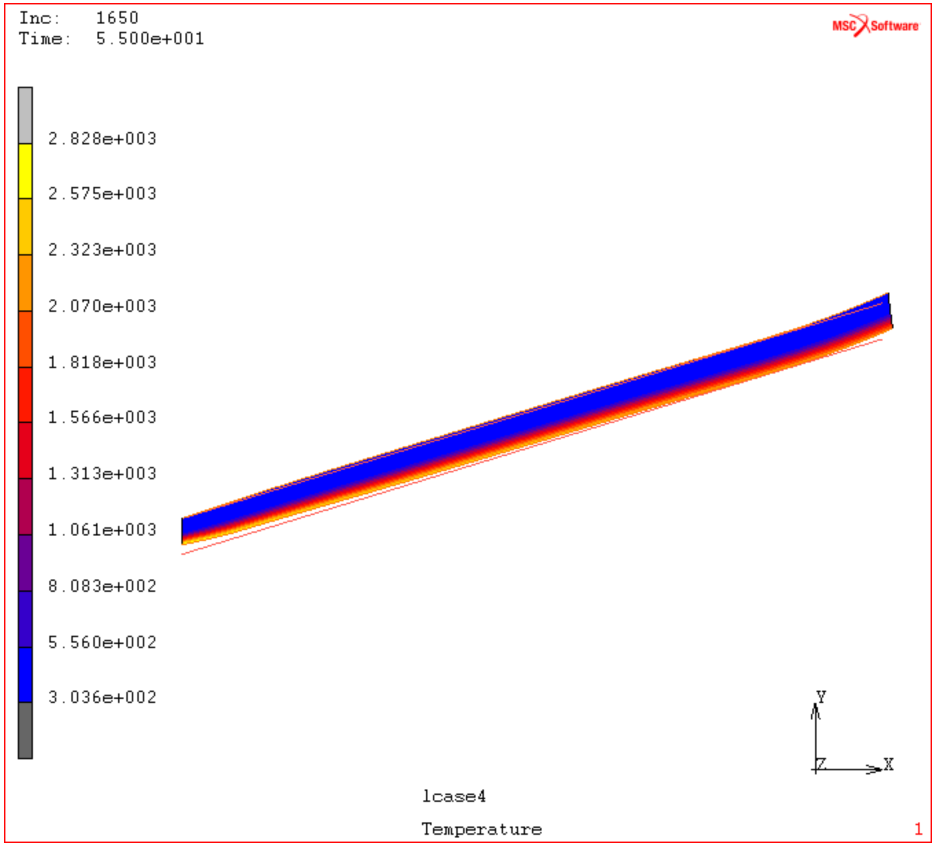


Simplified Throat Section – Stress



Simplified Exit Nozzle – 1-D





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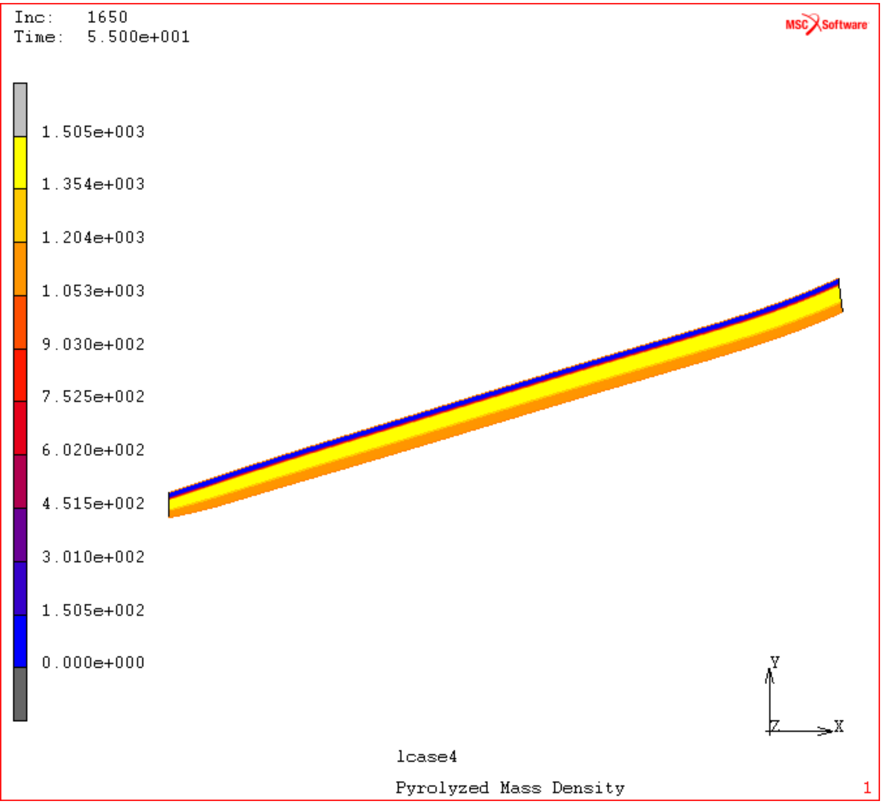

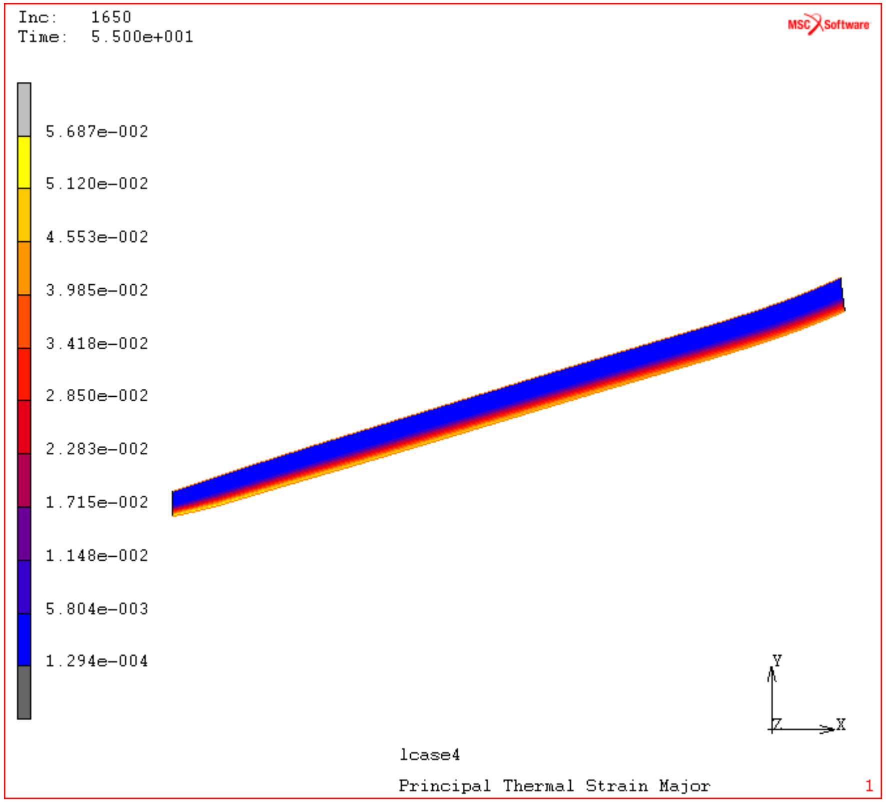

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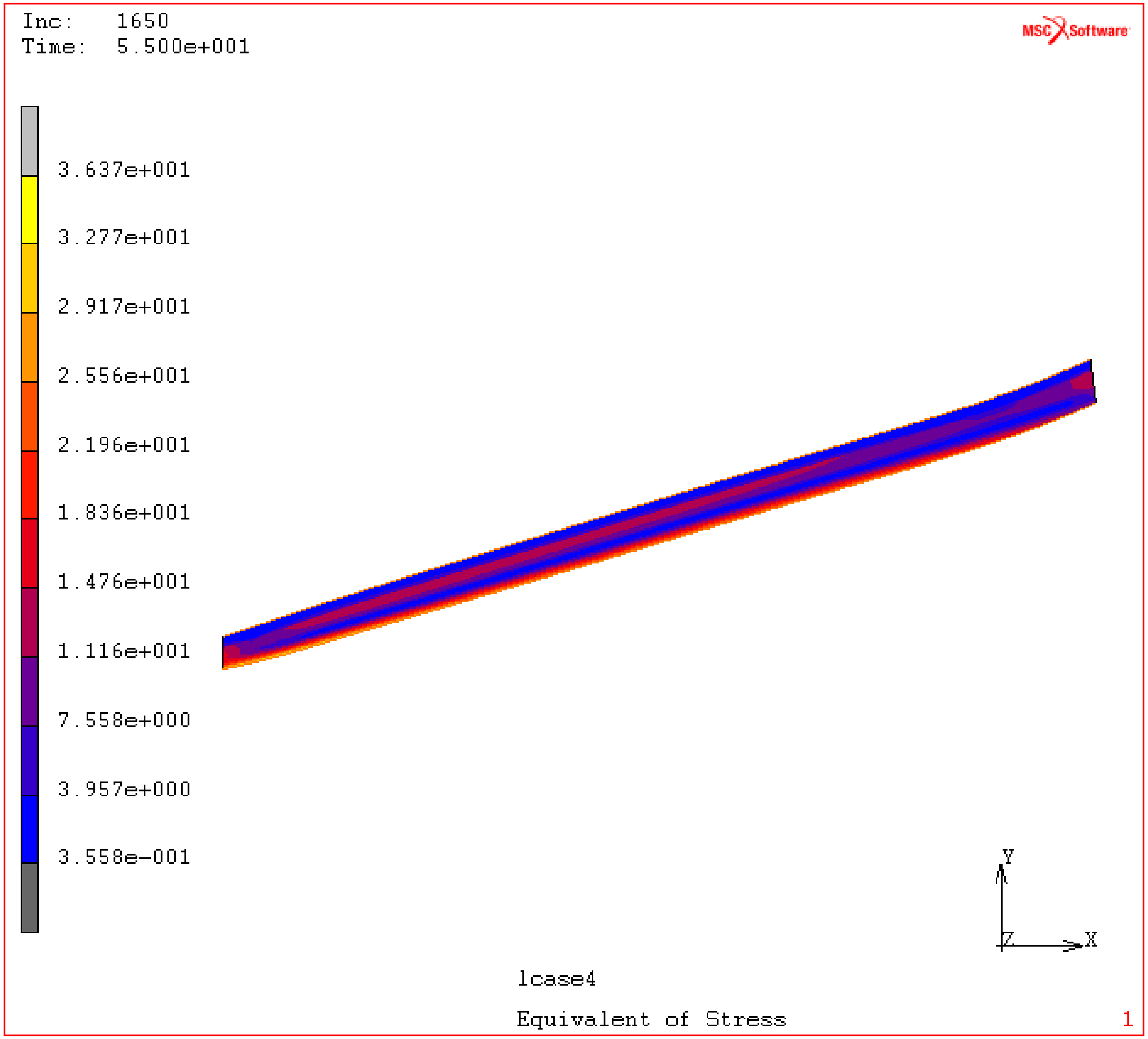
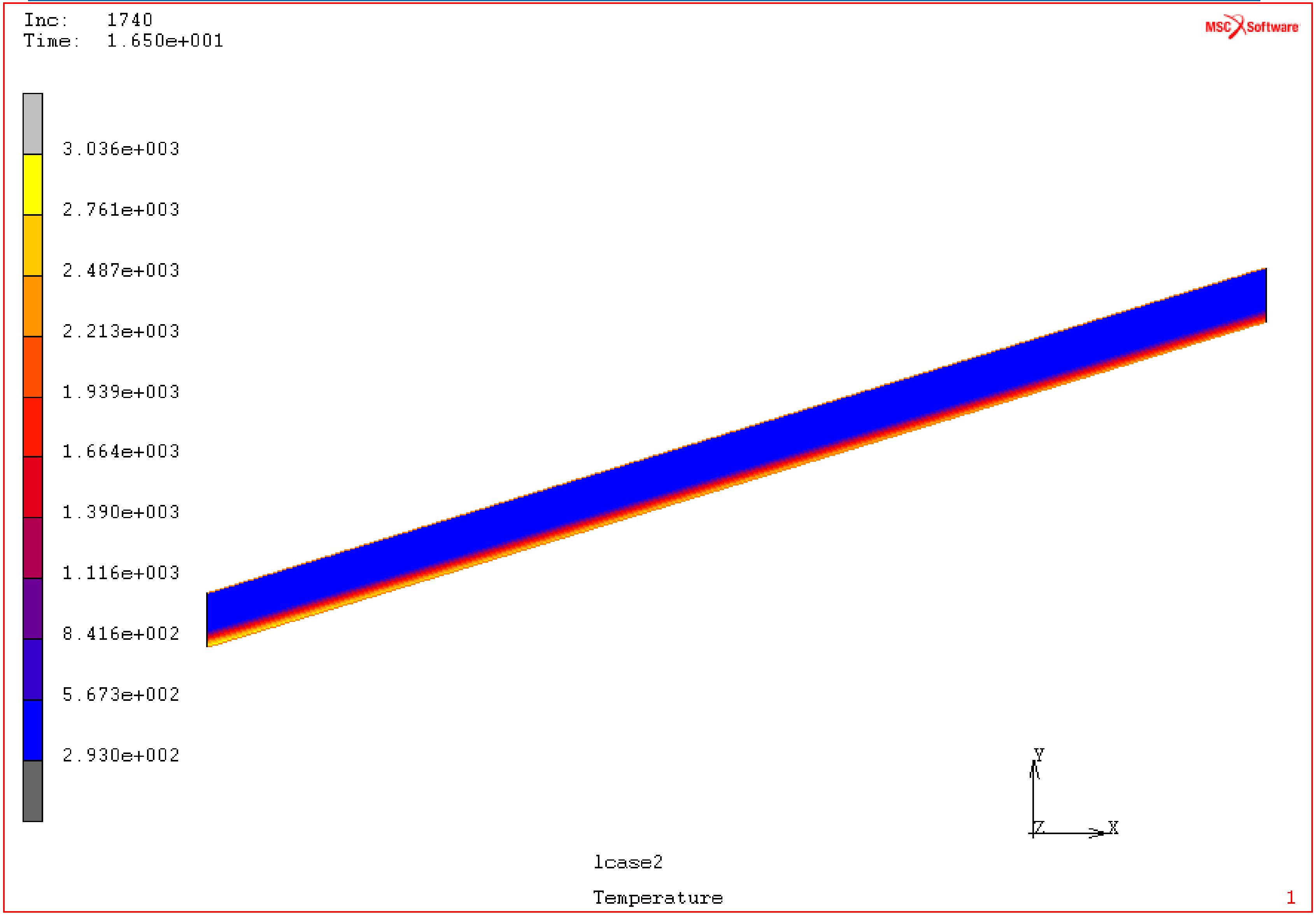
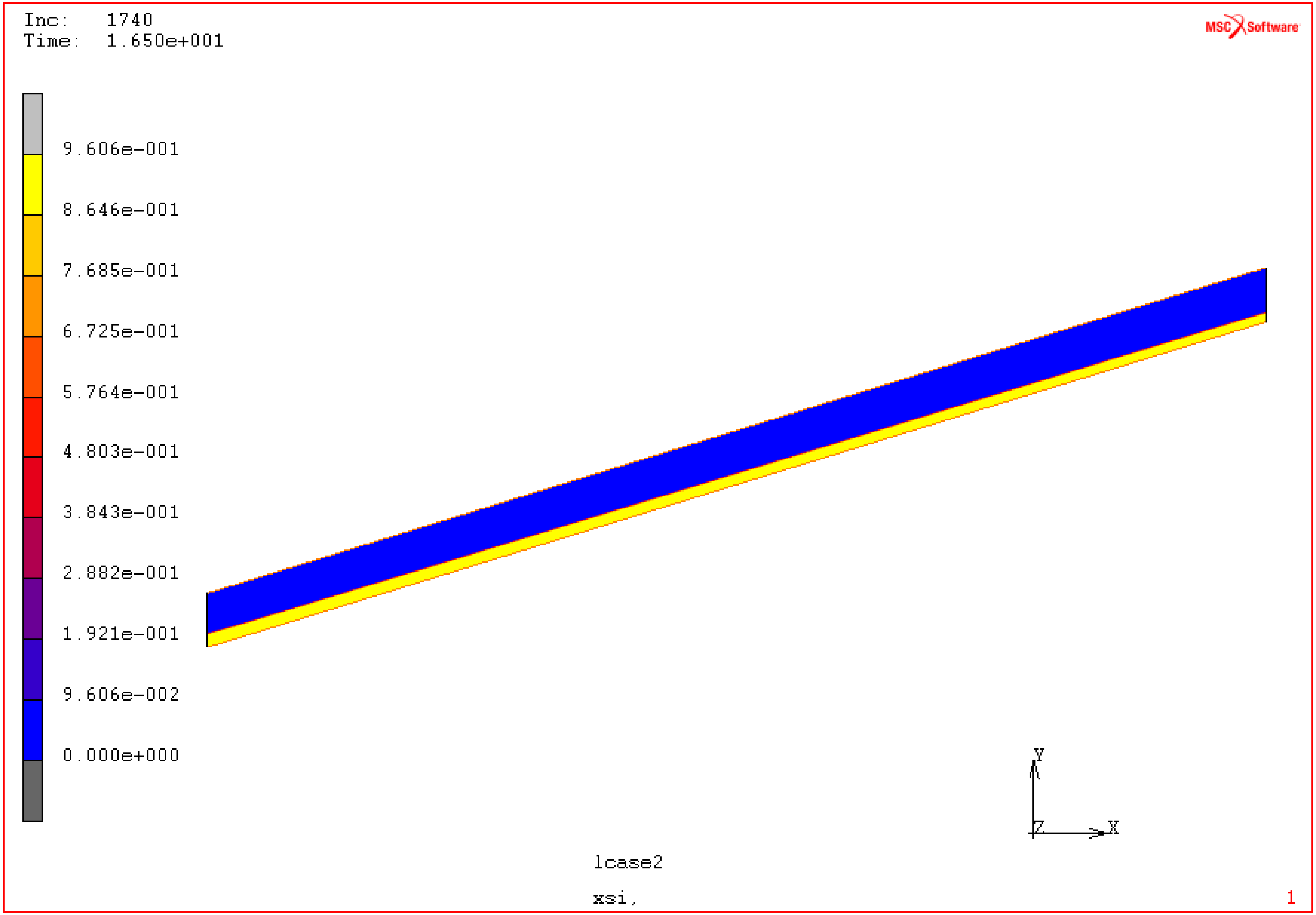


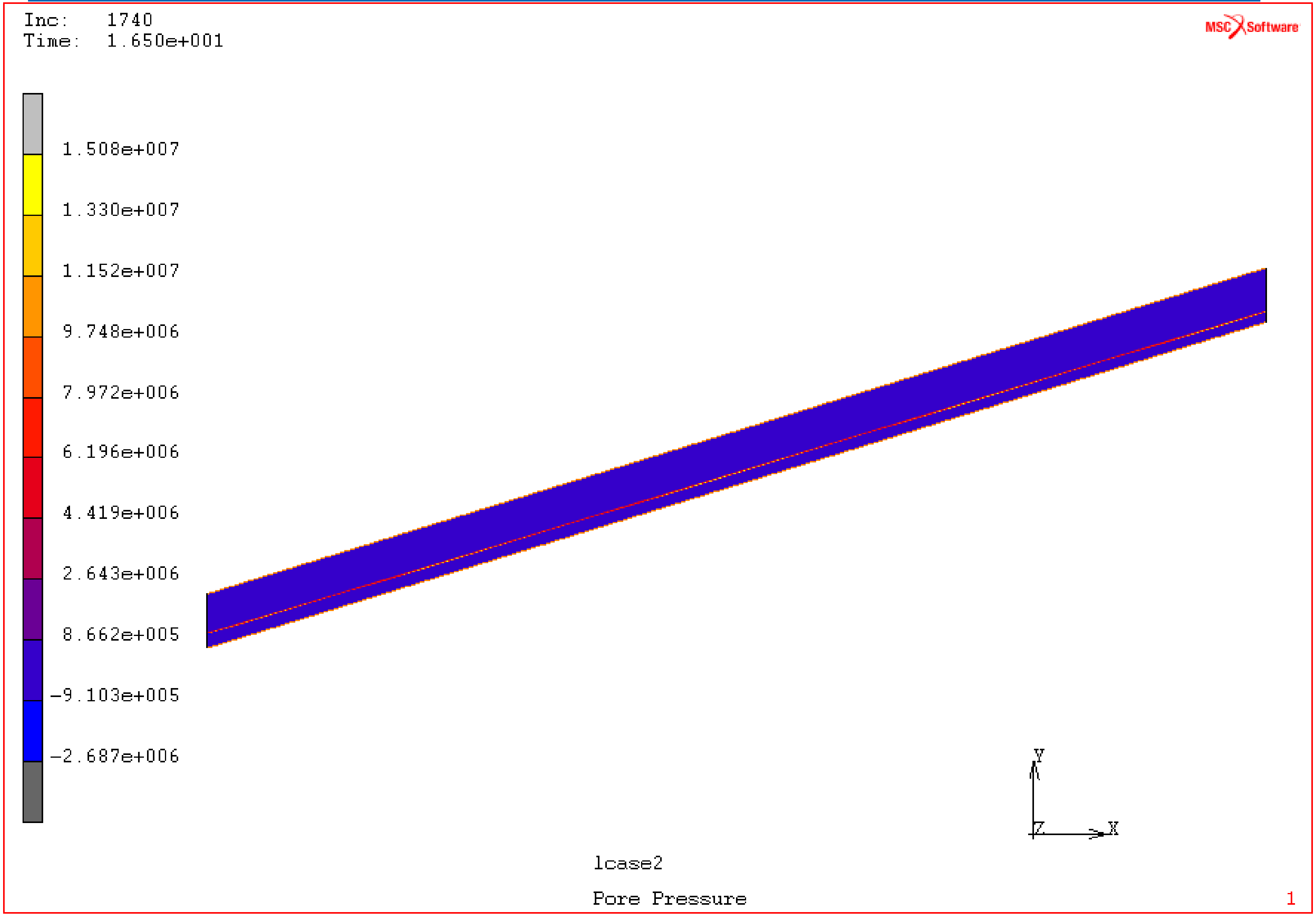
Simplified Exit – Darcy Flow - Temperature



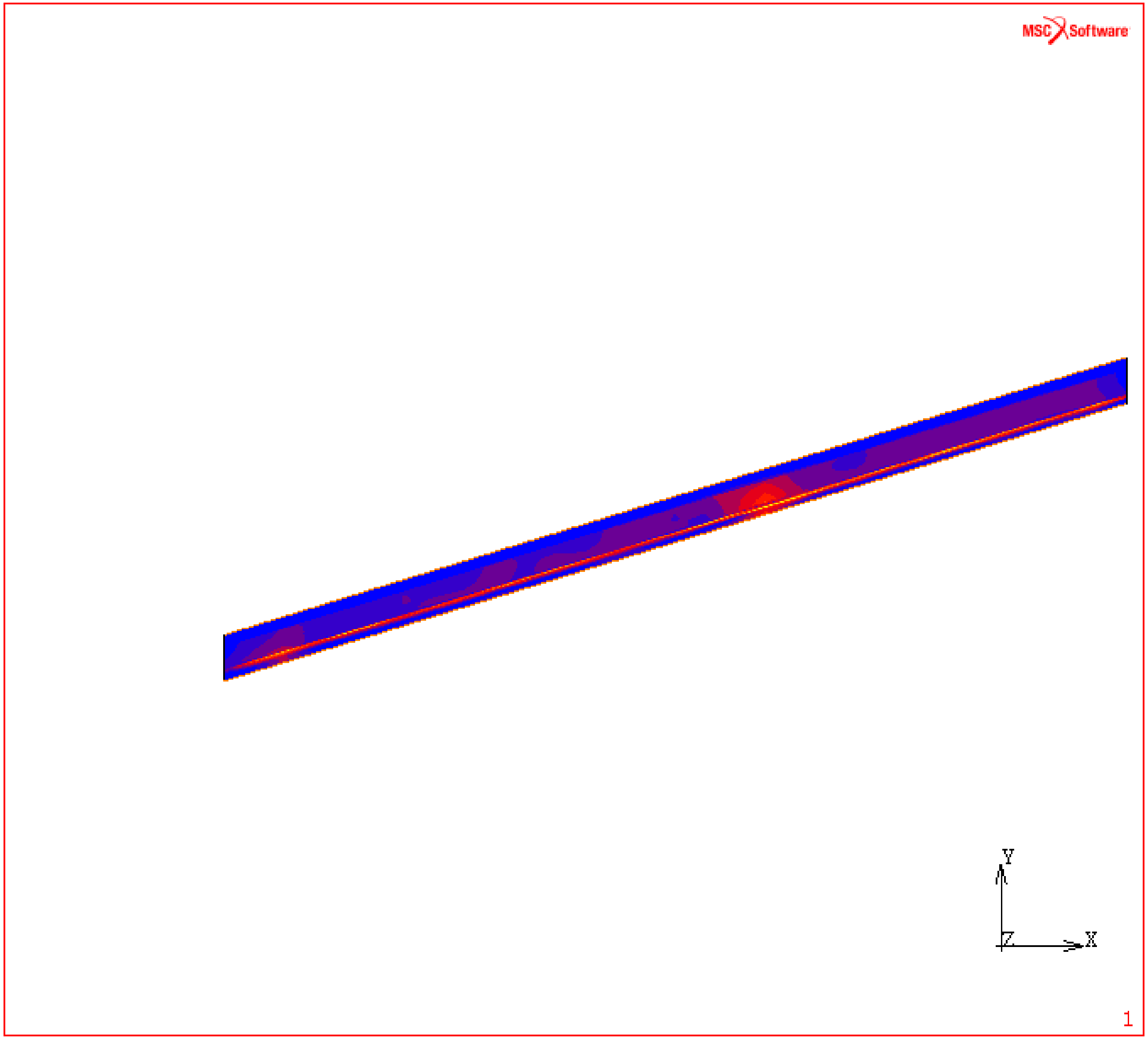
Simplified Exit – Darcy Flow - Xsi



Simplified Exit – Darcy Flow – Gas Pressure



Simplified Exit – Darcy Flow - Stress



Parameters

- TITLE
- ELEMENTS
- COUPLED
- STRUCTURAL
- HEAT
- PYROYSIS
- DIFFUSION
- ABLATION
- ADAPTIVE
- LARGE STRAIN
- FOLLOW FORCE

Model Definition

- Geometry
- POINTS
- CURVES
- CONNECTIVITY
- COORDINATES
- ATTACH NODES
- ATTACH EDGES
- STREAM DEFINITION
- ADAPT GLOBAL
- CONTACT
- CONTACT TABLE
- THROAT
- CAVITY DEFINITION

- Material Property
- ISOTROPIC
- ORTHOTROPIC
- ORIENTATION
- THERMO PORE
- TABLES
- LATENT HEAT
- EMISSIVITY
- CREEP

Model Definition

- Initial Conditions
- INITIAL PYROLYSIS
- INITIAL TEMP
- INITIAL PRESSURE

- Boundary Conditions
- SURFACE ENERGY
- FILMS
- FIXED TEMP
- FIXED PRESS
- FIXED DISP
- DIST FLUXES
- DIST LOAD
- RAD-CAVITY
- RECEDING SURFACE

Model Definition

- Controls
- SOLVER
- DEFINE
- POST
- CONTROL
- LOADCASE

History Definition

- Controls
- TRANSIENT
- AUTO STEP
- CONTROL
- LOADCASE

Conclusions

- Thermal Stress Capability utilizing Mixture Model based upon Pyrolysis Material has been added to Marc
- Coupled Thermo-Pore-Structural has been developed
- Less User Effort in Solving Coupled Problems than transferring temperature data between different codes in simulations with ablation

Thank You