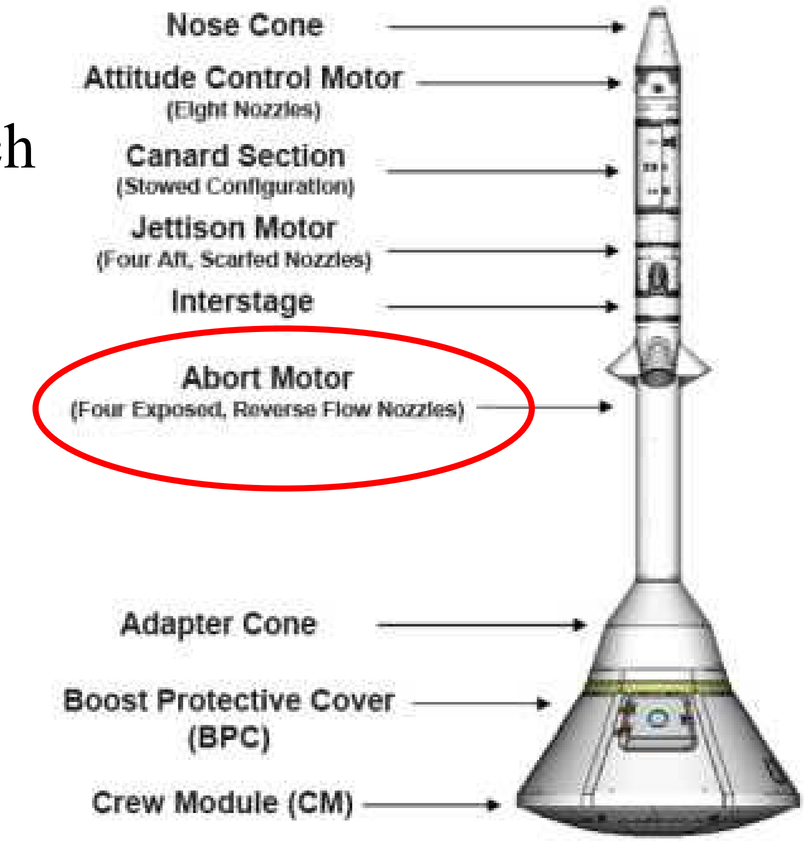
Propellant Bulk Temperature Modeling for the Orion Launch Abort System

Justin Fox and Joseph Bonafede
Orbital Sciences Corporation, Dulles, VA, 20148
ARES Corporation, Dulles, VA, 20148

Thermal & Fluids Analysis Workshop (TFAWS 2008)
San Jose State University, San Jose, CA
August 18-22, 2008

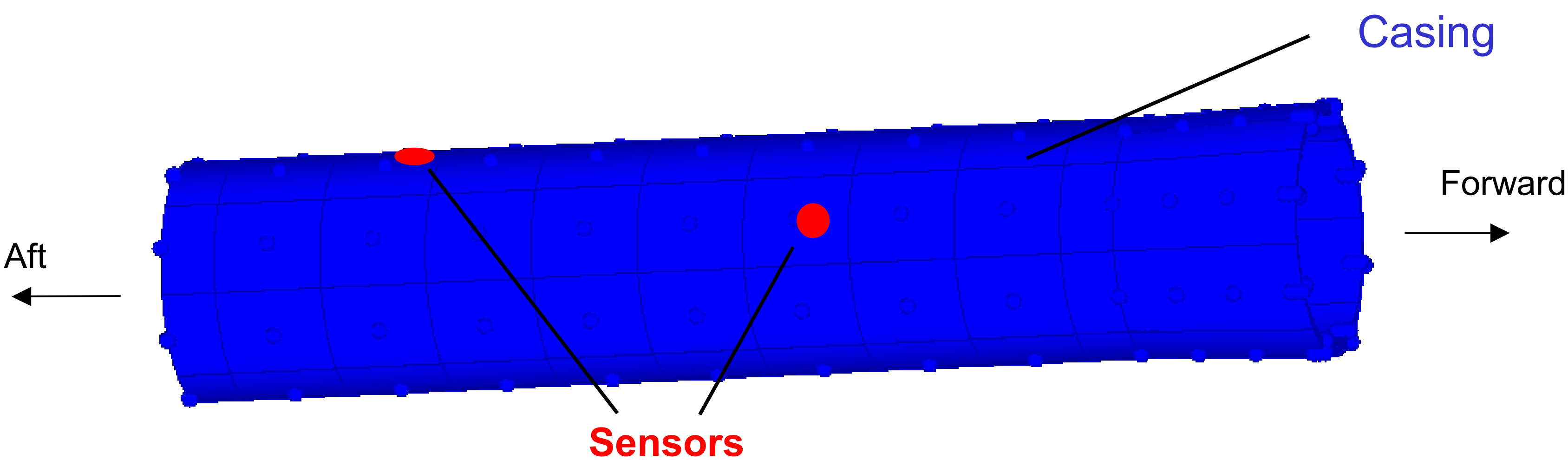
Propellant Mean Bulk Temperature (PMBT)

- Solid Rocket Performance Is Highly Dependent on Propellant Temperature
- Our Task: Predict The Pre-Launch Temperature of the Orion Launch Abort System Main Abort Motor
- Environment Inside the Motor Precludes Direct Sensing



Propellant Mean Bulk Temperature (PMBT)

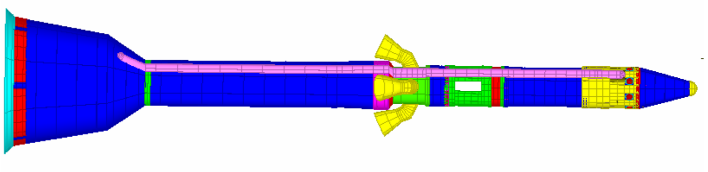
- External Case Temperature Sensors Available To Help Predict PMBT
  - More Reliable Than Measuring Various Environment Conditions To Predict PMBT
  - Must Account For Temperature Lag Between The Case And The PMBT
  - Correlate System-Level Model Or Develop New PMBT Model



Two Modeling Approaches Compared

- Analytical Model
  - Inputs: External Temperature History
  - Provides:
    - Bulk Temperature And Temperature Lag If Given Sufficient External Temperature History
    - Insight To Allow Temperature Lag Estimation If Given Some External Temperature History

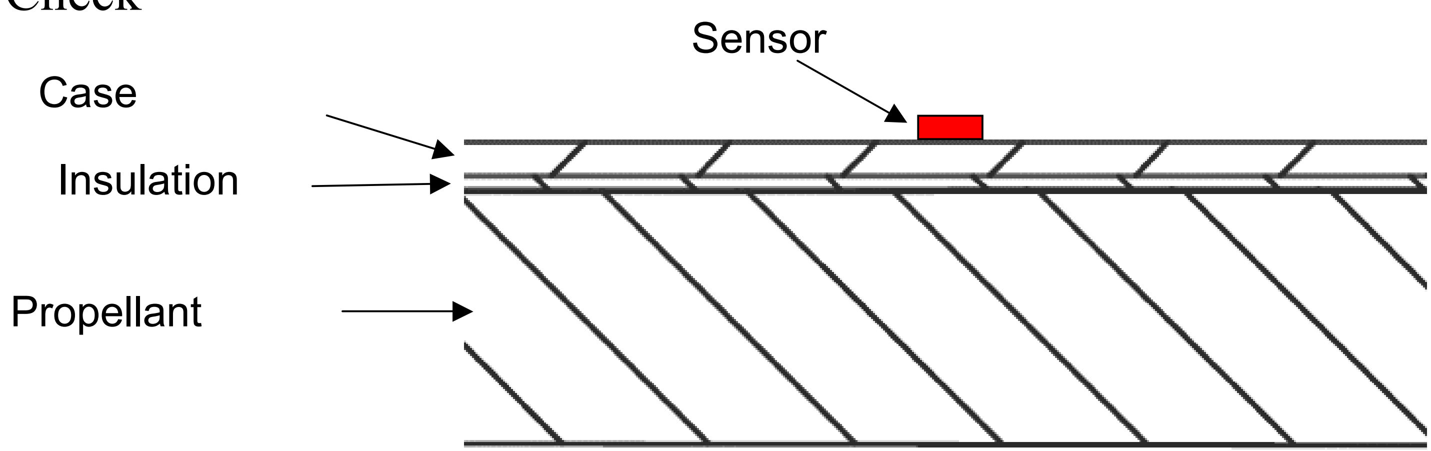
- System-Level Thermal Model



  - Inputs: External Environment Data
  - Provides:
    - Bulk Temperature and Temperature Lag If Given Actual External Environments
    - Temperature Lag Limits If Given Worst-Case External Environments

Analytical Model Assumptions

- 1-Dim Radial Model Focuses On Three Materials
  - Case, Insulation, and Propellant
  - Neglect Axial Conduction Into/Out Of AM
  - Neglect Contact Resistances Between Materials
  - Neglect Heat Capacity of Case and Insulation
  - Assume Sensor Temperature as Case OD Temperature
  - Model Propellant As Hollow Circular Cylinder (Use Min ID of Grain, But Equate Mass Using Density Multiplier)
- Solve PMBT As Function Of Time History Of Sensor Temperature
- Solve Analytically In Excel And Implement in Thermal Desktop As A Check



Analytical Solution

- Solution Steps, PMBT From External Temperature History
  - Set T_{init} (Assumed Uniform) Equal To Initial Sensor Temperature
  - Solve For PMBT Response To Unit Step External Temperature Change
  - Solve Duhamel Superposition Using External Temperature History And PMBT Response To Unit Step External Temperature Change
  - Use Sufficient History of Sensor Temperatures To Damp Initial Transient

$$\text{Step}: \quad T_{ext}(t) = \begin{cases} T_{init} & t < \tau_0 \\ T_{init} + \Delta T_{ext} & t \geq \tau_0 \end{cases}$$

$$\text{PDE for Step Response}: \quad (\rho c_p)_{prop} \frac{\partial T_{prop}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_{prop} r \frac{\partial T_{prop}}{\partial t} \right)$$

$$t \leq \tau_0 : \quad T_{prop} = T_{init}$$

$$r = r_{prop,ID} : \quad -k_{prop} \frac{\partial T_{prop}}{\partial r} = 0$$

$$r = r_{prop,OD} : \quad -k_{prop} \frac{\partial T_{prop}}{\partial r} = h_{eff}\left(T_{prop} - T_{ext}(t)\right)$$

$$\text{where} \quad (hA)'_{eff} = \left(\left((hA)'_{eff,case} \right)^{-1} + \left((hA)'_{eff,ins} \right)^{-1} \right)^{-1} = \left(\frac{\ln\left(r_{case,OD}/r_{case,ID}\right)}{2\pi k_{case}} + \frac{\ln\left(r_{ins,OD}/r_{ins,ID}\right)}{2\pi k_{ins}} \right)^{-1}$$

Analytical Solution, Unit Step Responses

- Series Solution Using Separation Of Variables
- Converges Well
  - Best At Large t^+ And Small r^+
  - Bulk Temperature Response Converges Even Better

$$\Psi^+(r^+,t^+) = 1-\Phi^+(r^+,t^+) = \sum_{n=1}^{\infty} A_n \left(\mathrm{J}_0(\lambda_n^+ r^+) - \frac{\mathrm{J}_1(\lambda_n^+ r_i^+)}{\mathrm{Y}_1(\lambda_n^+ r_i^+)} \mathrm{Y}_0(\lambda_n^+ r^+) \right) \exp\left(-\lambda_n^{+2} t^+\right)$$

$$\Psi_b^+(t^+) = 1-\Phi_b^+(t^+) = \frac{2}{r_o^{+2}-r_i^{+2}} \int_{x^+=r_i^+}^{x^+=r_o^+} \Psi^+(x^+,t^+) x^+ dx^+ = \frac{2r_o^+}{r_o^{+2}-r_i^{+2}} \sum_{n=1}^{\infty} \frac{B_n}{\lambda_n^+} \exp\left(-\lambda_n^{+2} t^+\right)$$

where

$$A_n = \frac{2\Psi_0^+ \mathrm{Bi}\, r_o^+ Y_1(\lambda_n^+ r_i^+)\left(\mathrm{J}_0(\lambda_n^+ r_o^+)\mathrm{Y}_1(\lambda_n^+ r_i^+) - \mathrm{J}_1(\lambda_n^+ r_i^+)\mathrm{Y}_0(\lambda_n^+ r_o^+)\right)}{\left(\lambda_n^{+2} - \mathrm{Bi}^2\right) r_o^{+2}\left(\mathrm{J}_0(\lambda_n^+ r_o^+)\mathrm{Y}_1(\lambda_n^+ r_i^+) - \mathrm{J}_1(\lambda_n^+ r_i^+)\mathrm{Y}_0(\lambda_n^+ r_o^+)\right)^2 - \lambda_n^{+2} r_i^{+2}\left(\mathrm{J}_0(\lambda_n^+ r_i^+)\mathrm{Y}_1(\lambda_n^+ r_i^+) - \mathrm{J}_1(\lambda_n^+ r_i^+)\mathrm{Y}_0(\lambda_n^+ r_i^+)\right)^2}$$

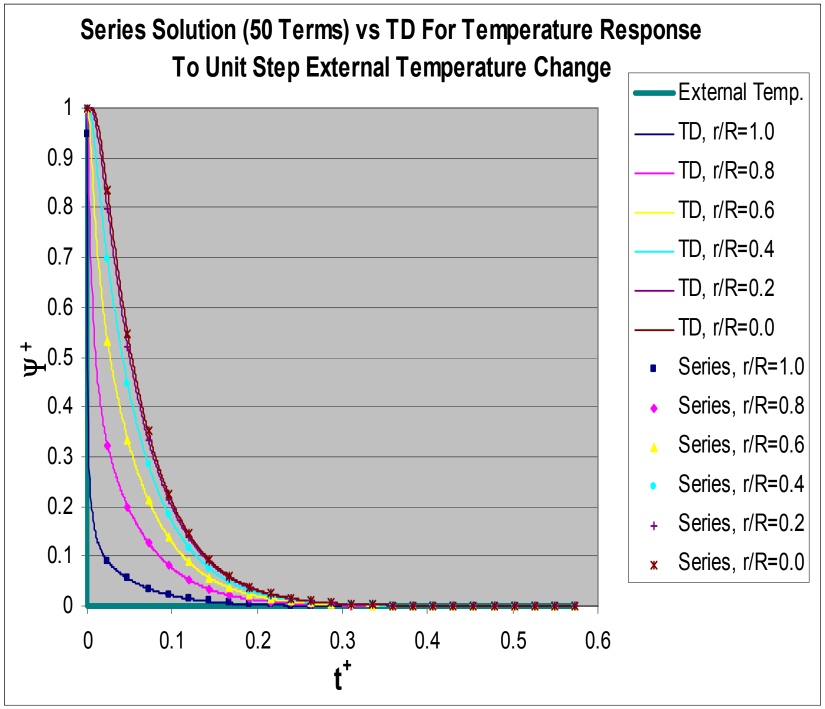
$$B_n = A_n \left(\mathrm{J}_1(\lambda_n^+ r_o^+) - \frac{\mathrm{J}_1(\lambda_n^+ r_i^+)}{\mathrm{Y}_1(\lambda_n^+ r_i^+)} \mathrm{Y}_1(\lambda_n^+ r_o^+) \right)$$

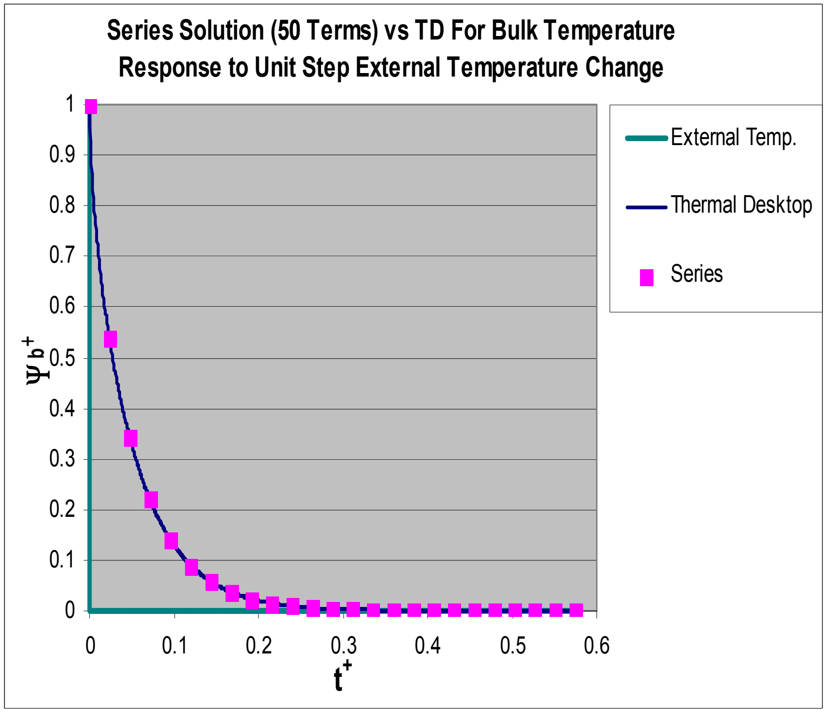
and where λ_{n}^+ are the positive roots of the characteristic equation

$$\mathrm{J}_1(\lambda_n^+ r_i^+)\left(\mathrm{Bi}\,\mathrm{Y}_0(\lambda_n^+ r_o^+) - \lambda_n^+ \mathrm{Y}_1(\lambda_n^+ r_o^+)\right) - \mathrm{Y}_1(\lambda_n^+ r_i^+)\left(\mathrm{Bi}\,\mathrm{J}_0(\lambda_n^+ r_o^+) - \lambda_n^+ \mathrm{J}_1(\lambda_n^+ r_o^+)\right) = 0$$

Analytical Solution, Unit Step Responses, Cont.

- Series Solution Verified With Numerical Solution Obtained From Thermal Desktop
- 50 Terms Used, But Usually Only A Few Required





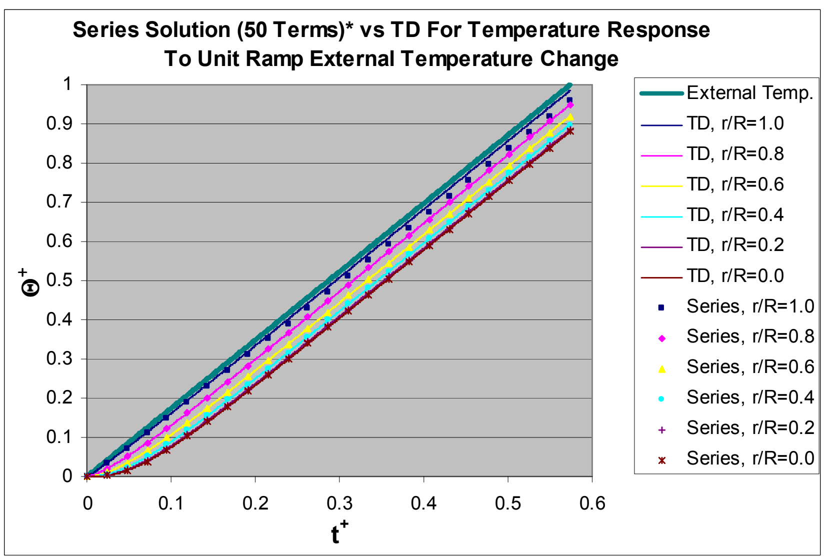
Analytical Solution, Duhamel Integral

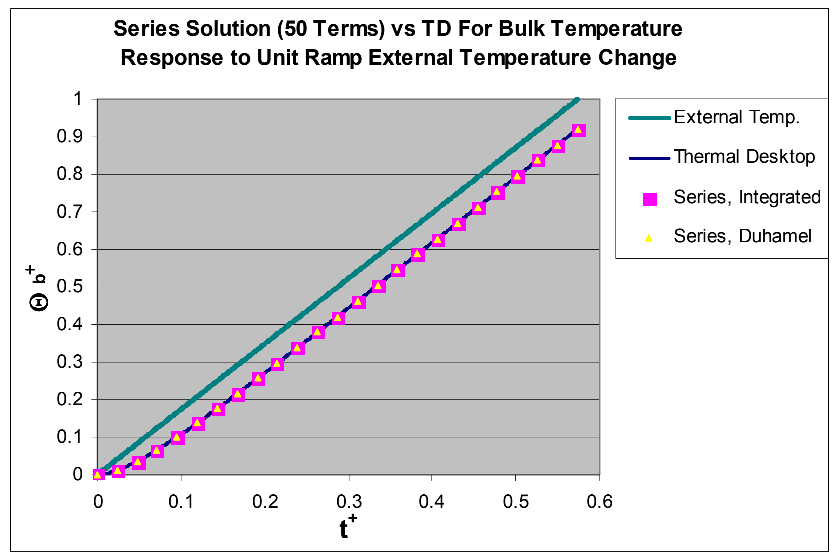
- Input: External Temperature History
- Output: PMBT For Times Up To Last External Temperature Input
- Accuracy
  - Depends On Replication Of True External Temperature History
  - Requires Sufficient Time History To Dampen Initial Transient In Order To Negate Assumption Of Uniform Initial Temperature

$$\theta_b(t^+) = T_b(t^+) - T_{init} = \int_{s^+=\tau_0^+=0}^{s^+=t^+} \theta_{ext}(s^+) \frac{d\Phi_b^+(t^+ - s^+)}{dt^+} ds^+ = \frac{2r_o^+}{r_o^{+2} - r_i^{+2}} \int_{s^+=\tau_0^+=0}^{s^+=t^+} \theta_{ext}(s^+) \sum_{n=1}^{\infty} \lambda_n^+ B_n \exp\left(-\lambda_n^{+2}\left(t^+ - s^+\right)\right)$$

Analytical Solution, Ramp Test Case

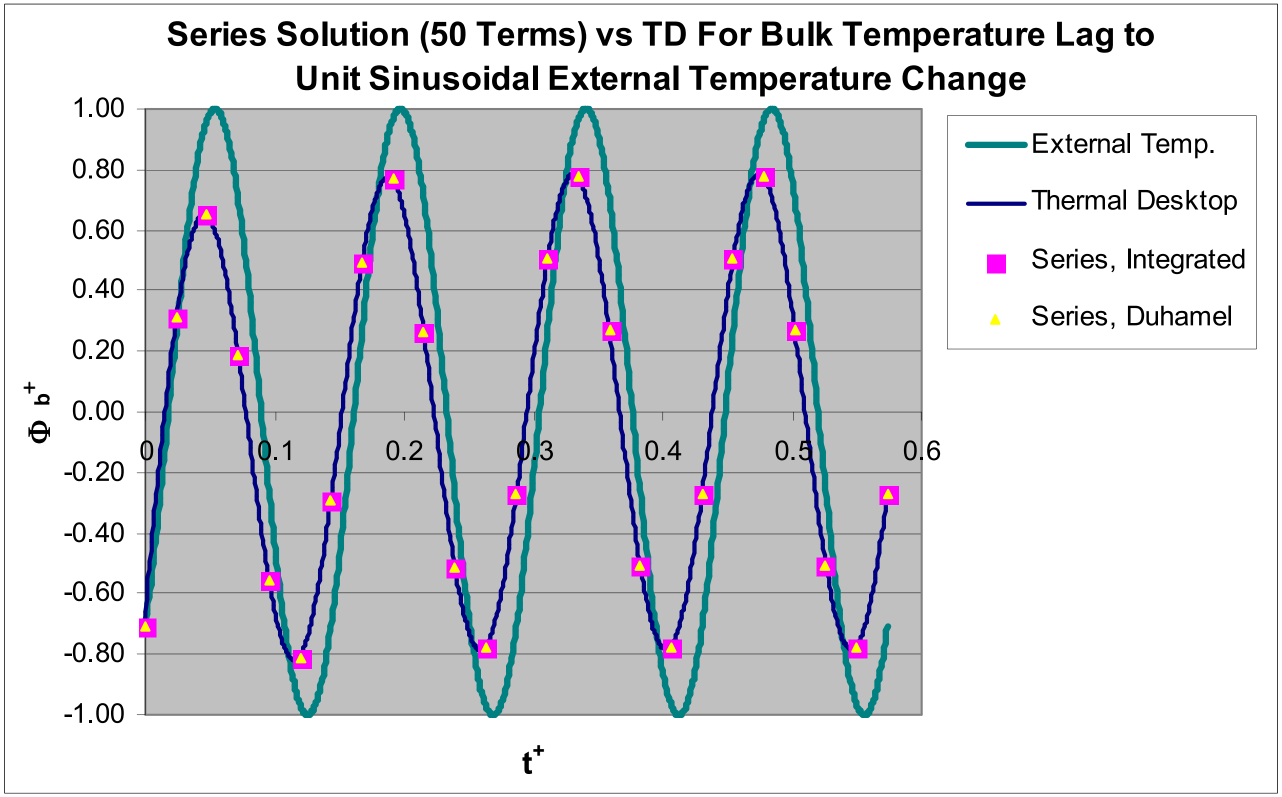
- Convergence
  - No problems With PMBT Response
  - Temperature Response Problematic At Large (t^+, r^+), But Otherwise Good
- Developing Temperature Lag
  - Non-Dimensional Temperature Lag, 0.045648
  - Non-Dimensional Time Constant $\sim(\lambda_1^+)^{-2}$, Using First-Term Approximation





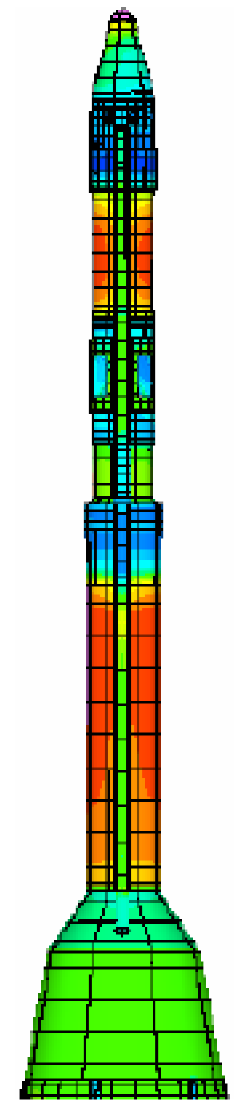
Analytical Solution, Sinusoid Test Case, Lag

- Developing Amplitude And Phase Change
  - Non-Dimensional Amplitude, ~0.80
  - Phase Lag, slight



System-Level Numerical Model

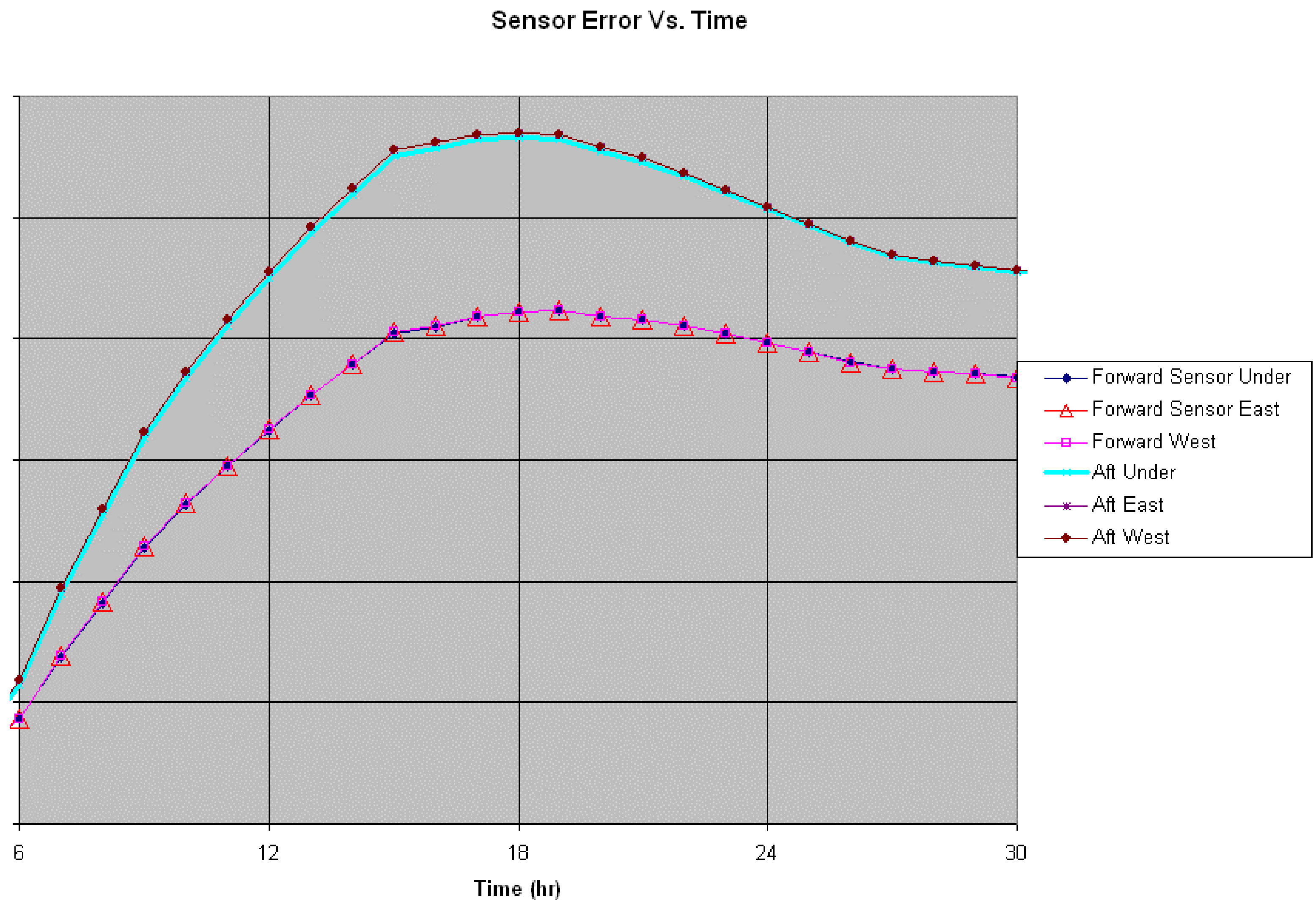
- LAS Modeled in Thermal Desktop v5.1
  - ~10k Nodes
  - 800 Surfaces/Solids
- Incorporates Environmental Effects
  - Sky (Sink) Radiation Temperature
  - Solar Radiation as a Function of Time of Day
  - Ambient Air Temperature
  - Wind
- Given Environmental Assumptions, This Model Predicts the Maximum Error Between the Sensors and the PMBT
  - Worst Case Error Arises During Worst Case Heating and Cooling Cases



Worst Case Conditions – Sudden Heating Case

- Air Temperature
  - 99% Variation for Edwards AFB – (i.e. WSMR)
    - Maximum temperature change in 3hrs = 20.7^{o}F
    - Maximum temperature change in 6hrs = 33.7^{o}F
    - Maximum temperature change in 12hrs = 37.8^{o}F
  - Create a Worst Case Heating Condition
    - Run Cold Case for 4 days – December Values
      - 1% Air Temperature – Dec.
      - 1% Sky Temperature, 99% Radiation – Dec.
      - 0 Wind Velocity
    - At 6AM on 5th day (just before sunrise), air temperature increases at maximum NEDD rate.
    - Temperature continues to rise until it intersects the 99% Hot Case Air Temperature

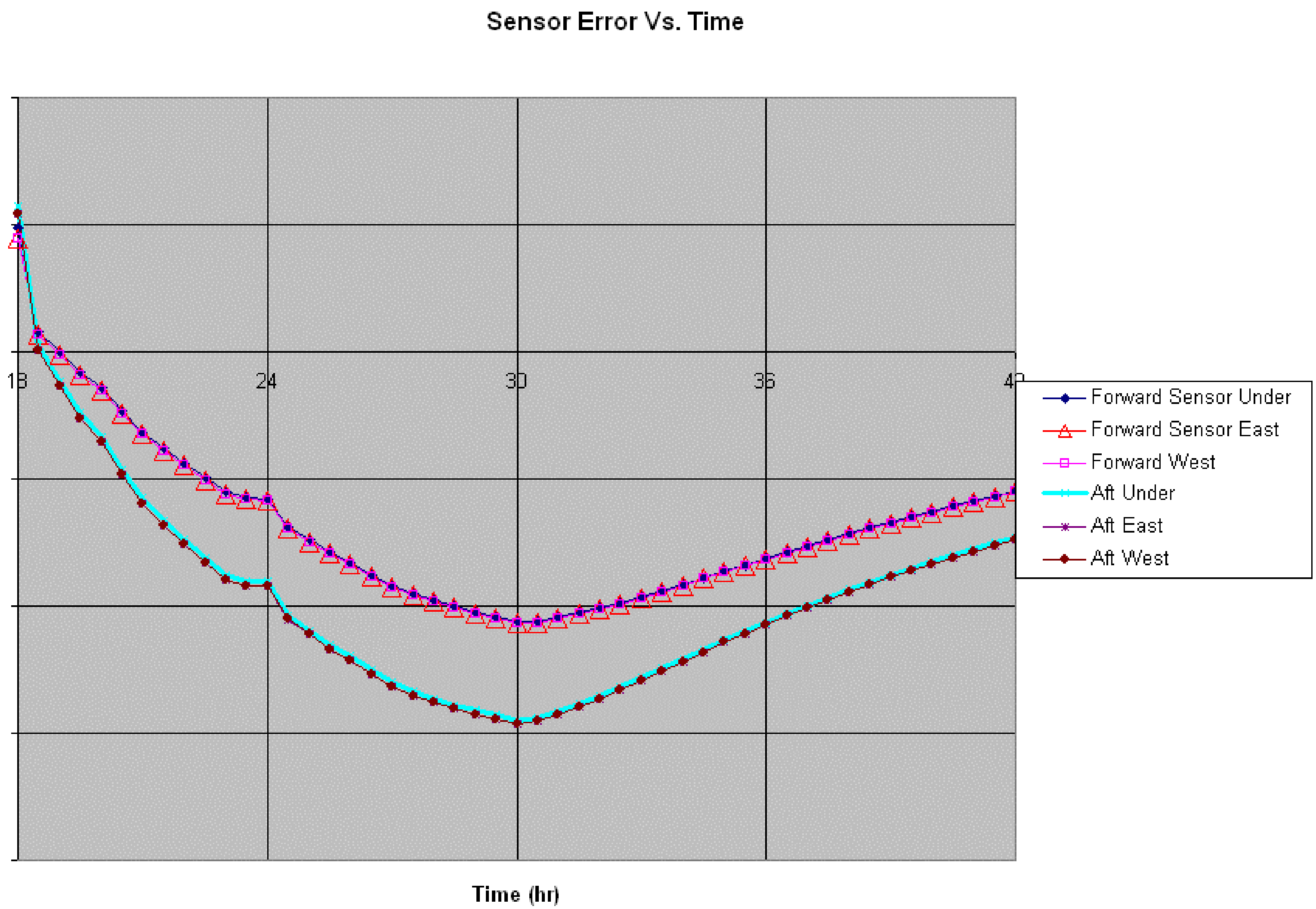
Sensor Lag Vs. Time – Sudden Heating Case



Worst Case Conditions – Sudden Cooling Case

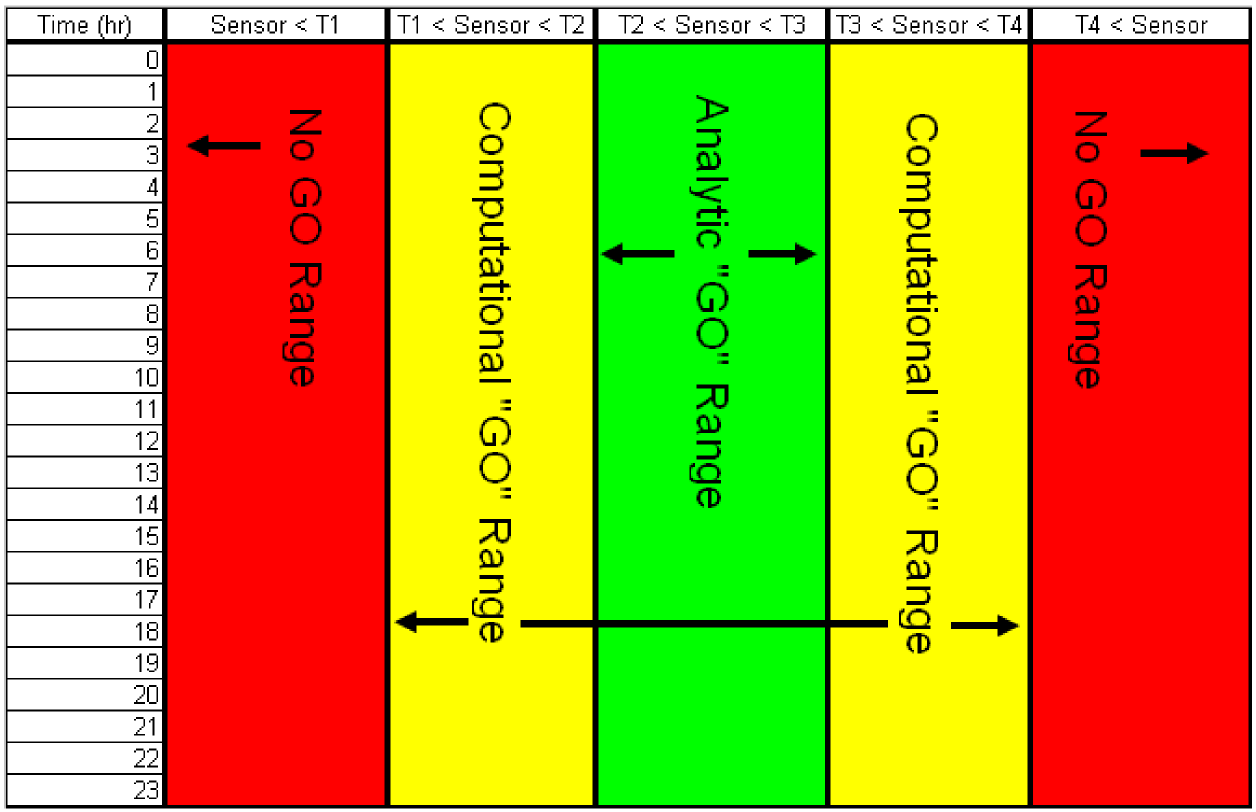
- Air Temperature
  - NEDD 99% Variation for Edwards AFB
    - Maximum temperature change in 3hrs = 20.7^{o}F
    - Maximum temperature change in 6hrs = 33.7^{o}F
    - Maximum temperature change in 12hrs = 37.8^{o}F
  - Create a Worst Case Cooling Condition
    - Run Hot Case for 4 days – December Values
      - 99% Air Temperature – Dec.
      - 1% Sky Temperature, 99% Radiation During the Day
      - 99% Sky Temperature at Night
      - 0 Wind Velocity
    - At 6PM on 5th day (just before sunset), air temperature decreases at maximum NEDD rate.
    - Temperature continues to fall until it intersects the 1% Cold Case Air Temperature

Sensor Lag Vs. Time – Sudden Cooling Case



Possible Use of These Models

- Worst Case Day-Of-Flight Placarding
  - Analytic Range = Physical Limit
  - Computational Range = Limit Given Assumed Environments



Possible Use of These Models

- Could Also Provide Ranges Vs. Time of Day

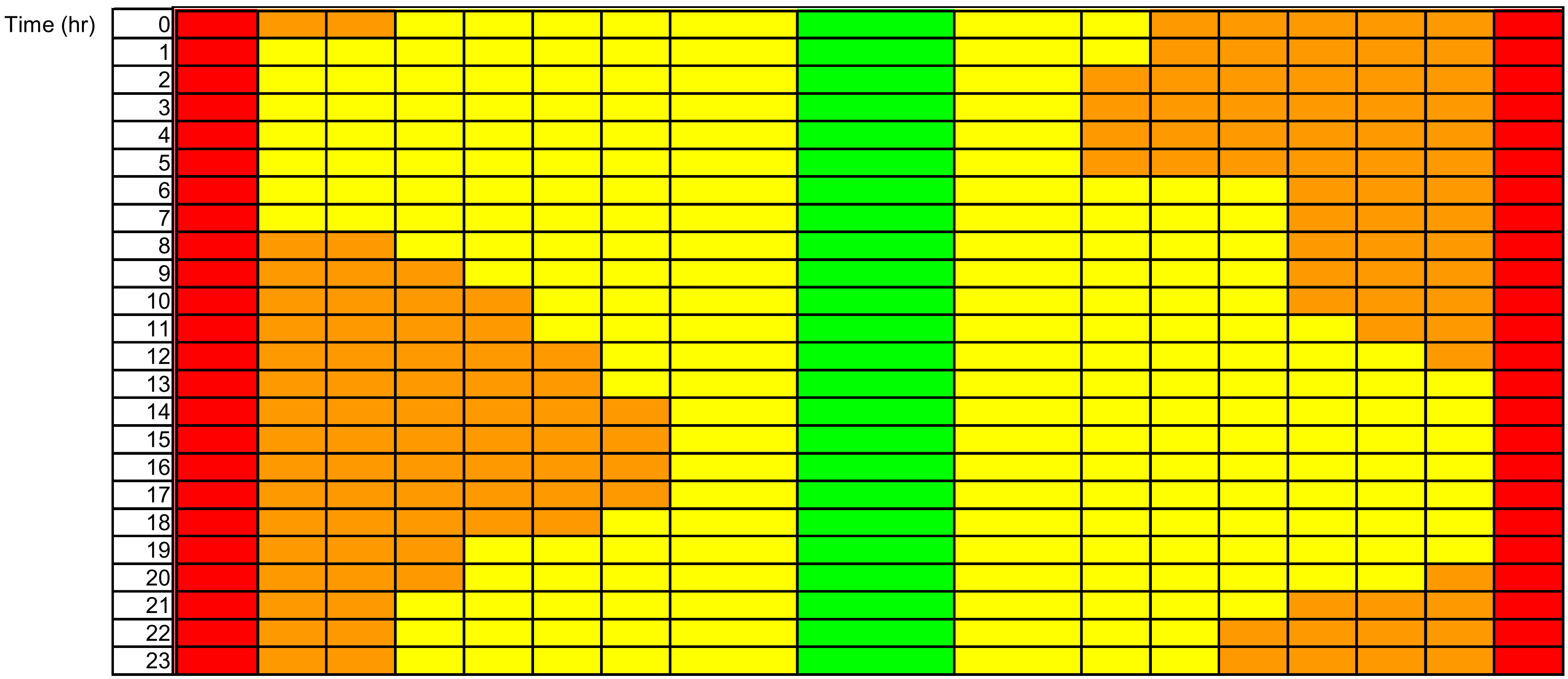


Table based on worst case environment specifications

Likely PMBT Restriction - Must have thermal team input

Possible PMBT Restriction - Must have thermal team input

Some Potential for PMBT Restriction - Must have thermal team input

Go - Unlikely PMBT Restriction

Conclusions

- Two Models Have Been Developed to Predict the LAS Abort Motor Propellant Temperature Based on External Sensor Readings Only
  - Analytic Model Could Provide Conservative Day-of-Flight Ranges
  - Computational Model Can Incorporate Environmental Assumptions to Provide a Less-Conservative Range
- Both Models Could Be Used in Near Real Time Along with Recent Data to Predict PMBT if Operators So Chose
- Orbital Sciences and Its Thermal Analysis Team Are Proud to Continue their Support of Lockheed Martin and NASA's Ambitious Manned Spaceflight Objectives