NASA Thermal and Fluids Analysis Workshop 2003

Tutorial

Aerothermal Analysis and Design Overview

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Outline

- **Process Overview**
- **Aerothermal Analysis & Design Process**
  - **System design requirements**
  - **Aerothermal boundary conditions**
  - **Candidate material technologies**
  - **Analytic model development**
  - **Preliminary flight design**
  - **Ground aerothermal testing**
  - **Flight design/verification and validation**
- **Analysis and Design Methodologies**
- **Summary**

Process Overview

- **Define system requirements**
  - **Environments**
  - **Material technology (TRL)**
    - **Airframe, nozzle, fins/leading edges, radomes/IR windows**
  - **Internal components**
    - **Electronics, propellants, fin root bearings, seals**
  - **Weight/Cost**
- **Conduct component level & system analysis & design (shape, material, trajectories)**
- **Conduct ground test and evaluation to validate component design models**
- **Perform flight design**
  - **Instrument flight system to further validate analytic models**

Aerothermal Analysis & Design Process

Define System Requirements

environments
durability, geometry
volume/weight

Select Candidate Material Technology

Material phenomena of interest

Properties
application, weight,
Volume, TRL, cost
producibility

Analytic Model Development/Predictions

Existing models
Develop models

Ground Test Facilities

<u>Selection Criteria</u>
Heat flux, shear, pressure,
total temperature, run time,
test cell, cost, availability

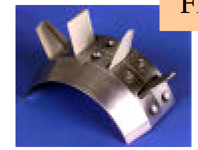
screening tests
performance tests

Flight design using
refine models

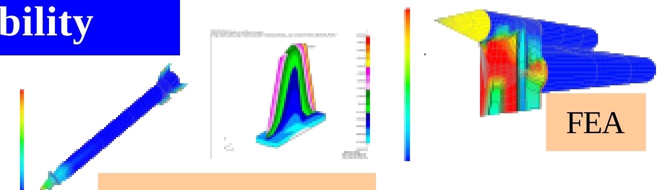
Flight Test with Instrumentation and Validate Design Models

Iteration throughout process may be necessary

Fins



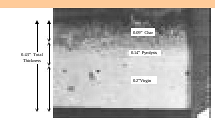
material technology applicability



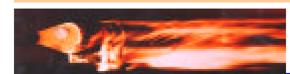
FEA

Material Response

Char/Intumescence

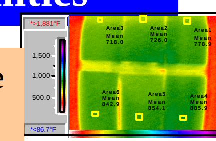


Shear/Aeroheating



phenomena of interest define facilities

Match Surface Temperature



System Design Requirements

- Reusable/single use
- Fabrication/manufacturing cost
- Schedule (TRL requirement)
- System integration
- Aerothermal environment (thermal, pressure, surface reactions/catalysis)
- Rain/sand requirements
- Flight time
- Storage/transportation/environmental extremes

System Design Requirements

- Airframe/structure operating temperature
  - Metallics <1000°F (811 K)< Refractory metals
  - Ceramics/Ceramic Matrix Composites > 2000°F (1367 K)
  - Ultra High Temperature Ceramics (UHTC) >3000°F (1922 K)
  - Composites (anisotropic properties)
    - Graphite epoxy < 350°F (450 K)
    - Cyanate ester (PT-30) < 550°F (561 K)
    - Pthalonitrile < 1100°F (867 K)
- Leading edge/control surface
  - Durability (rain, cyclic heating, reusable)
  - Thermal expansion and insulative ability
  - Strength at temperature

System Design Requirements

- **Geometries of interest**
  - Shape (stagnation, conical, flat, wedge, leading edge, incidence angle)
  - Substructure (operational temperature limits)
  - Weight/volume constraints
- **Aerothermal environment**
  - Trajectories (velocity, altitude, angle of attack,time)
  - Flight geometries
  - Recovery enthalpy/temperature
  - Local aerodynamic shear & pressure
  - Local heat flux (transient/integrated)
  - Ionization/plasma potential

Aerothermal Boundary Conditions

Phenomena which must be quantified

- Boundary layer
  - Blowing (if applicable – decomposing materials)
  - Velocity/temperature gradients
  - Thickness
- Shock interactions/effects
  - Enhanced heating due to shock attachment (shock jetting)
- Ionization (induces RF blackout, catalycity)
  - Sodium/Potassium/air
- Recovery conditions (enthalpy, temperature)
- Convective heat transfer (wall shear)
- Real/ideal gas effects

Candidate Material Technologies

- **Thermal properties (temperature/directional dependent)**
  - **Thermal conductivity/specific heat**
  - **Density (weight limits)**
  - **Decomposition (char/pyrolysis)**
  - **Ablation product species, ionization potential, catalytic efficiency**
- **Mechanical properties (temperature dependent)**
  - **Strength (shear)**
  - **Strain (motor growth/bending)**
  - **Durability (impact, environmental extremes, …)**
- **Reusable or single use**
- **Cost/manufacturability/TRL**

Analytic Model Development

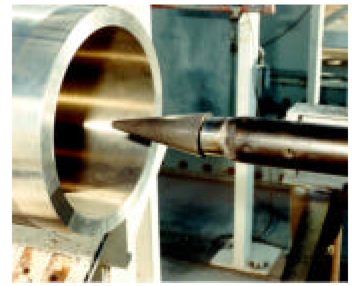
- Reusable technologies (NASA) – Aeroheating + FEA Codes
- Non-reusable (DoD) – Aeroheating + Decomposition + FEA Codes
  - Simplified approaches if applicable
    - Conduction models (unreliable if significant decomposition or ablation)
    - Simplified heat of ablation/Q* models (requires significant test data for specific environment of interest, limited use)
  - Complex charring material models
    - Application to wider range of environments
    - Requires characterization of complex phenomena
    - Decomposition (char/pyrolysis/intumescence)
    - Mechanical erosion/thermochemical ablation
    - Properties dependent on temperature/char state/direction

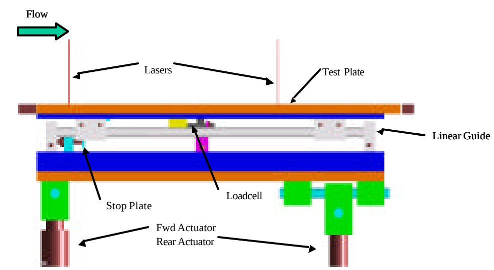
Preliminary Flight Design

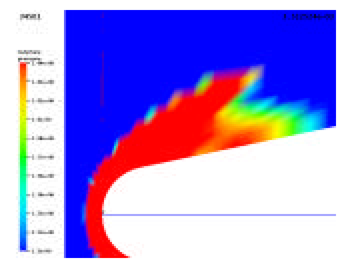
- **Perform predictions with available material models**
  - **Aerothermal response (CMA)**
  - **In-depth conduction (FEA)**
  - **Note: Models may not exist or need development**
- **Develop understanding of expected material phenomena/behavior for flight**
- **Rank material performance (both TPS & Structure)**
  - **Volume/weight constraints for required thickness (substructure temperature limits)**
  - **Application process (spray,trowel,mold,sheet)**
  - **Cost**
  - **Availability**
  - **Technology readiness level (flight qualified?)**

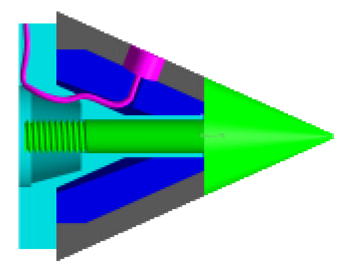
Ground Aerothermal Testing

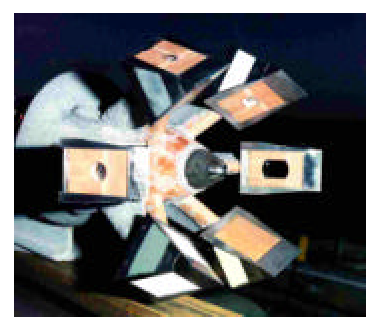
- Ground test simulation of flight conditions
  - Match aeroheating
    - Heat Flux (calorimeter)
    - Shear
    - Pressure
    - Recovery conditions
  - Configuration (test rhombus)
  - Instrumentation
  - Screening tests
- Facility availability
- Test cost





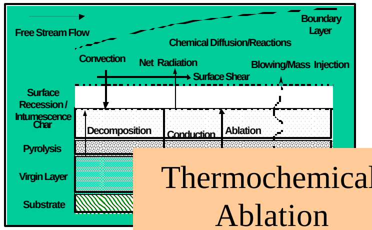




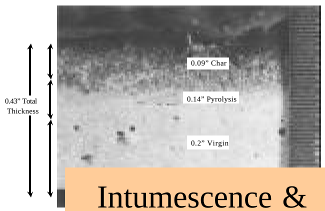


Ground Aerothermal Testing

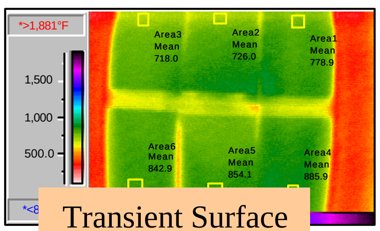
- **Material performance characterization tests**
  - **Identify phenomena to characterize**
    - **In depth conduction (thermal properties)**
    - **Decomposition**
    - **Erosion/thermochemical ablation**
    - **Surface temperature**
    - **Thermal expansion & durability**
  - **Select facility to characterize phenomena of interest**
    - **Thermal properties (thermal response)**
    - **Decomposition**
    - **Mechanical Erosion/Intumescence**
    - **Ionization/plasma**
    - **Heat flux/surface temperature response**



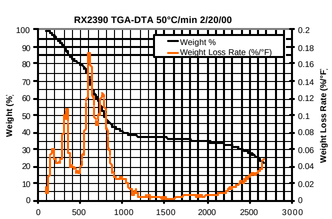
Thermochemical Ablation



Intumescence & Decomposition



Transient Surface Temperature

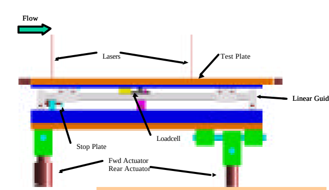


TGA/DSC

Strain

Mechanical Shear

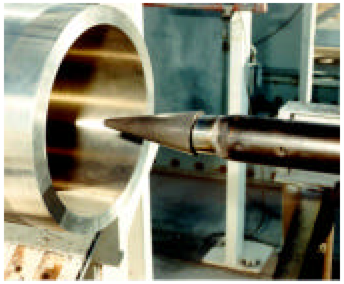
Shock/Impact Effects

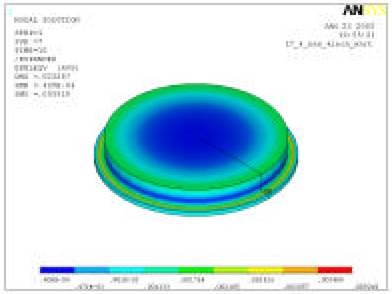


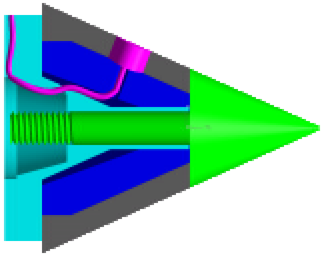
Hot Wall Drag

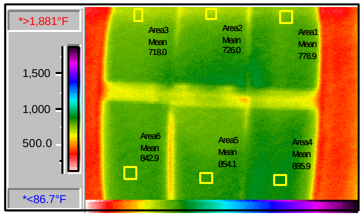
Instrumentation

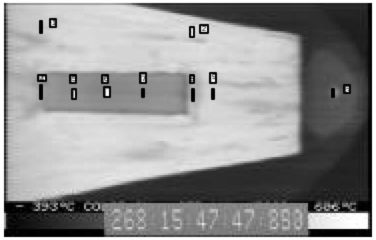
- Calorimeter matching test specimen
- Heat flux
  - Thin skin
  - Plug calorimeter (copper,steel,water cooled)
  - Heat flux gage (Schmidt-Boelter, Gardon, Null Point)
- Flow field (pressure, temperature, boundary layer)
- Embedded thermocouples
- Infrared surface temperature (wavelength, emissivity)
- Erosion rate sensors
- Chemical species/injection

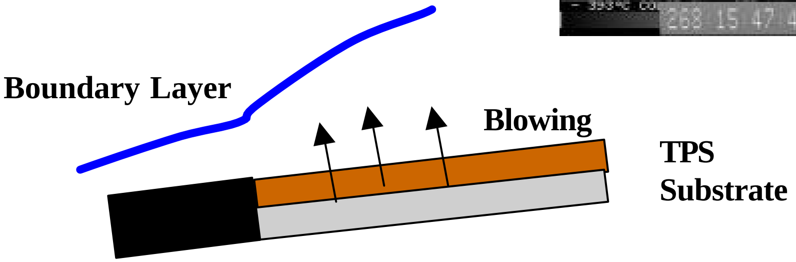








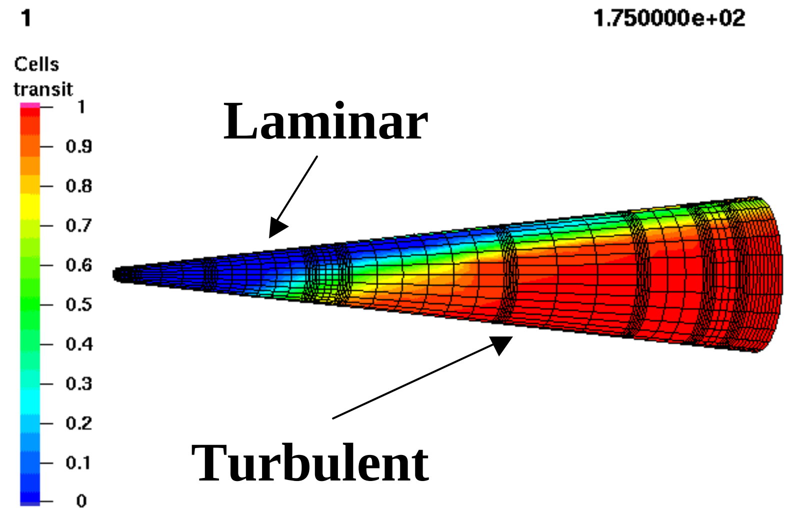




Instrumentation

Transition Occurrence

- **Altitude/velocity/AOA**
- **Surface roughness**
- **Critical for aerothermal boundary condition definition**



Gage	Onset Indicator	Measures $\dot{Q}$	Map Transition Front	Measures Turbulent Level $\dot{Q}$	Cost	TM Bandwidth
Delta-T	yes	yes	yes	yes	low	low
Standard Calorimeter	yes	yes	yes	no	low	low
Ported Acoustic	yes	no	could	no	high	high
Unported Acoustic	yes	no	could	no	med	med
Base Pressure	yes	no	no	no	low	low
Accelerometer	yes	no	partially	no	high	high

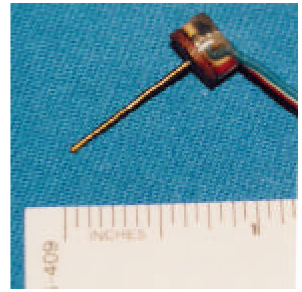
Table by Astrometrics

Instrumentation

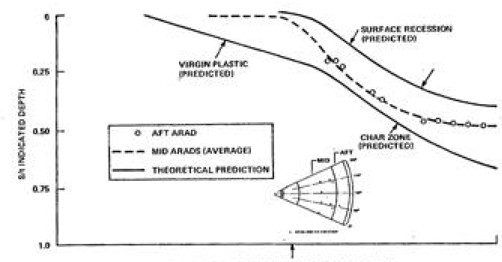
DOD Aerospace "Off-the-Shelf" Heat Shield Instrumentation

Minuteman Launch

Minuteman Re-entry Vehicle

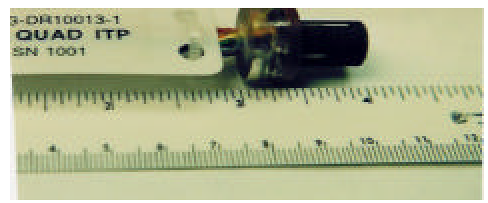


Transient Recession Rates

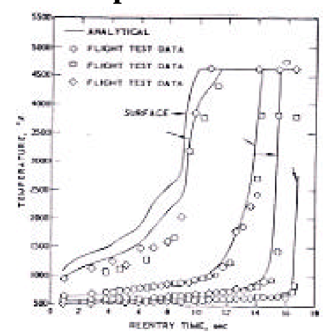


ARAD sensor to measure the char virgin interface recession history

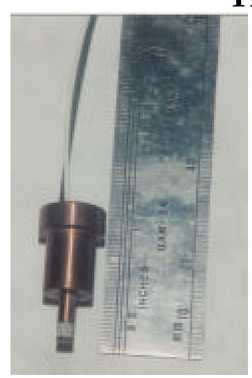
Non-Intrusive Embedded Thermocouples

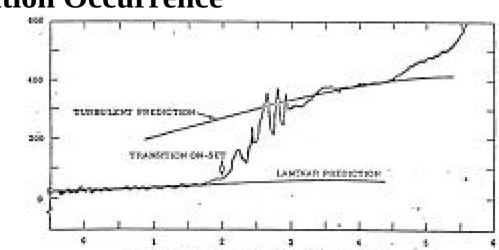


Quad Isothermal Plug Thermocouple
To Determine In-Depth Temperatures



Transition Occurrence

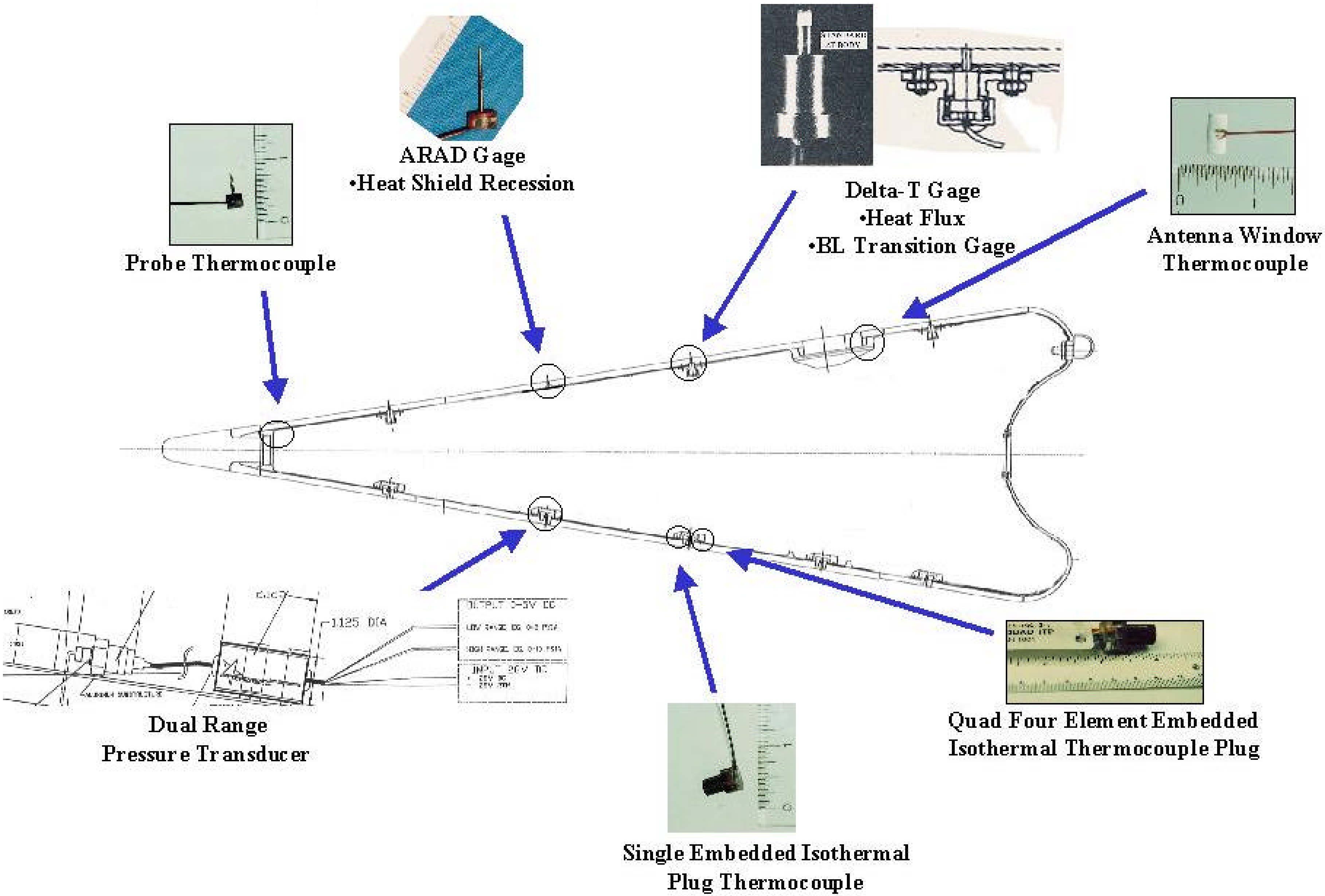




Delta-T Gage To Determine
Onset of Boundary Layer
Transition Altitude

Instrumentation Charts provided by John Cassanto of Astrometrics <u>(610) 280-0869</u>
AstrometricsJMC@aol.com

Typical Flight System Instrumentation



Minimum Flight Instrumentation Requirements

- **Transition sensors (boundary conditions)**
- **Ablation sensors (heatshield response)**
- **Multi-element embedded plug TCs (TPS)**
- **Temperature probes (internal components)**
- **Backface structure temperature sensors**
- **Antenna window temperature sensors**
- **Dual range pressure transducers**

Flight Design Verification and Validation

Utilize validated computational model developed from ground test data to refine system design

- **Material requirements**
  - **Predicted thermal response**
  - **Predicted surface removal/intumescence**
- **Substructure response (thermal/structural)**
- **Flight instrumentation requirements**
- **Telemetry capability (RF signal effects due to ablation products)**

Flight Design Verification and Validation

- **Data reduction**
- **Final computational model refinement**
- **Predictions for full range of possible flight requirements**
  - **Ground tests cannot always fully match flight**
  - **Flight tests don’t always impart worst case flight**

Analysis and Design Methodologies

- Summary of Methods
  - Engineering Methods
  - Complex Flow Field Analysis
- Analytic Codes
  - Aerothermal Boundary Conditions
  - Material Response

Summary of Methods

- **Engineering Methods are relatively efficient and can provide a means of obtaining first order boundary conditions for simple configurations**
  - **Panel methods**
  - **Streamline tracing**
  - **Equivalent running length**
  - **Convective transfer expressions (Conical/flat plate/sphere/cylinder)**
- **These methods can be supplemented with more complex flow field solutions to assess and correct pressure predictions and recalculate heat transfer coefficients**
- **Engineering methods also provide efficient transient thermal response and boundary condition predictions with material shape change/ablation**
- **Results can be integrated with FEA models for more complex 3-dimensional conduction effects**

Summary of Methods

- **Computational fluid dynamics (CFD) codes may be used for complex and/or chemically reacting flows**
- **Transient flow field predictions are generally not possible due to**
  - **Length of solver run times**
  - **Cost of discretizing domain for 3D geometry (grid)**
  - **Inability to efficiently consider transient wall temperature or ablation response**
- **Predictions are generally limited to a few points in trajectory/time**
- **Used in a tabulated manner for verifying and modifying engineering method predictions**

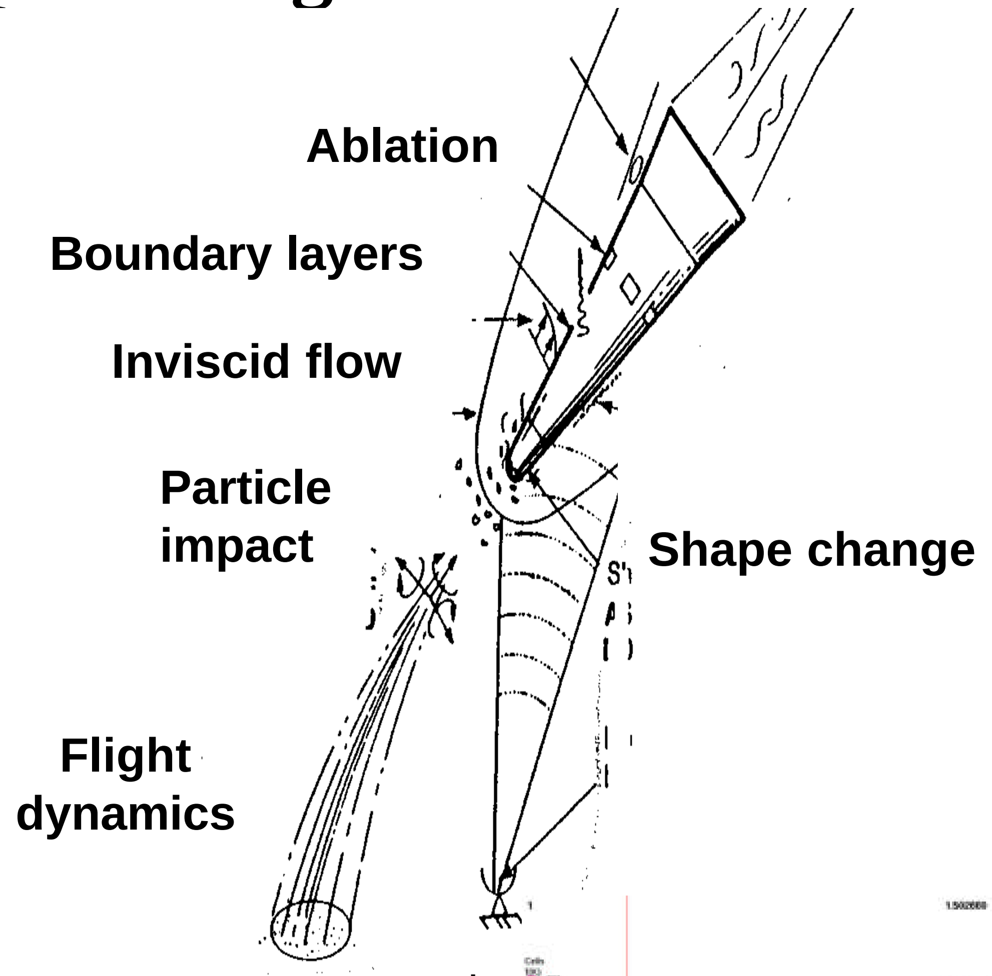
Engineering Methods

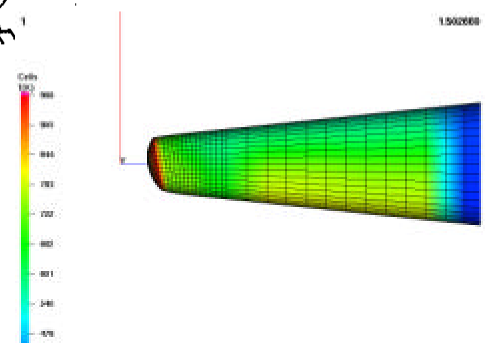
- Shape change
- Streamline tracing
- Surface pressure
- Shock shape
- Boundary layer flow

Shape Change

- Geometry definition
- Freestream properties
- Inviscid flowfield
  - Surface pressure
  - Shock shape
- Boundary layer heating
- Material response and ablation
- Change in the geometry of the vehicle
- Particle impact erosion
- Coupled shape change / flight dynamics
- In-depth thermal response

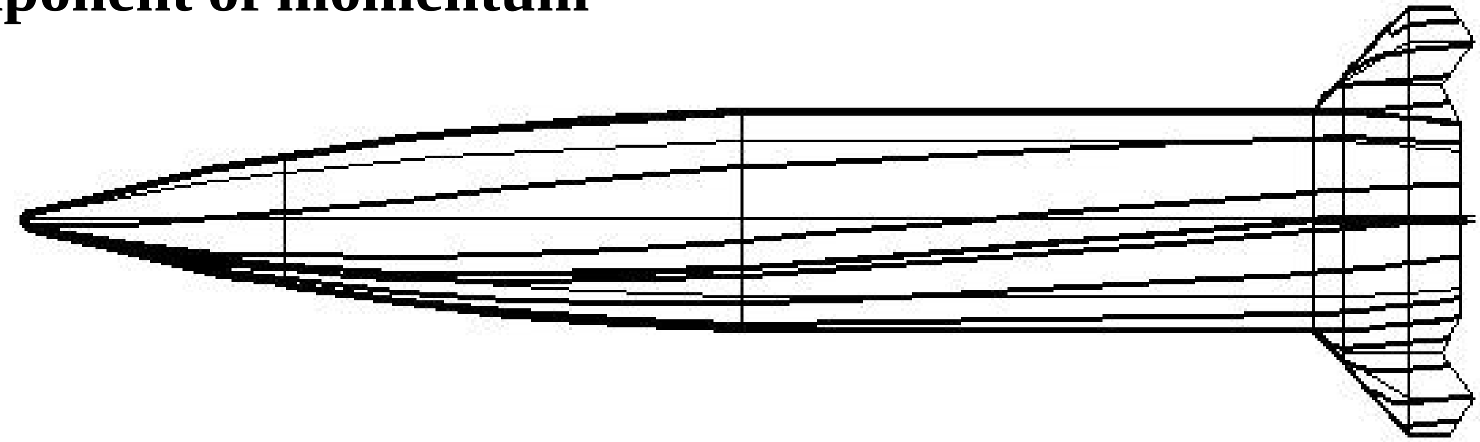
Other factors – Efficiency
Robustness Accuracy





Streamline Tracing

- **Axisymmetric analogy for 3D flowfield predictions**
  - **Assumes no flow crossing a streamline**
  - **Modeled as an axisymmetric solution**
  - **Body radius replaced with the metric coefficient**
- **Streamlines calculated using method of steepest descent based on the Newtonian approximation**
- **Newtonian flow model assumes that a stream of particles (air molecules) impinging on a surface retains its tangential component of momentum**



Surface Pressure

Windward side (cos h < 0) (h is the angle between the wind vector and the outward surface normal)

Modified Newtonian $$C_p = C_p^* \cos^2 h$$

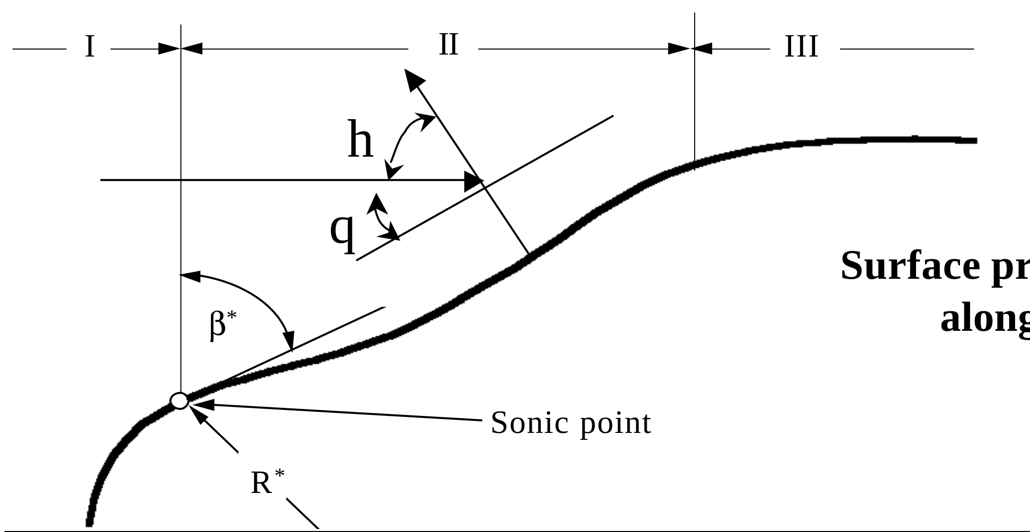
PANT Correlations

Leeward sides (cos h >0)

Newtonian Pressure: $$C_p = 0$$

Small Disturbance Theory $$C_p = \frac{2}{\gamma M_\infty^2}\left\{\left[1 - \left(\frac{\gamma - 1}{2}\right) M_\infty \nu\right]^{2\gamma/(\gamma-1)} - 1\right\}$$

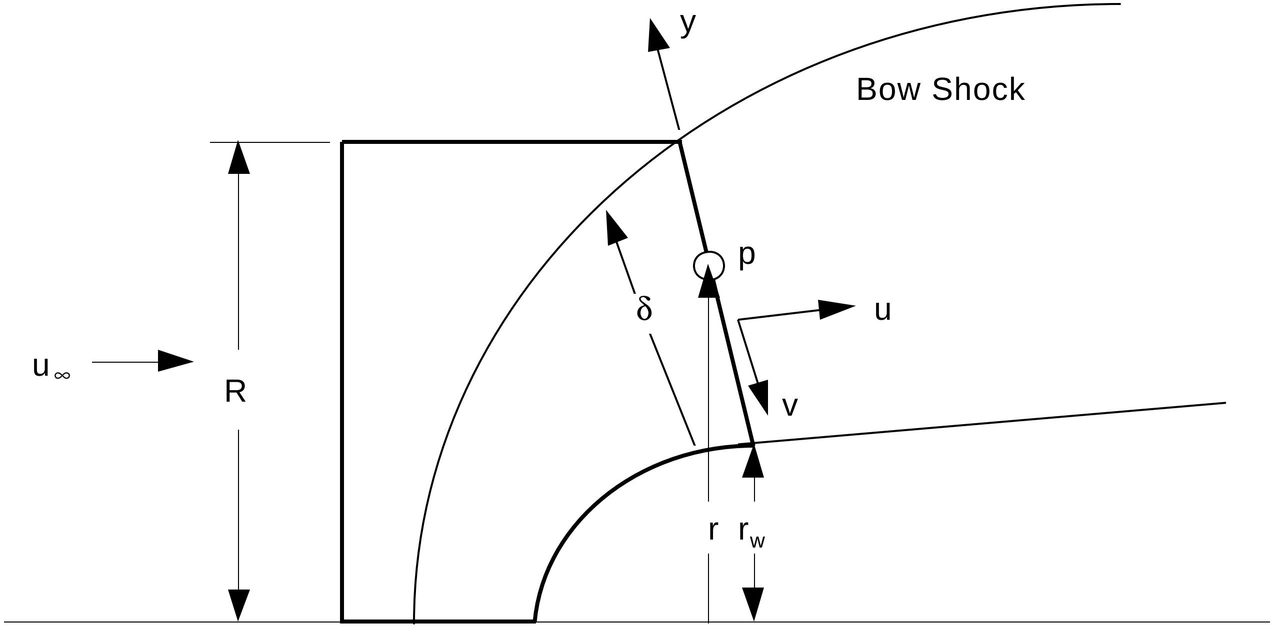
Separation Correlations



Surface pressure calculated along streamline

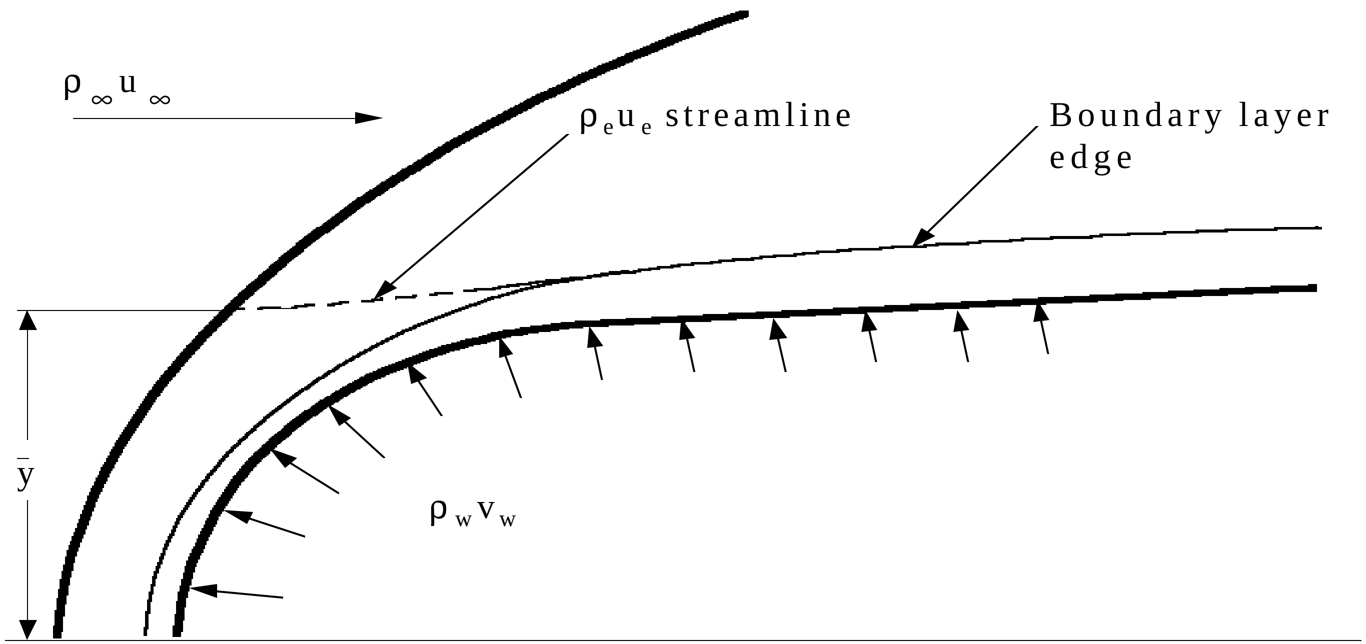
Shock Shape

Thin shock layer approximation for bow shock solving the global continuity and axial momentum equations. Integrands Approximated by linear distributions between the body surface and the shock.



Boundary Layer Flow

Entrainment relation - means of determining boundary conditions for the solutions of the momentum and energy equations. Edge state determined by lookup on pressure and entropy in a real-gas Mollier table. Pressure taken from inviscid pressure correlations and entropy is calculated by balancing mass entrained into boundary layer and mass crossing bow shock.



Boundary Layer Flow

Transitional Boundary Layers:

Transition from laminar to turbulent flow is modeled through the use of the Persch intermittency factor. Once the transition criteria is met, MEIT calculates both laminar and turbulent solutions and uses this factor to determine the actual state of the boundary layer. The parameters C_f, C_h, H, F, and R are determined by the expression:

$$P = (1 - f)P_\ell + f P_t$$

where f is the intermittency factor defined by:

$$f = 1 - \frac{a}{\mathrm{Re}_q^2 (C_{f,t} - C_{f,\ell})}$$

where

$$a = \mathrm{Re}_{q,tr}^2 (C_{f,t} - C_{f,\ell})_{tr}$$

Boundary Layer Flow

Influence Coefficients:

- Basic laws - represent simplest flowfield developing a boundary layer (incompressible flow, smooth wall, isothermal, impervious, irrotational inviscid flow)
- Assumption - laws can be modified to account for nonideal phenomena through use of influence coefficients
- These factors generally derived by comparing convective transfer with the ideal flat-plate result for the same boundary layer state.
- The factors are derived for only one nonideal mechanism at a time

Boundary Layer Flow

Method utilized in ATAC3D - Influence Coefficients:

It is assumed that the Stanton number, C_h, and the skin friction coefficient, C_f, can be written as:

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

where $C_{x,y,0}$ refers to the basic law for incompressible flow along an impervious, isothermal flat plate

x indicates heat, *h*, or momentum, *f*, transfer

y indicates laminar, *l*, or turbulent, *t*, flow

z indicates the nonideal effect being considered

- *b*, **acceleration**
- ***B*, blowing**
- ***p*, property and Mach number effects**
- ***r*, roughness effects**
- ***tr*, transition proximity**

Complex Flow Field Analysis

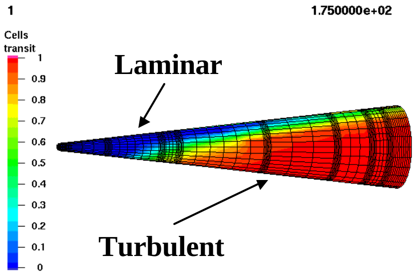
- **Required due to geometry and/or flow physics**
- **Geometry complexity creates flow complexity**
  - **–Shock-shock interactions**
  - **–Shock-boundary layer interaction**
  - **–Wakes**
  - **–Expansion waves**
  - **–Flow separation/recirculation/reattachment**
  - **–Chemistry/surface reactions**
  - **–Flow injection**

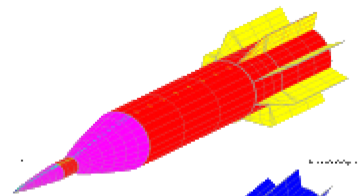
– Engineering methods used to identify regions where CFD is required

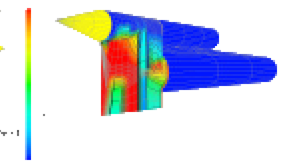
– CFD utilized to provide refined boundary conditions for engineering methods

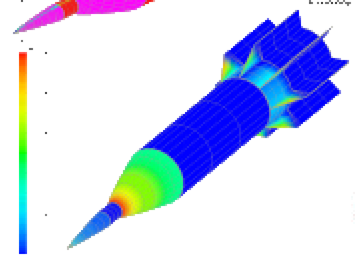
Analytic Codes for Boundary Conditions

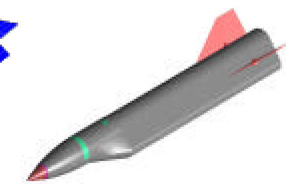
- **Engineering Methods**
  - ATAC3D/MASCC
  - Miniver/Lanmin
  - IGHTS/RGHTS
  - Bell Aeroheating Handbook



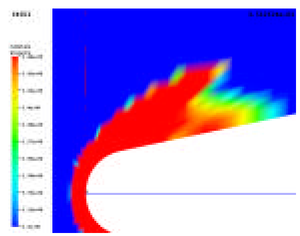


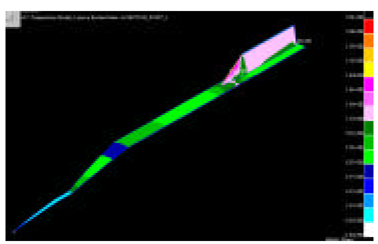


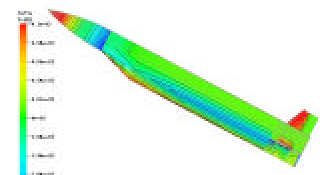




- **CFD**
  - Aerosoft - GASP
  - CFDRC - Fastran
  - Fluent
  - Giants/LAURA (NASA - Axisymmetric)
  - KIVA
  - CFDL3
  - Overflow
  - WIND







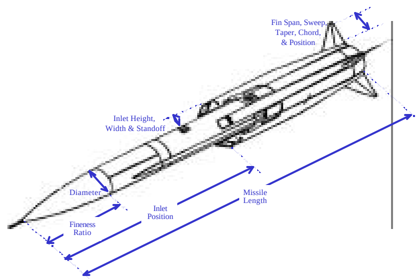


Figure 2 : Air Launched Low Volume Ramjet configuration used as a validation

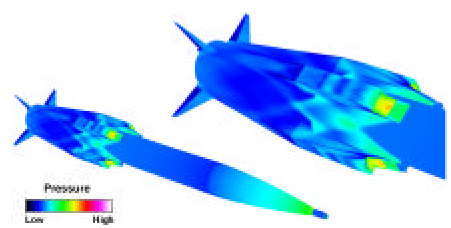


Figure 10: High Fidelity Aerodynamic Solution (Pressurecoefficient at Mach 2.5, α =0°)

- **Coupled Design Codes**
  - IHAT (Miniver/ATAC3D/Overflow)
  - Giants (TITAN, GIANTS, MARC-FEA)

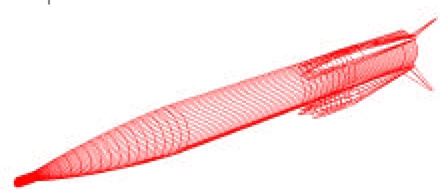
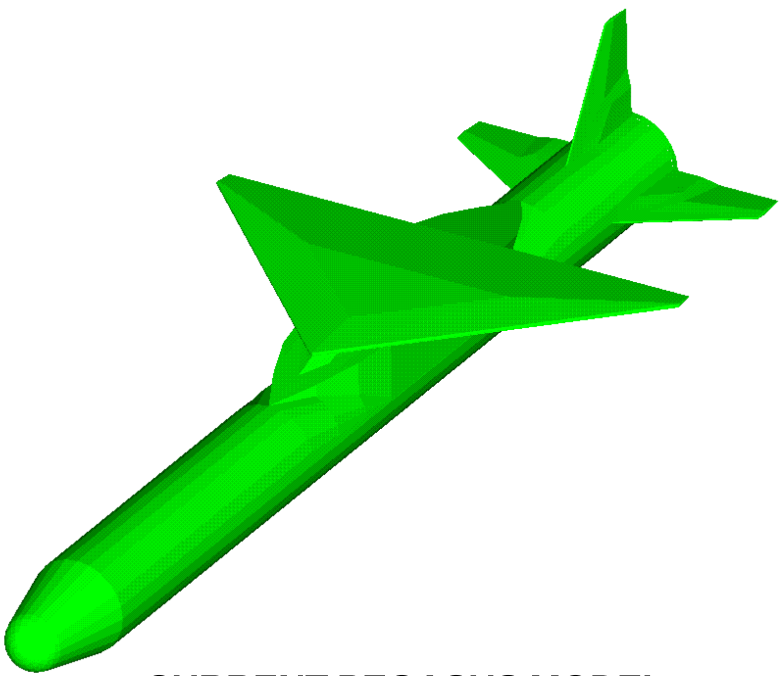


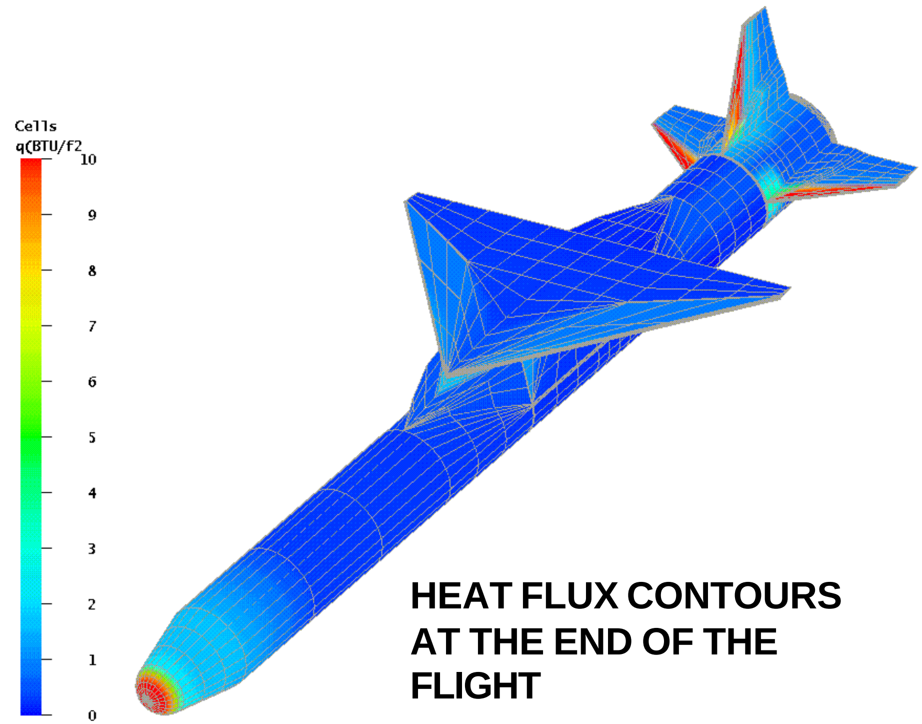
Figure 7: Low-fidelity aerodynamic grid.

Comparisons with Pegasus â Flight Data

- First Pegasus â flights included instrumentation to measure interface temperatures on the wing, fin, and wing fillet.
- Previous analytical models of Pegasus considered the fuselage, wing and fins as separate entities. The current model includes the entire configuration.
- Calculation modeled the first 82 seconds of the flight, up to first stage burnout
- 64 complete flowfield solutions were obtained to model the variation of the freestream conditions during the flight.



CURRENT PEGASUS MODEL

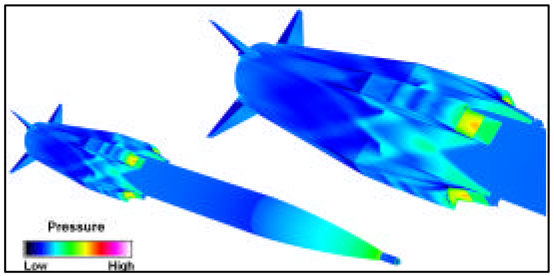


HEAT FLUX CONTOURS AT THE END OF THE FLIGHT

Coupled CFD/Aerothermal Analysis

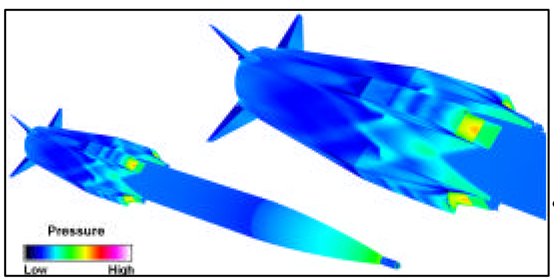
CFD, Thermal & Structural Modeling Process for Complex Vehicles Shapes

CFD Solution with Adiabatic Wall



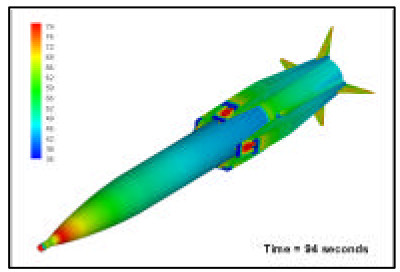
$T_{recovery}$

CFD Solution with Fixed T_{wall}



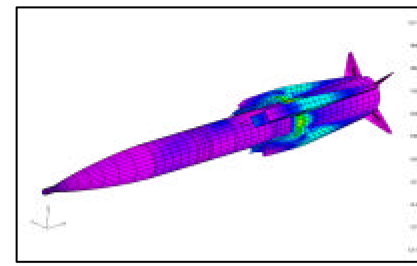
Heat Flux

3D Thermal Analysis



Temperature Distribution

Stress Analysis



Pressure

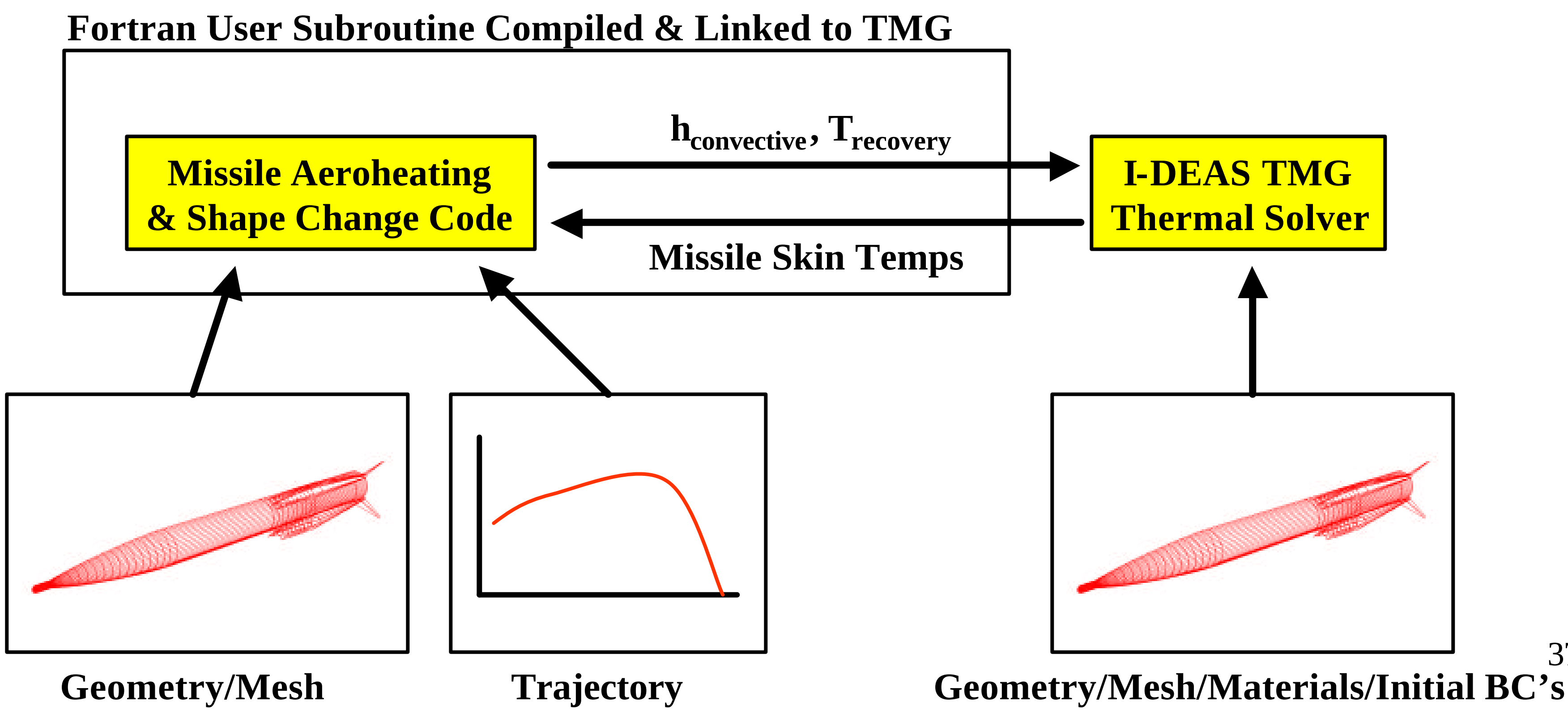
Other BC's

- **Time-dependent heat flux and $T_{recovery}$ interpolated from CFD mesh to thermal mesh.**
- **Time-dependent pressure distribution interpolated from CFD mesh to structural mesh.**

Technical POC: Rick Burnes Naval Air Warfare Center, BurnesRR@navair.navy.mil

Coupled CFD/Aerothermal Analysis

- At each thermal solution time-step in a transient analysis:
  - Missile skin temperatures and time-step passed to MASCC
  - MASCC computes hconv and Trec using missile skin temperatures and
  - trajectory for current time-step.
  - Heat load on each surface element in thermal model at current time-step
  - computed using: $Q_{element} = (h_{convective})(A_{element})(T_{recovery} - T_{element})$



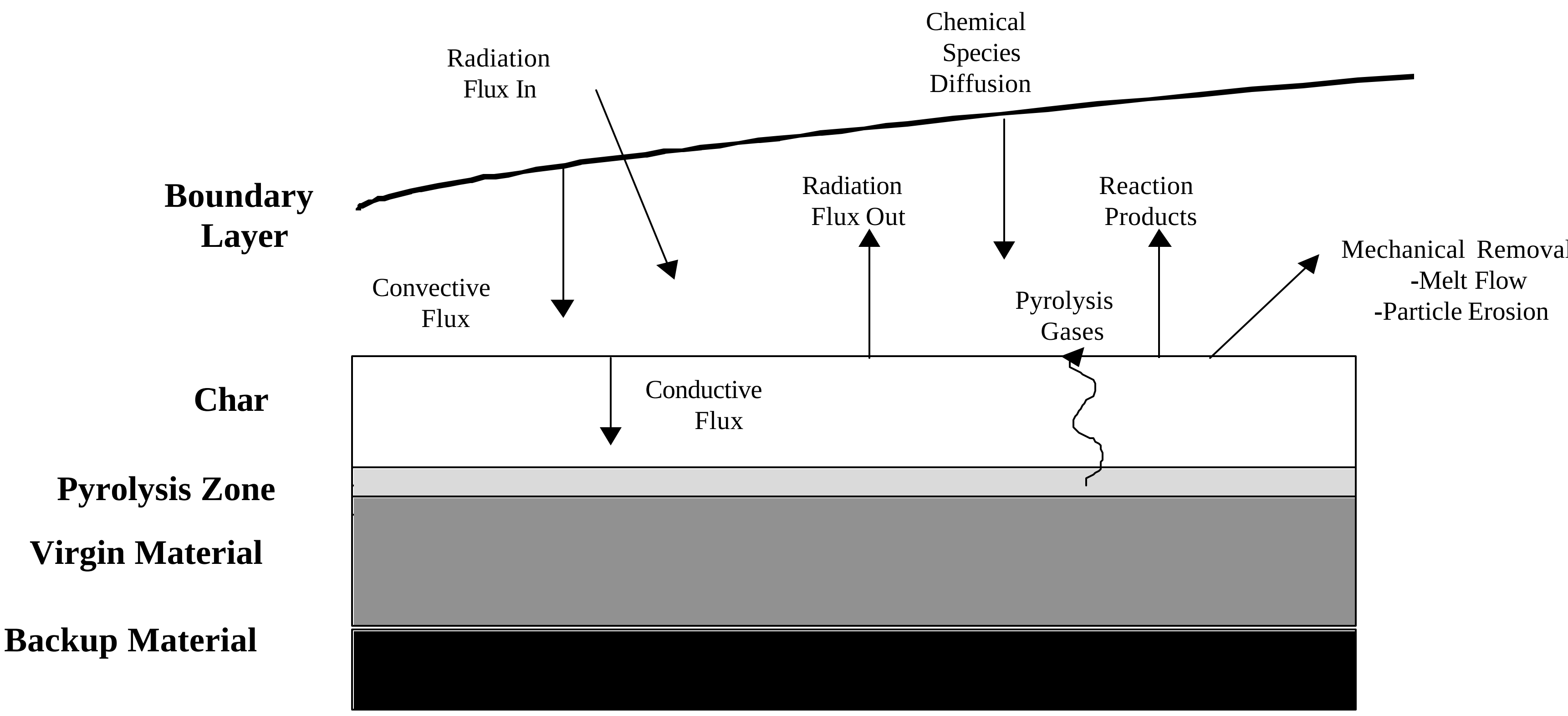
Analytic Codes for Material Response

- **Charring Material Model**
  - **CMA (Aerotherm)**
    - **CMA87: Charring Material/Ablation**
    - **CMA92FLO: CMA87 + Pore Pressure**
  - **Numerous independently developed codes**
    - **FIAT: 1-D NASA Charring Material Analysis**
    - **TITAN: 2-D NASA Charring Material Analysis**
- **Q* Model**
  - **Simplified Heat of Ablation Model (modified Q* model)**
- **Conduction Models**

Charring Material Models

- **Modeling Capabilities**
  - **In-depth decomposition**
  - **Conduction**
  - **Thermochemical ablation**
  - **Fail temperature model for mechanical erosion**
  - **Pyrolysis gas generation and injection/blowing**
  - **Addition of intumescence for conduction effects**
- **Application**
  - **Generally required for decomposing materials to obtain accurate in-depth thermal response**
  - **Applicable to a wide range of environments once material thermodynamic model is developed**
- **Limitations**
  - **Requires specific material property data such as kinetic decomposition constants, temperature dependent properties of char, pyrolysis, and virgin material, and heat of decomposition**

Charring Material Thermal Response and Ablation and Model (CMA)

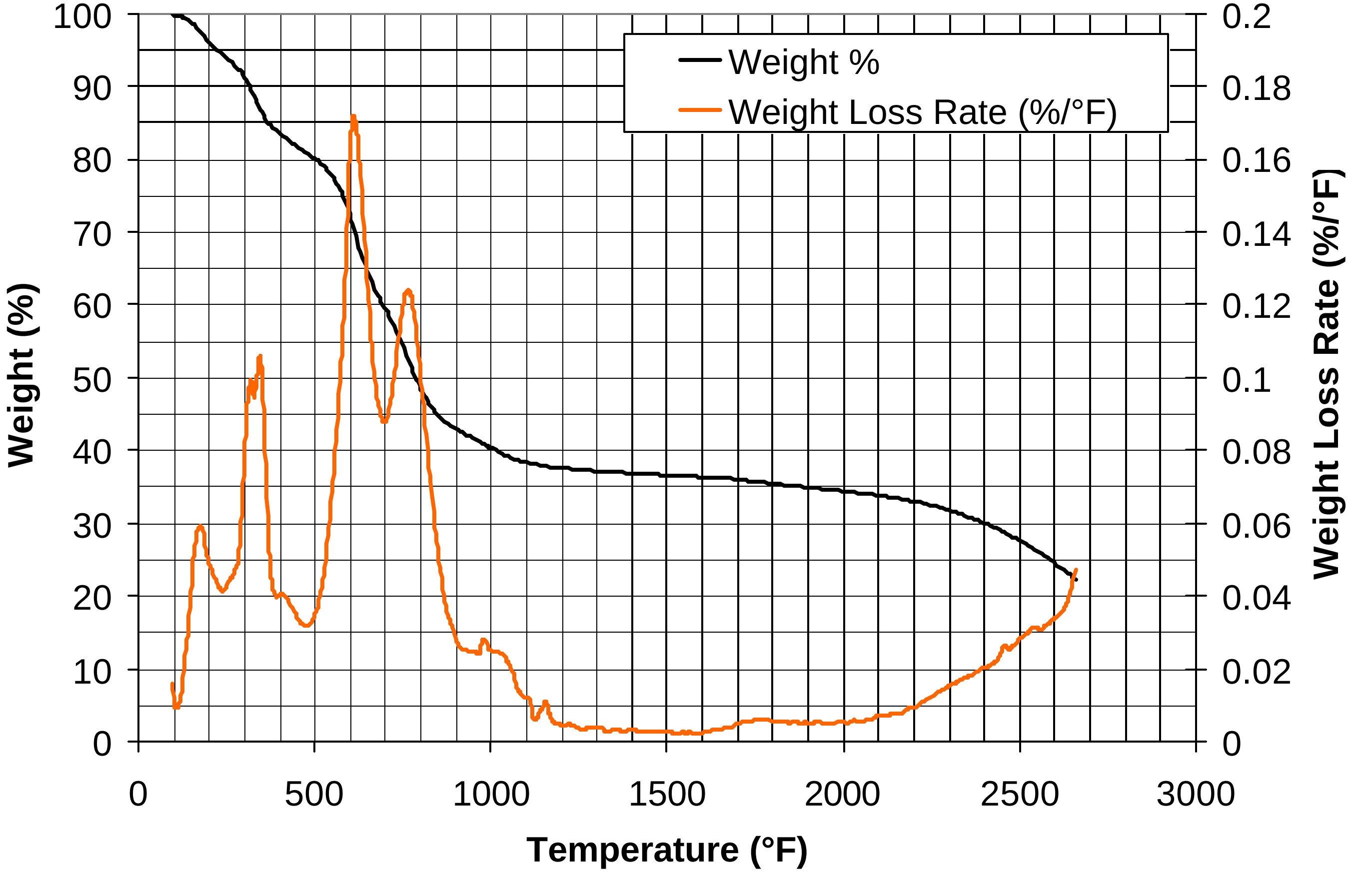


Surface and In-depth Energy Balance

$$H\left(h_r - h_e^{T_w}\right) + M \sum \left(Z_{ie}^* - Z_{iw}^*\right) h_i^{T_w} - \dot{m}_{tc} h_w^{T_w} - \dot{m}_e h_s - F \sigma \varepsilon_w T_w^4 + \dot{m}_{tc} h_s - \dot{q}_{cond} = 0$$

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

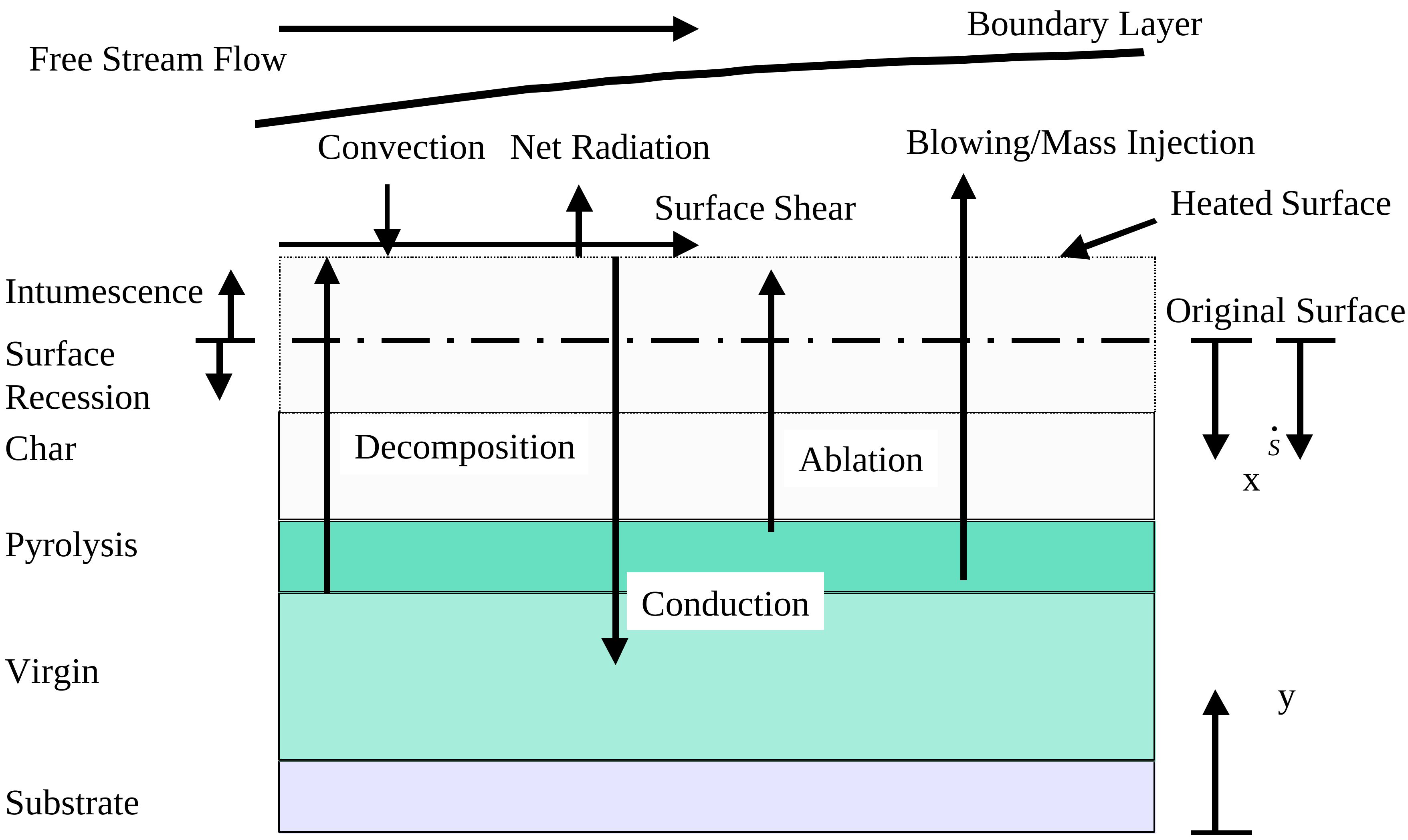
In Depth Decomposition Kinetics Model



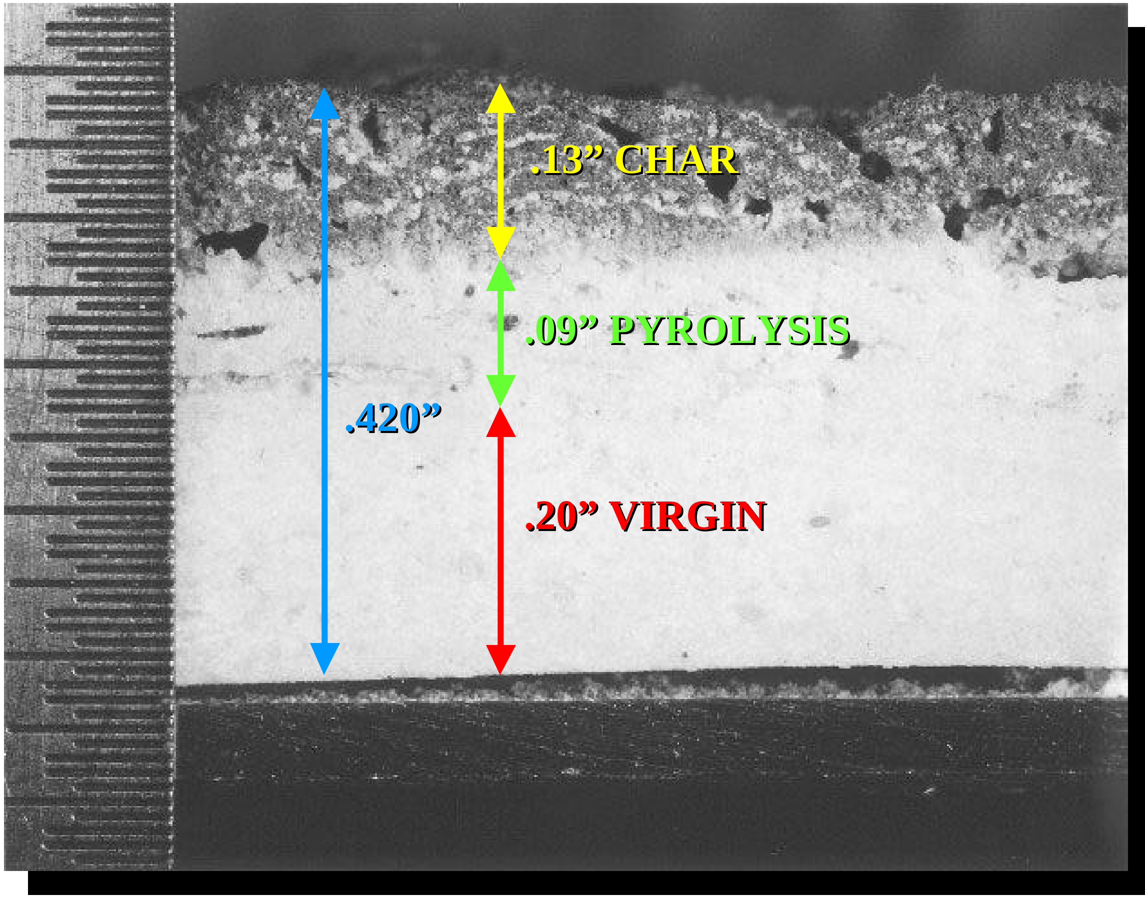
$$\rho = \Gamma(\rho_A + \rho_B) + (1 - \Gamma)\rho_C$$

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

CMA Intumescence Model Development

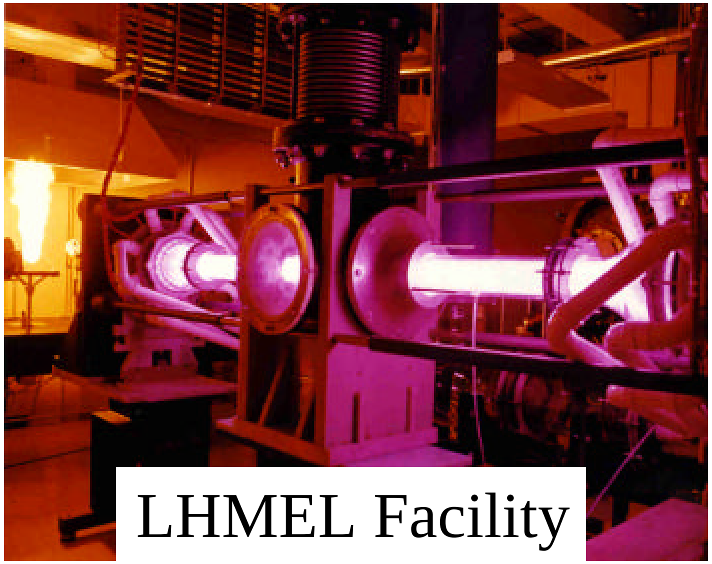


Intumescence Behavior



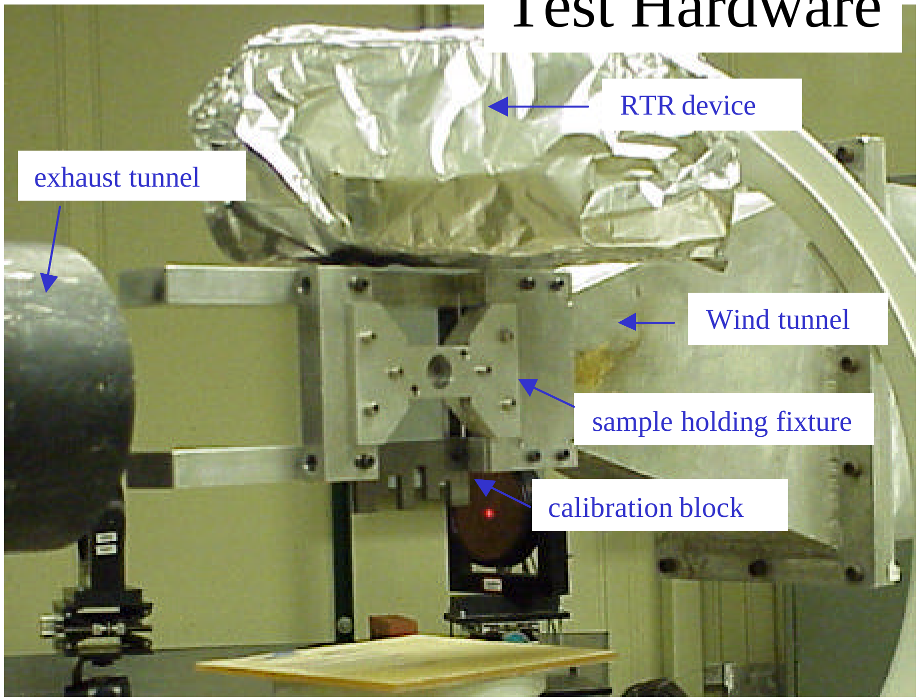
Pretest Thickness =0.3”
Char Depth =0.13”
Pyrolysis Depth =0.09”
Virgin Material Depth =0.2”
Posttest Thickness =0.42”
Intumesced =120%

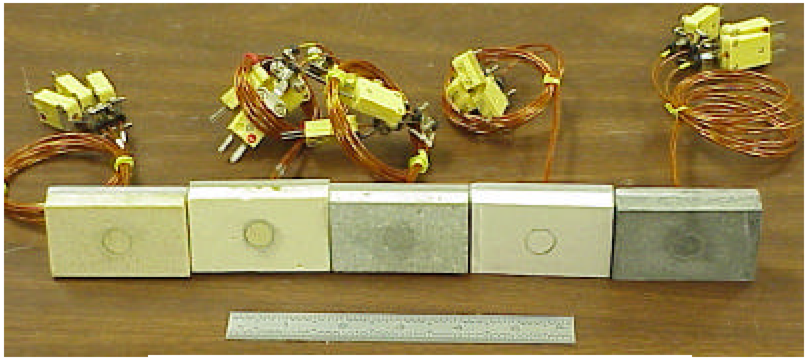
LHMEL Test Configuration



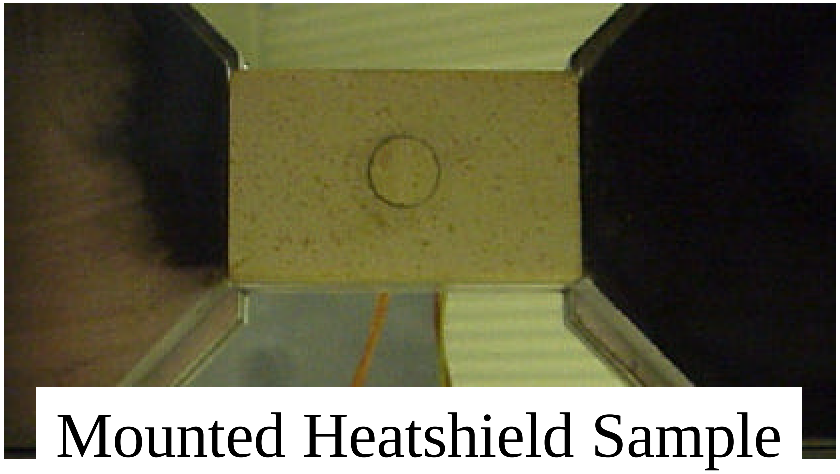
LHMEL Facility

Test Hardware



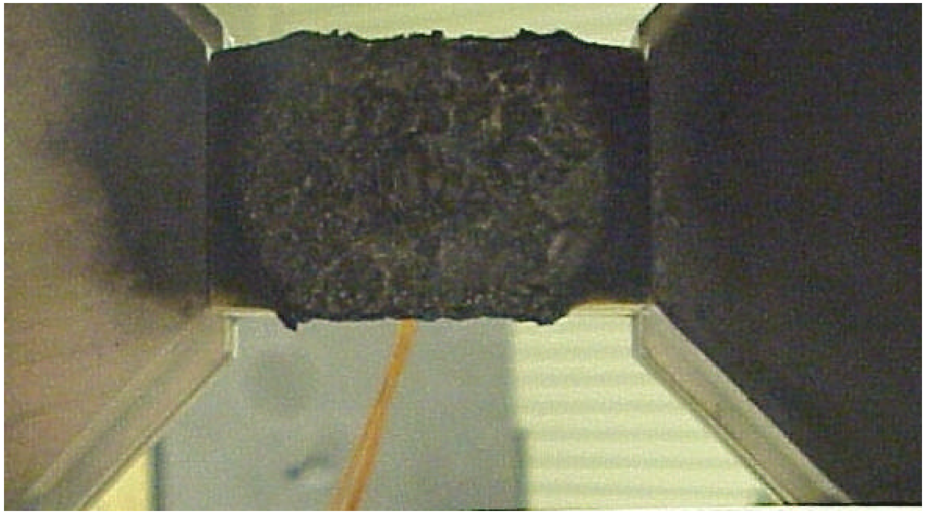


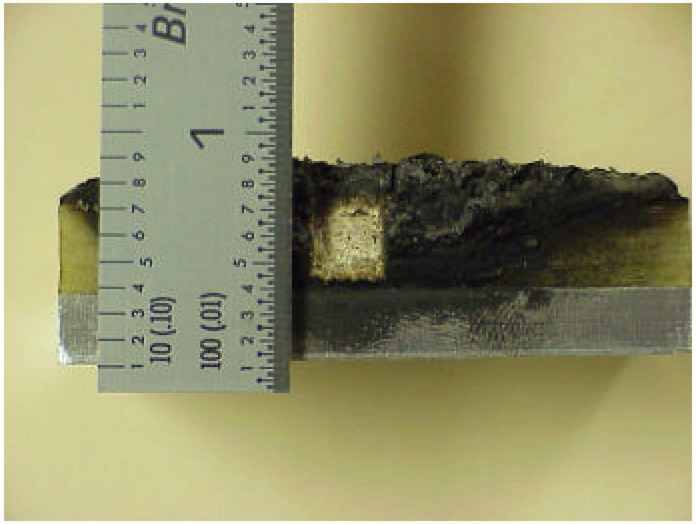
Heatshield Samples

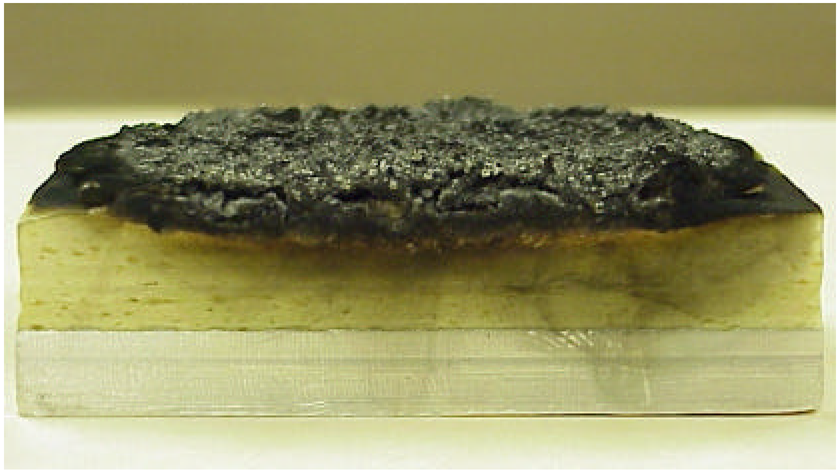


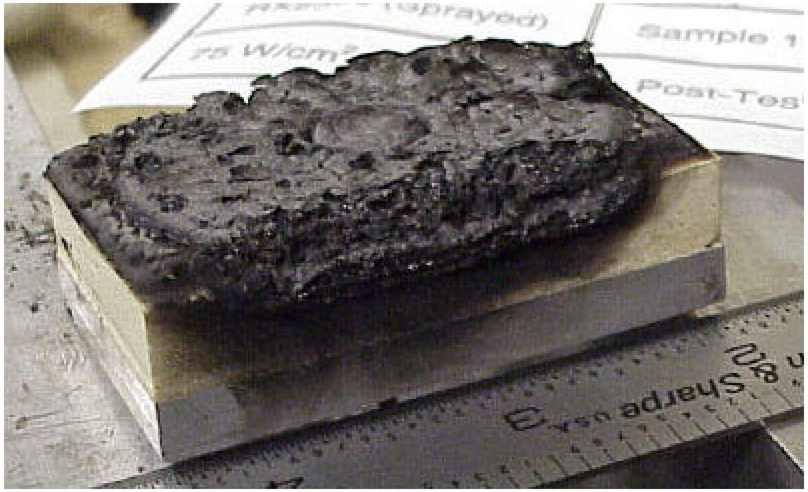
Mounted Heatshield Sample

Posttest Samples

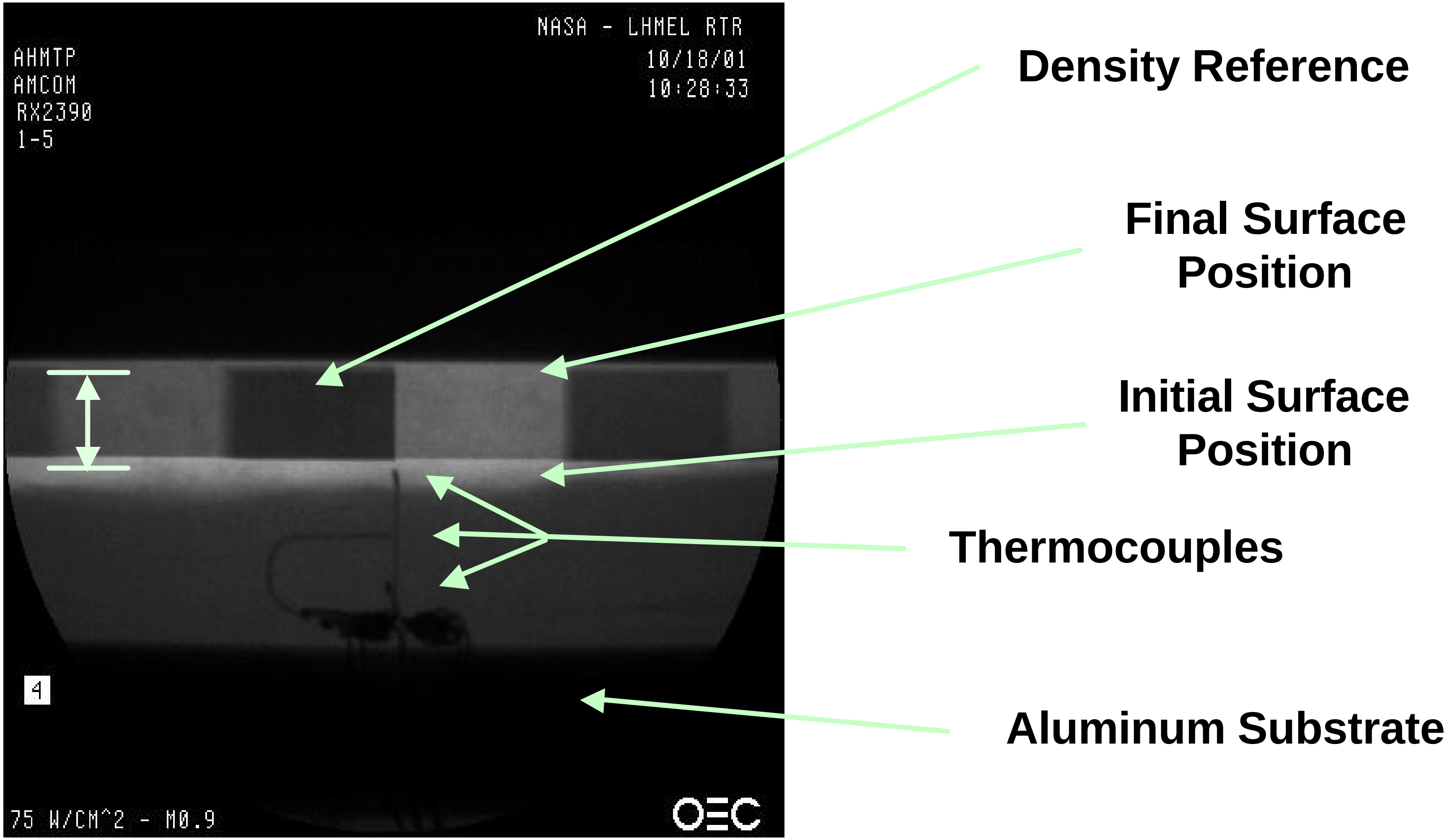




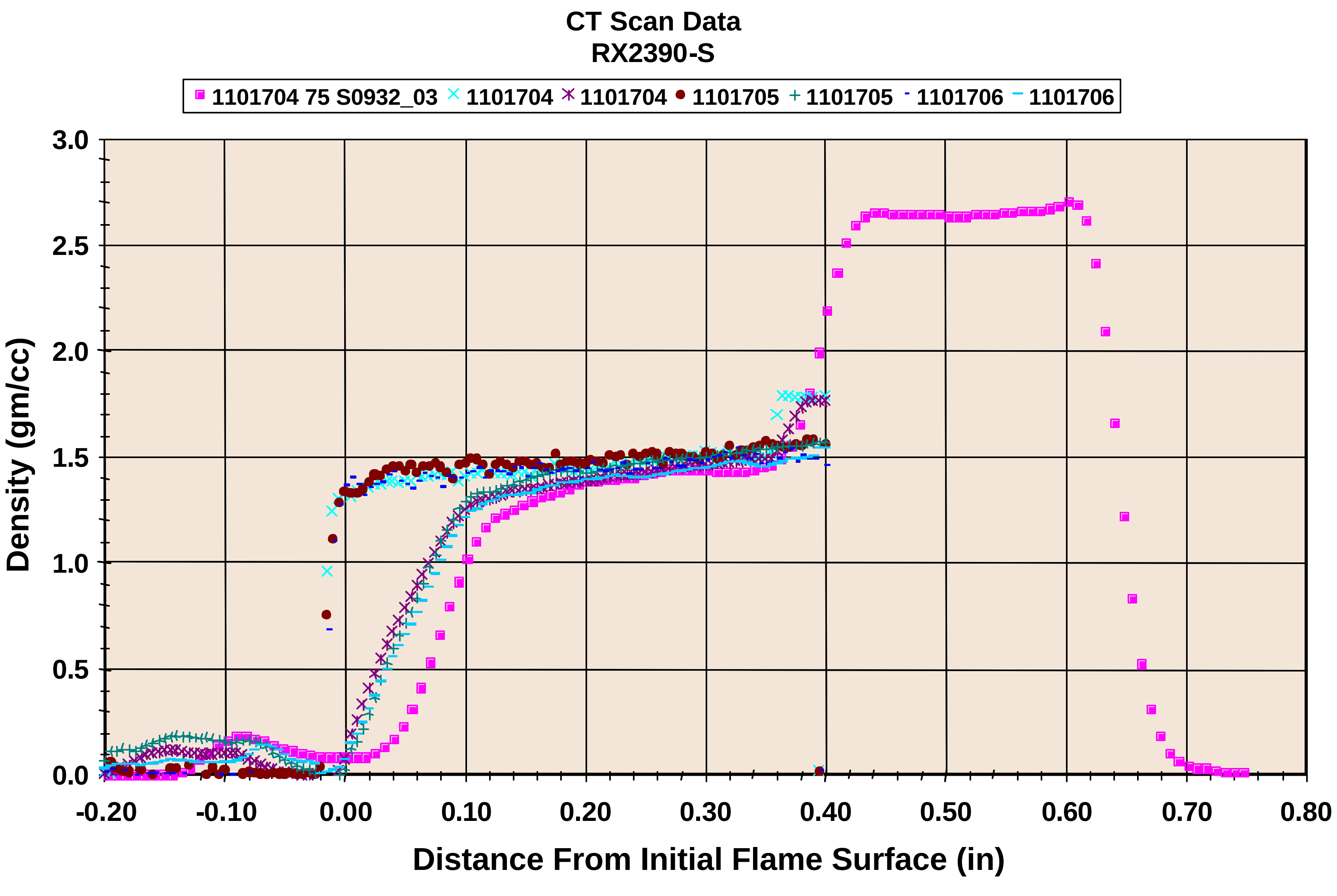




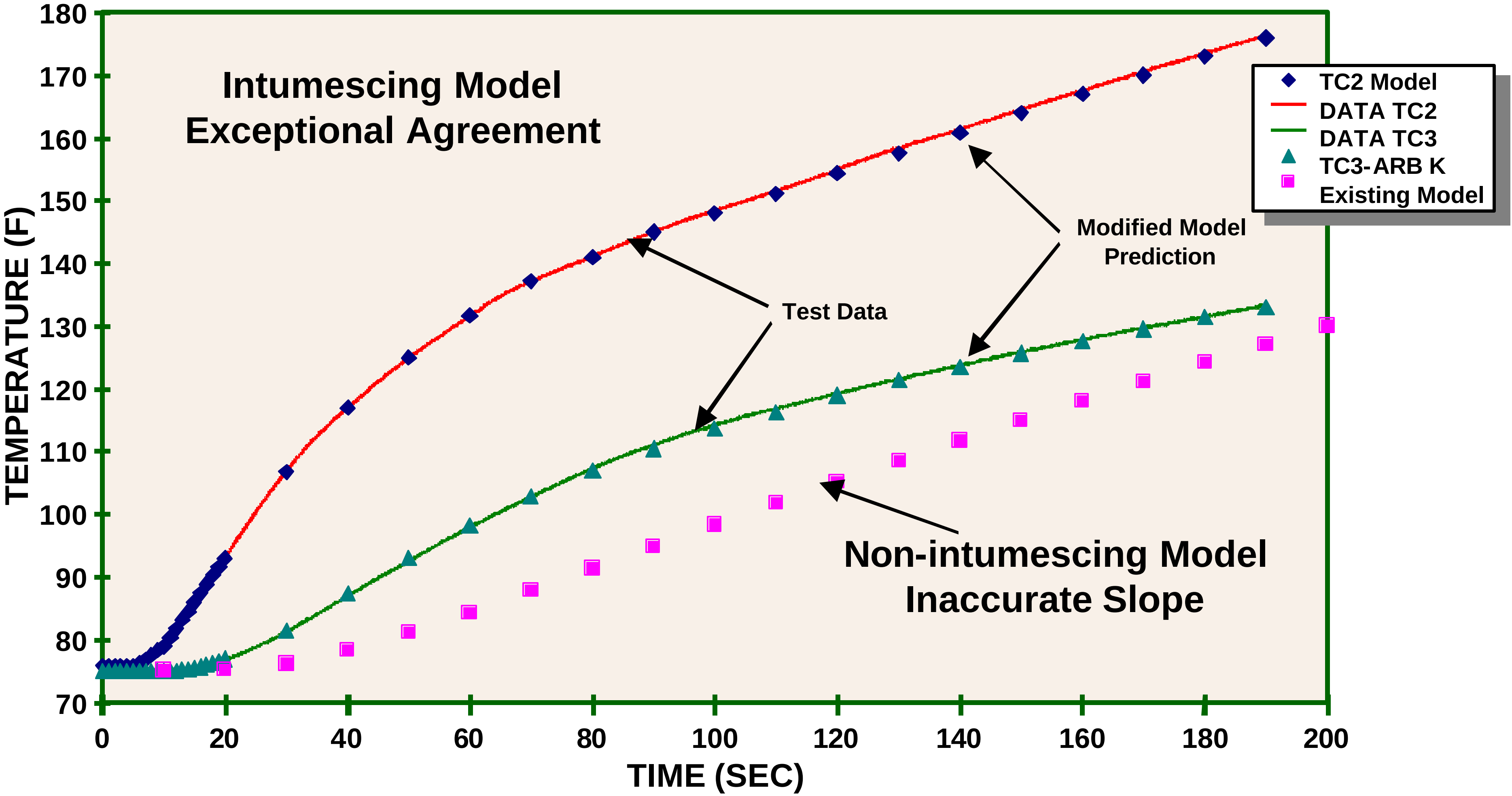
LHMEL Radiography Results



LHMEL Digitized RTR Results

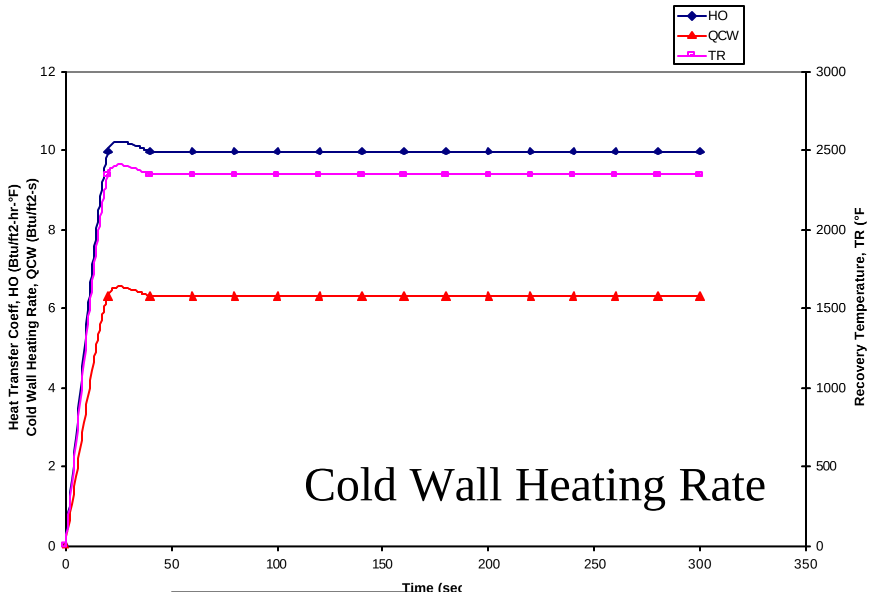


Comparison of Non-Intumescing and Intumescing Model Predictions

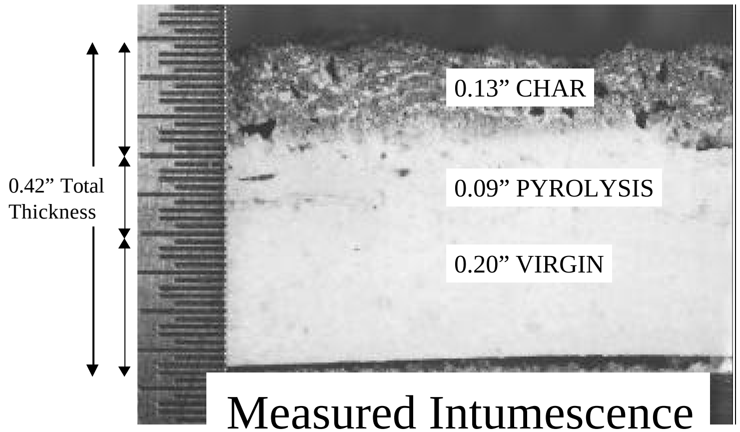


NASA HGTF Low Shear Hypersonic Tests

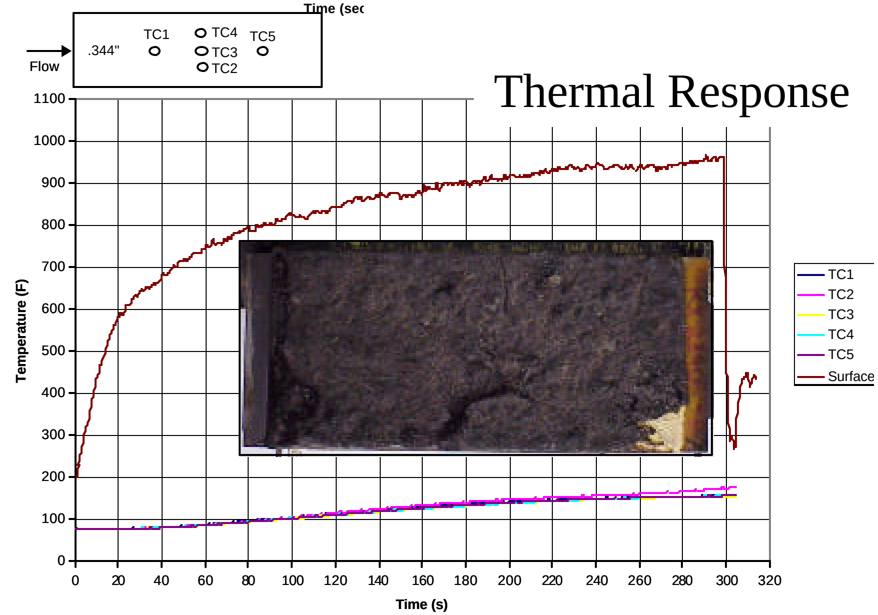
Test Facility And Configuration



Cold Wall Heating Rate

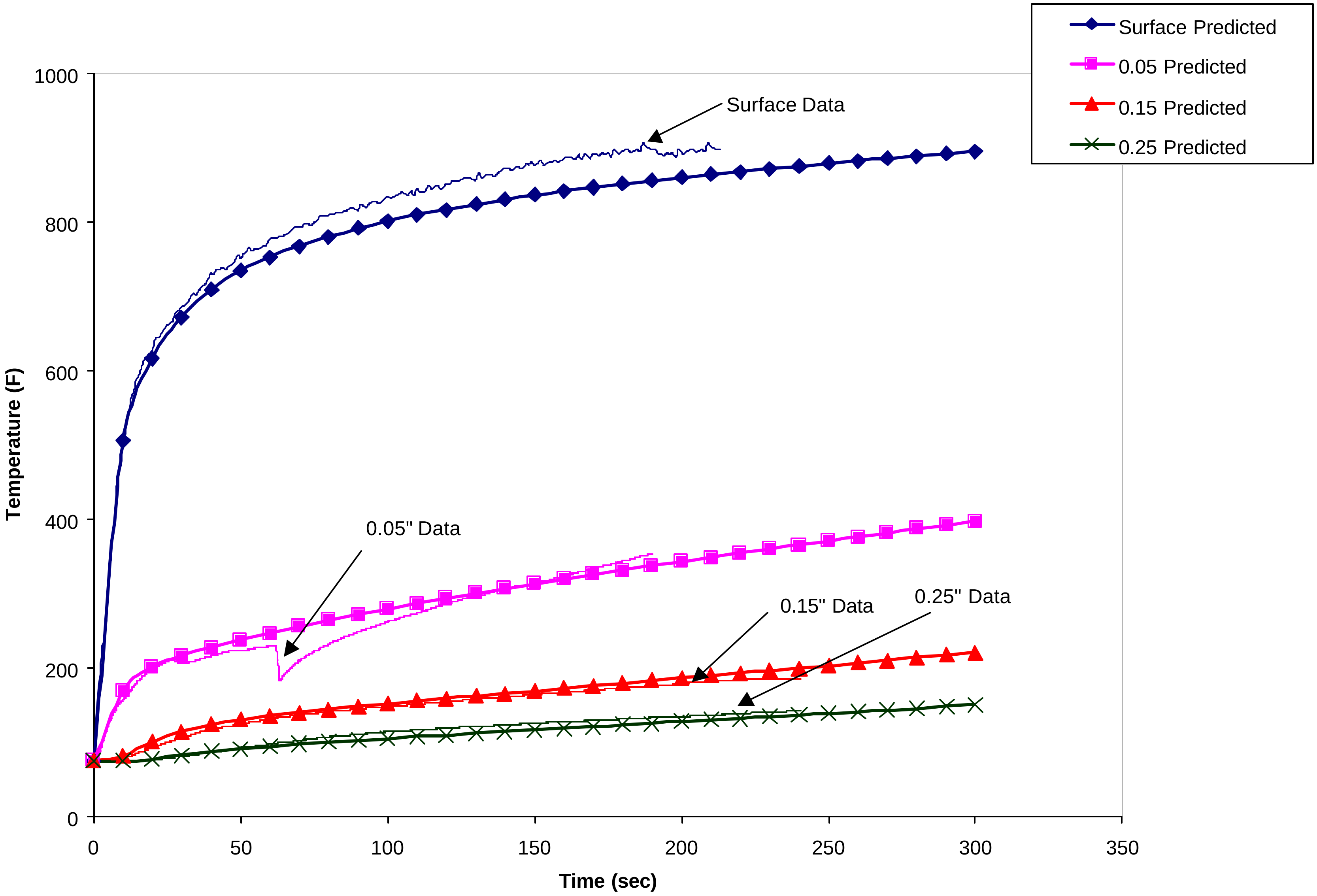


Measured Intumescence and Decomposition

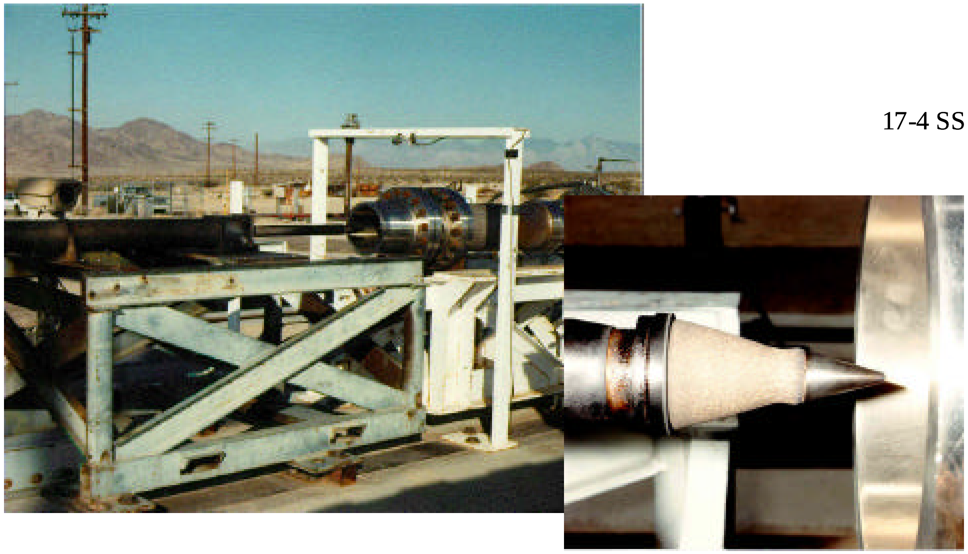


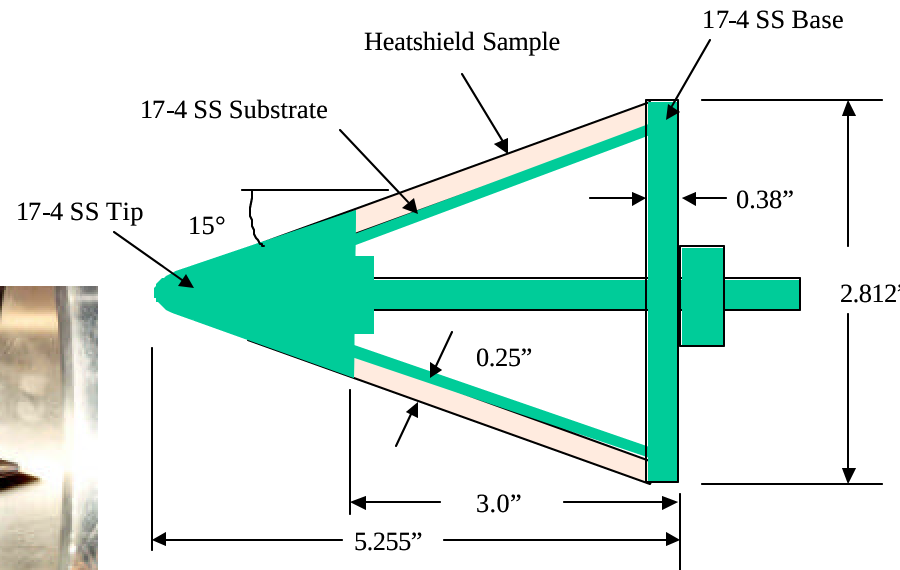
Thermal Response

Model Thermal Predictions for HGTF Test

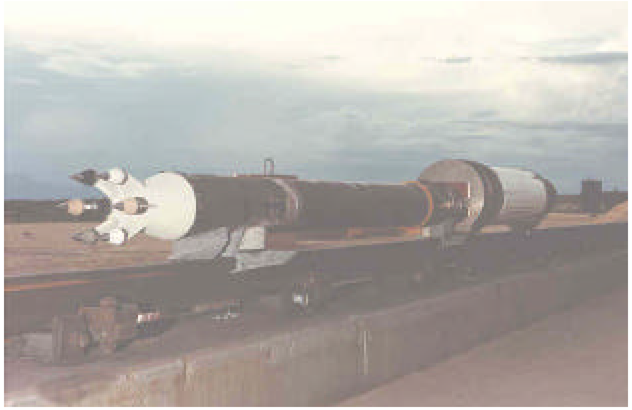


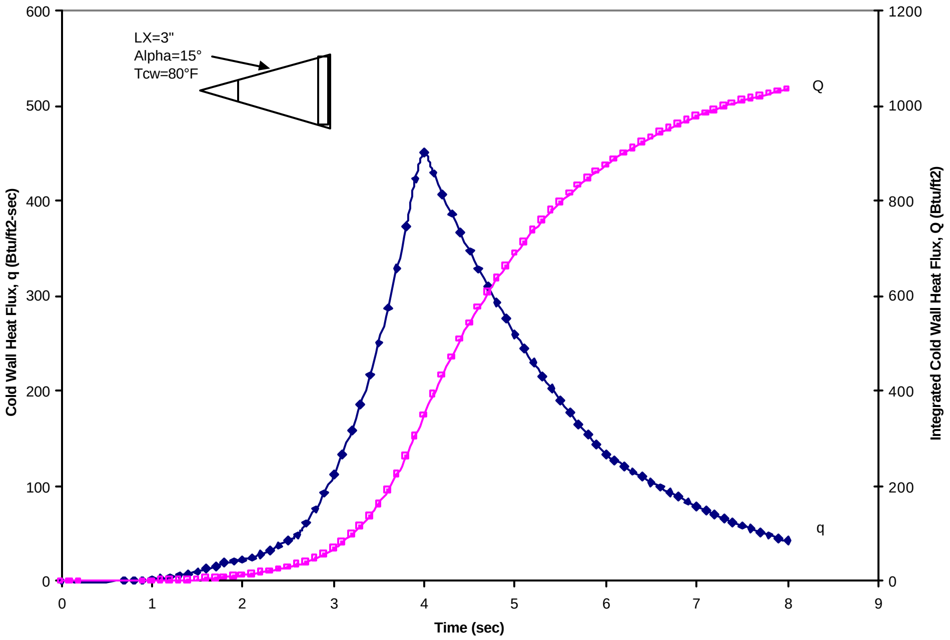
NAWC T-Range Ablation Tests

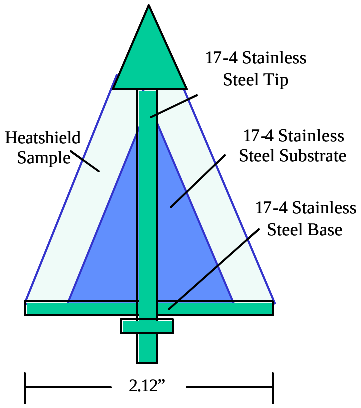




HHSTT High Shear Test Configuration

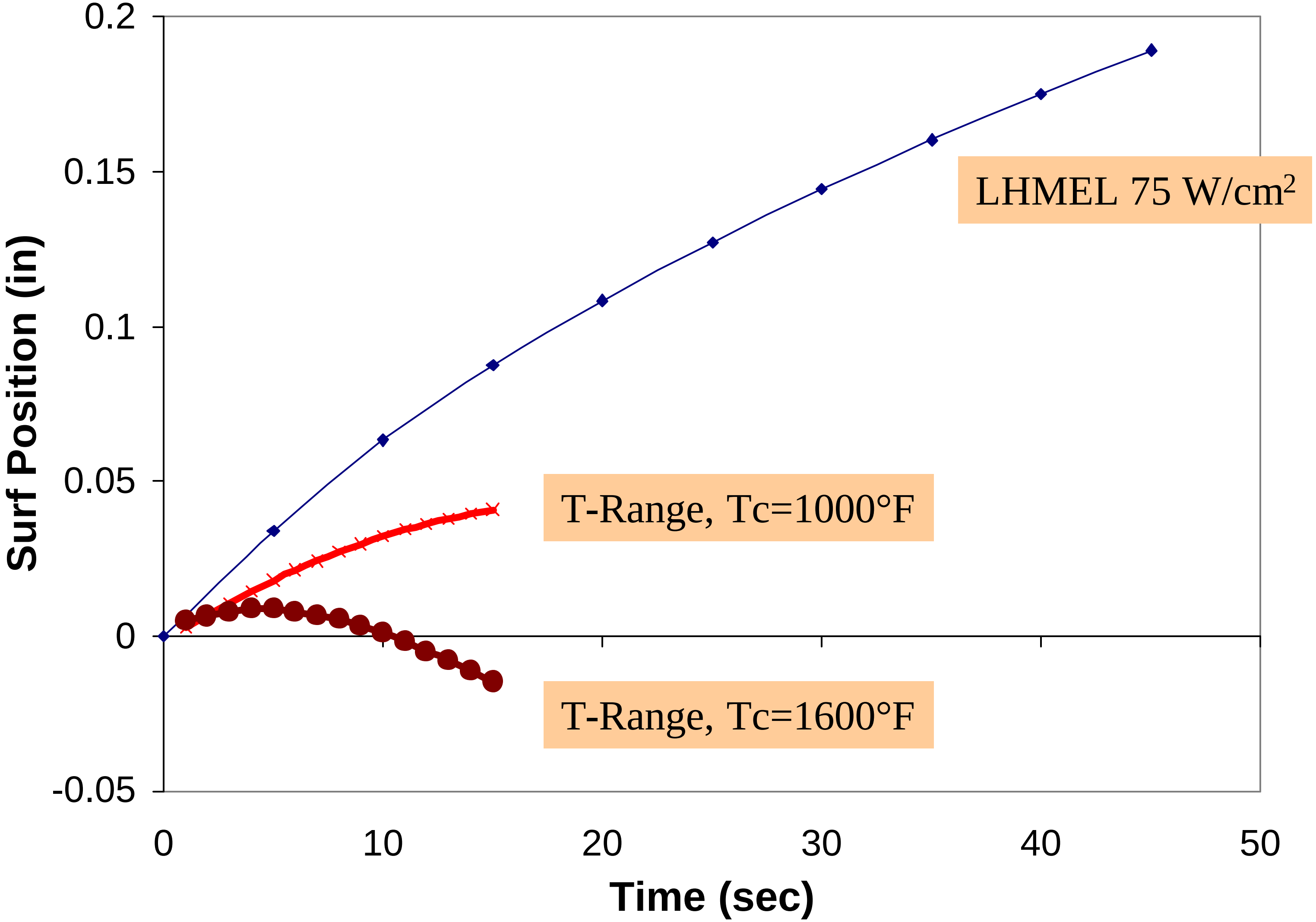






15° Conical Sample

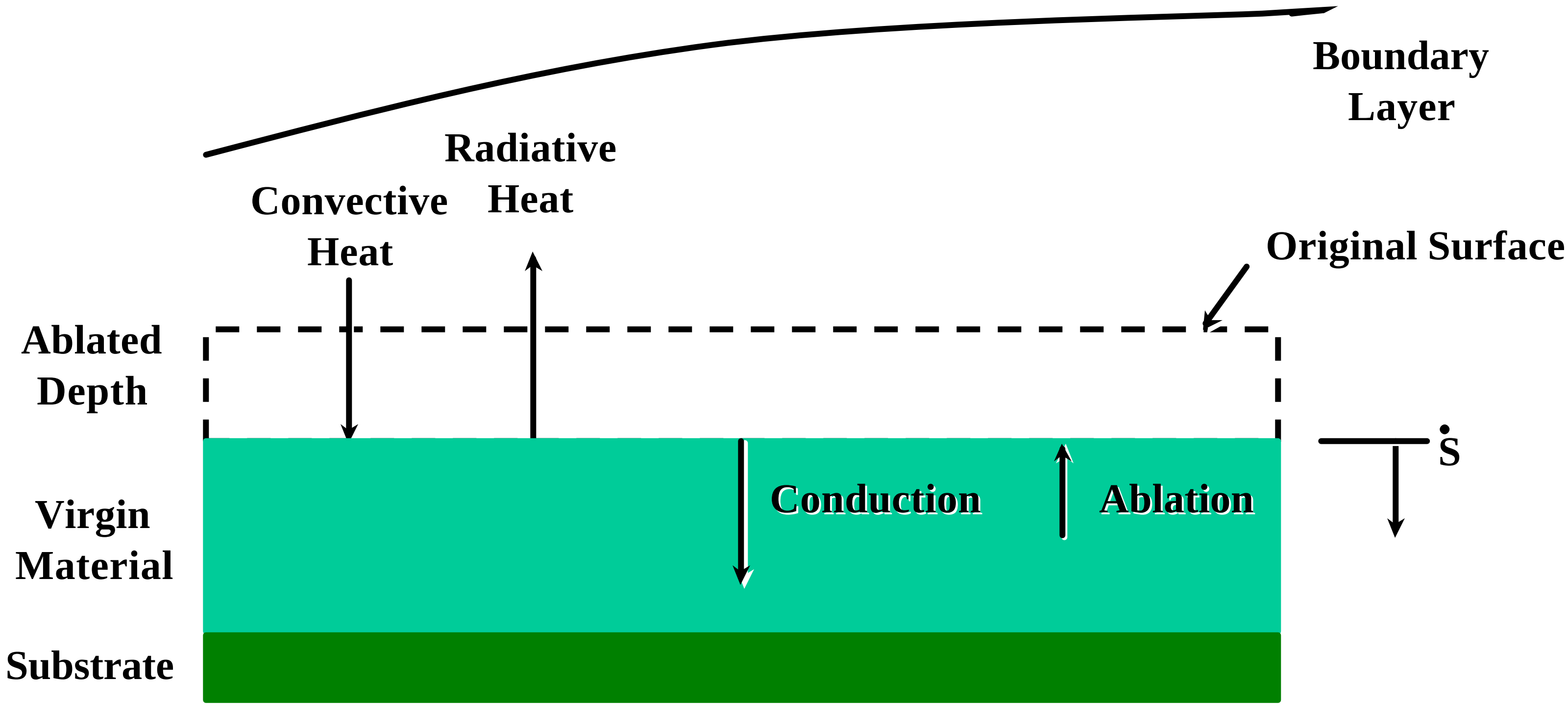
Coupled Intumescence and Mechanical Erosion Modeling



Q* Models

- **Modeling Capabilities**
  - **Ablation measured to virgin/pyrolysis interface(ablation temperature, heat of ablation)**
  - **Conduction**
  - **Blowing for sublimation process**
  - **Simplification of required input parameters**
- **Application**
  - **Generally applicable to materials/environments with high mechanical erosion/ablation**
  - **Not appropriate for highly decomposing/intumescing materials**
- **Limitations**
  - **Requires ablation performance test data for heating/shear environment of interest**
  - **Can provide misleading results if extrapolated to other environments**
  - **Does not necessarily provide realistic surface temperature response or physical surface removal prediction (simplified heat of ablation model)**

Heat of Ablation Model Development



Energy Balance

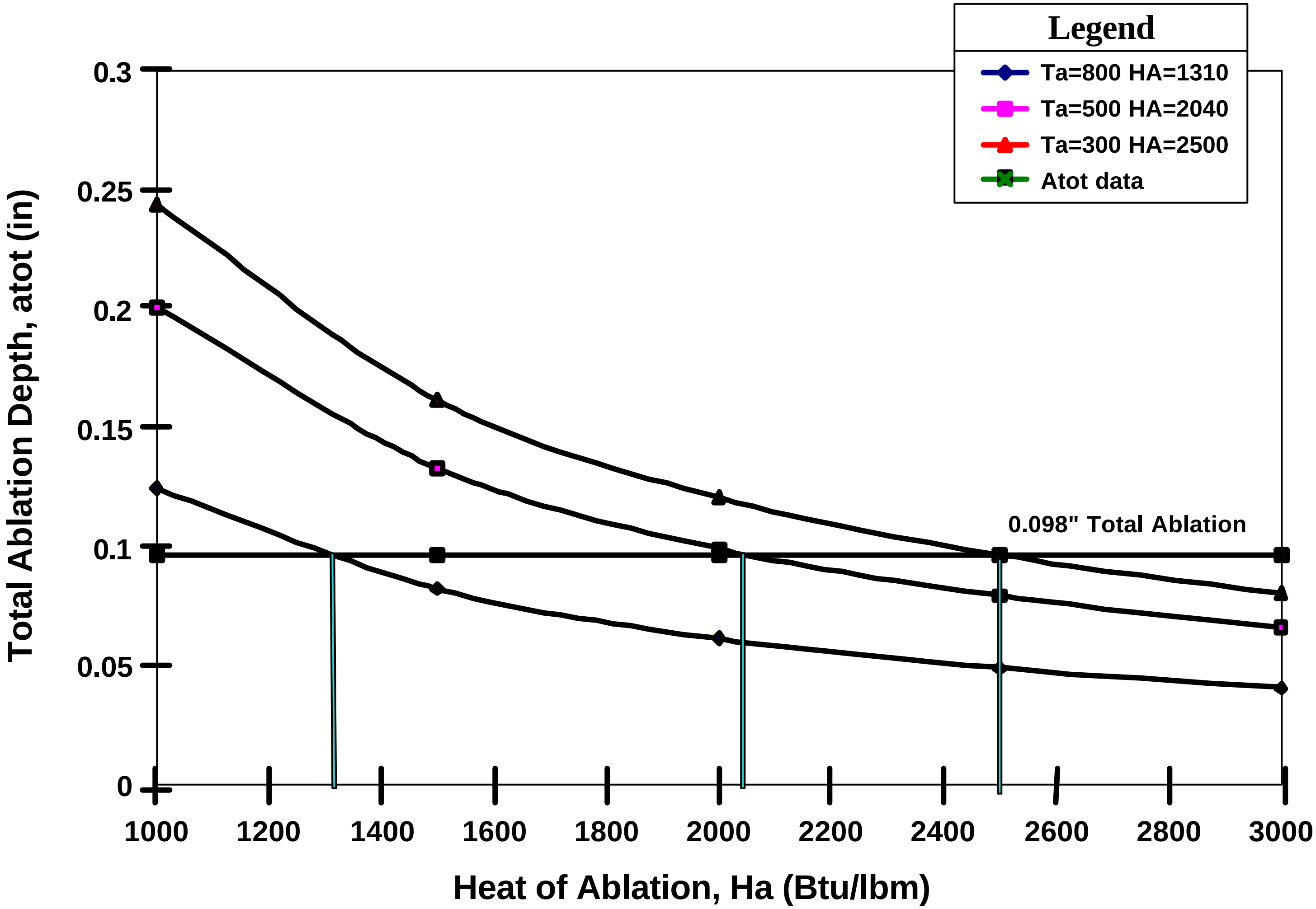
$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right)$$

Ablation Surface Boundary Condition

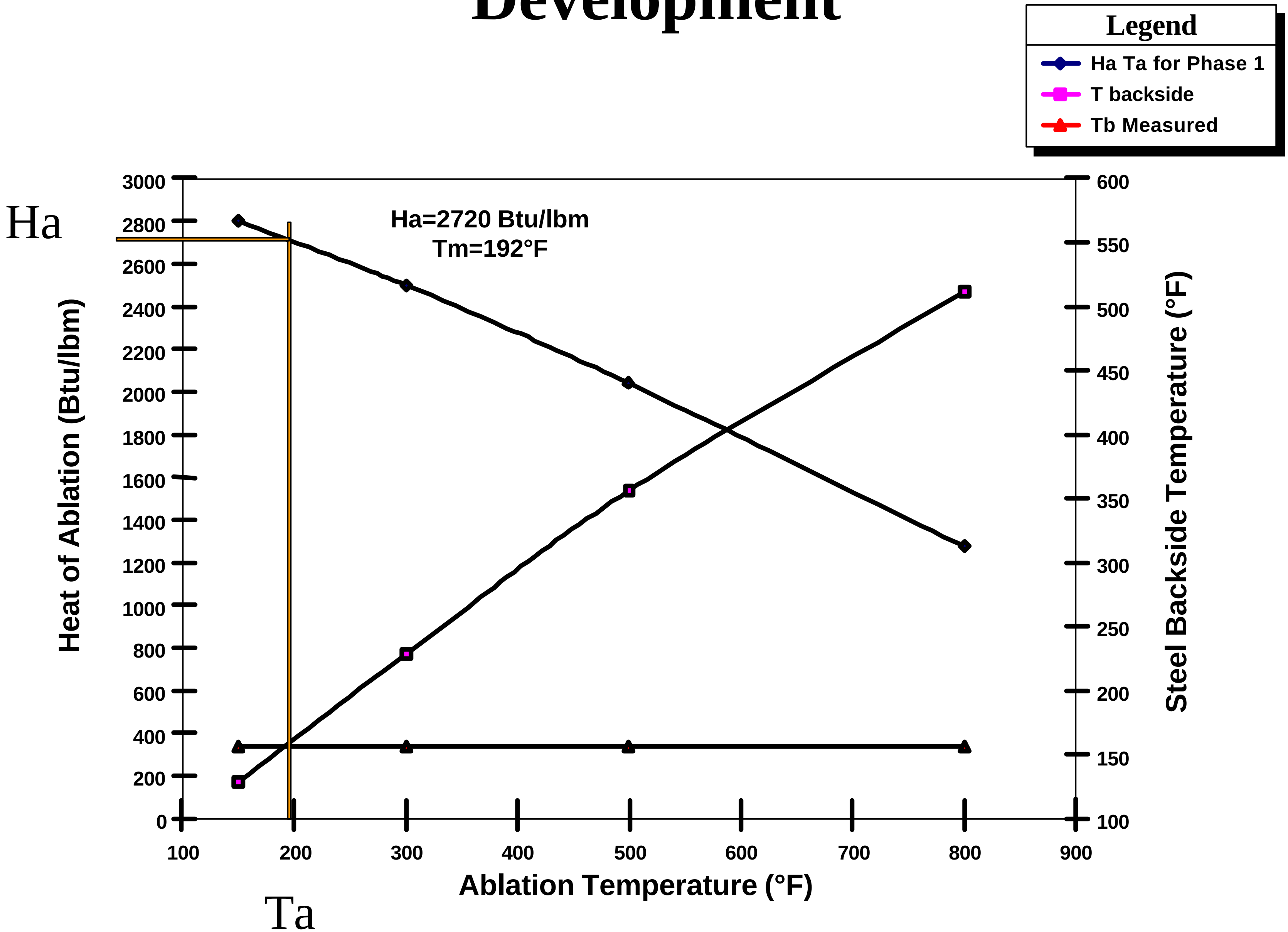
$$-k\frac{\partial T}{\partial x}\Big|_{x=s} = q_c(t) = \rho \dot{s} H_a$$

$$Ha = \frac{\dot{q}}{\rho_{virgin} * \alpha_{tot}} = \frac{\int h(T_r - T_a)dt}{\rho_{virgin} * \alpha_{tot}} \; ; \quad \textit{(during period of ablation)}$$

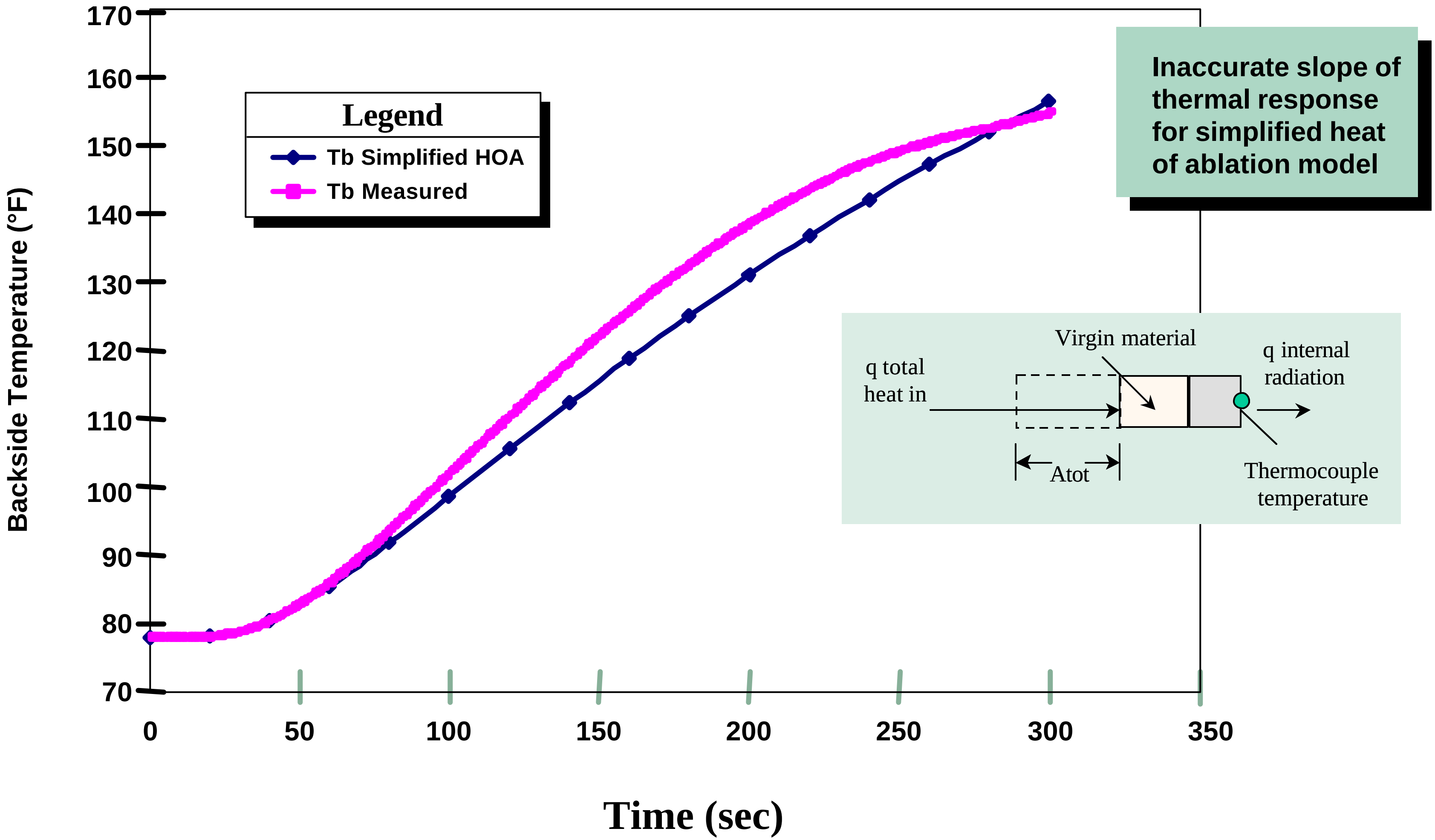
Typical Heat of Ablation Model Development



Typical Heat of Ablation Model Development



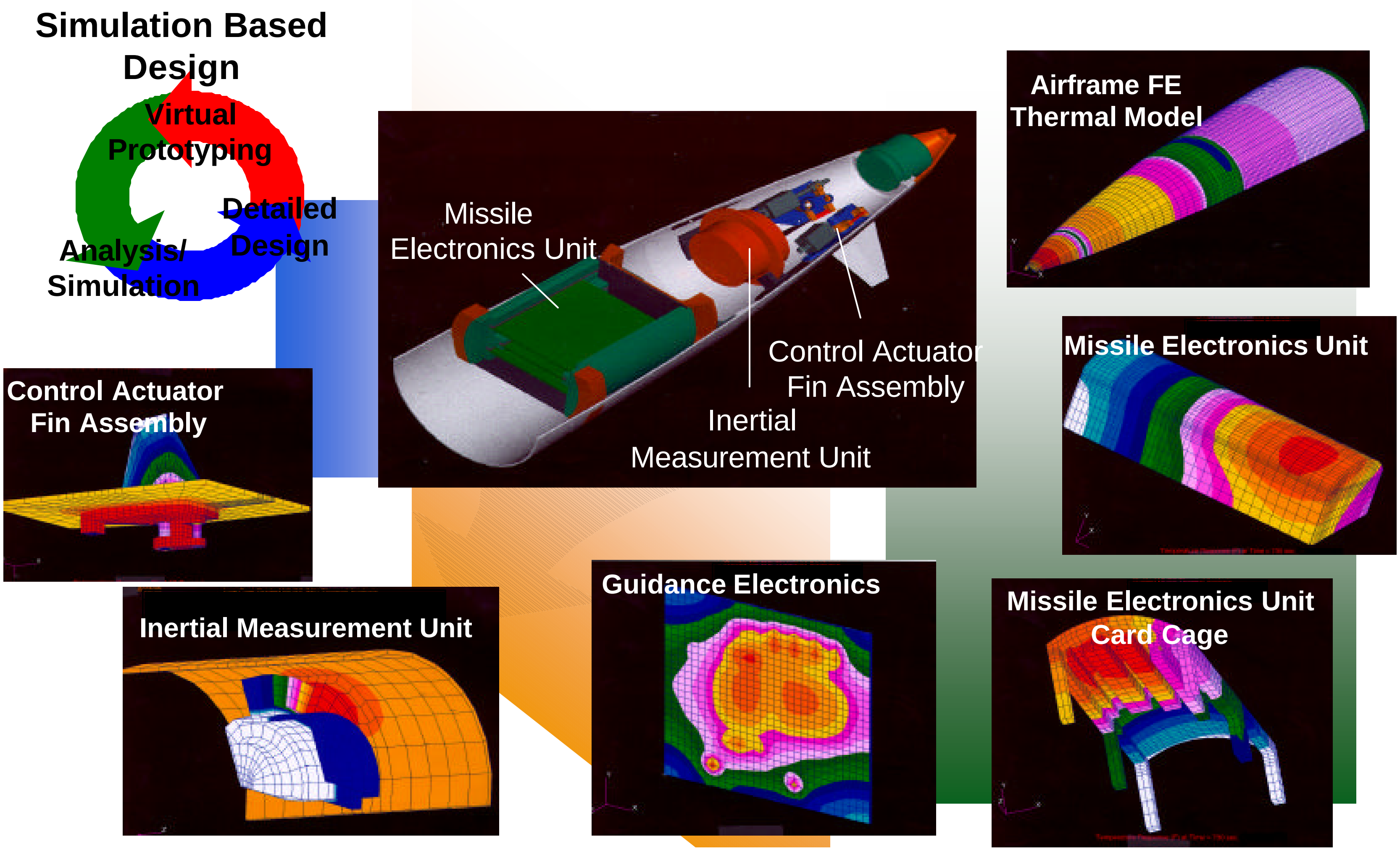
Typical Heat of Ablation Model Development



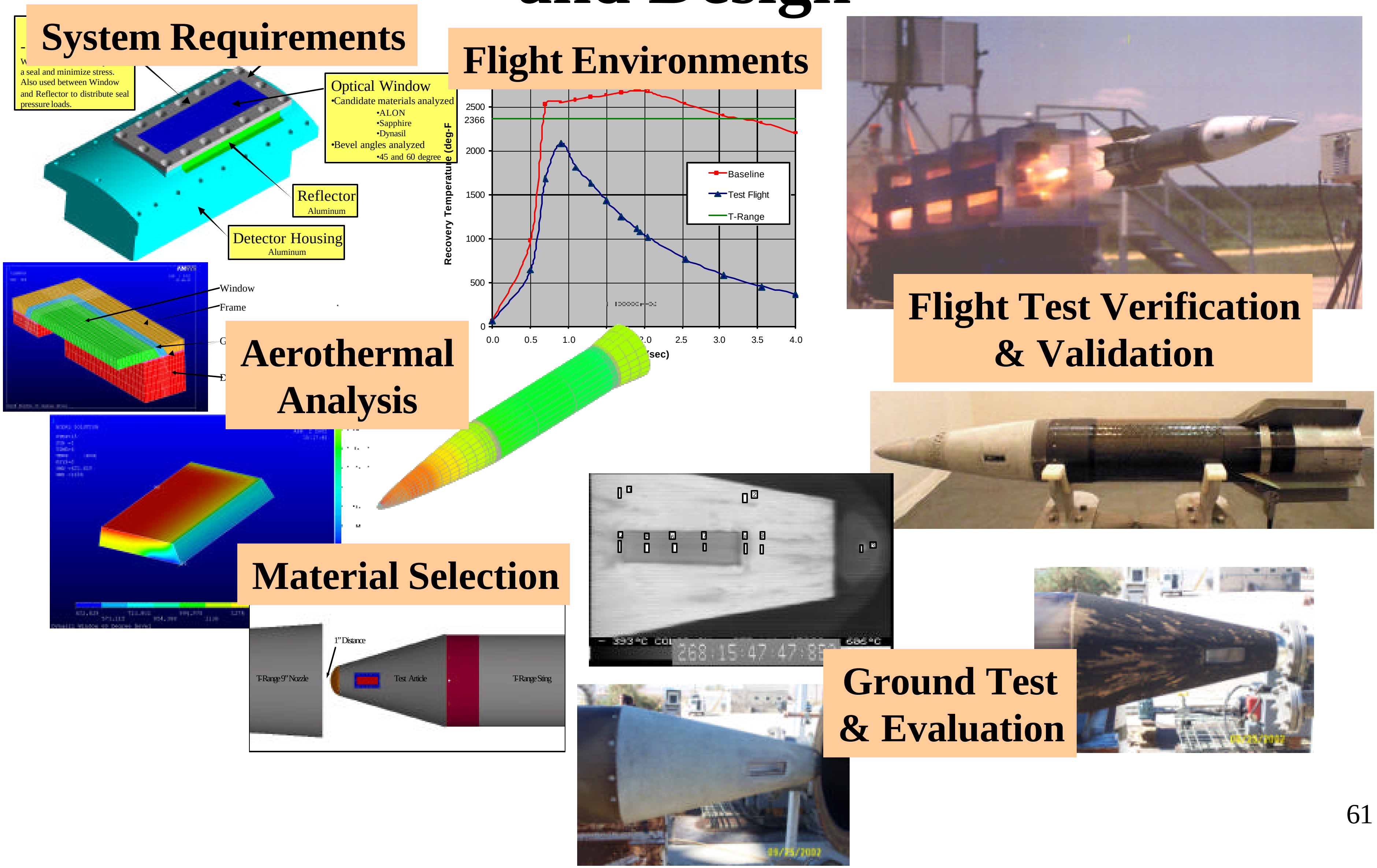
Conduction Models

- **Modeling Capabilities**
  - Conduction
  - Modified thermal properties to account for other thermal response phenomena (density change)
- **Application**
  - Generally applicable to materials/environments with no decomposition or surface removal/ablation
  - Common approach for finite element analysis until a coupled ablation capability is developed
- **Limitations**
  - Does not allow surface removal
  - Does not generally account for density changes that effect conduction
  - Can provide misleading results if used for ablating/decomposing materials

Examples of Aerothermal Analysis and Design



Examples of Aerothermal Analysis and Design



Summary

- **This tutorial has provided a brief overview of the aerothermal analysis and design process**
- **Various components of this process have been discussed**
- **A limited survey of existing methodologies and corresponding codes have been provided**

Summary

- The goal of this tutorial was to define a general process in which aerothermal analysis and design should be conducted.
- It is imperative for the designer to consider a wide range of issues when conducting aerothermal analysis and design.
- Flexibility should be maintained during the process to ensure critical issues are adequately resolved prior to system final design.
- Engineering methods represent an efficient approach to design. However, more complex approaches should be utilized to supplement these engineering methods when deemed necessary.