Thermal Modeling of an Advanced Geared Turbofan for Distributed Engine Control Application

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Outline

Summary

- Presents a method for modeling the dynamic thermal environment of a gas turbine engine with an eye toward control system component reliability as it relates to the implementation of distributed engine control.
- Application is to a conceptual N+3 generation geared turbofan.
- The resulting model is shown to run in real-time within a multi-model simulation environment that demonstrates the ability to interact with hardware to drive test equipment

Outline

- Background/Motivation
- Thermal Modeling Methodology
- Thermal Modeling Techniques
- Application to an Advanced Geared Turbofan
- Real-Time Capabilities
- Summary

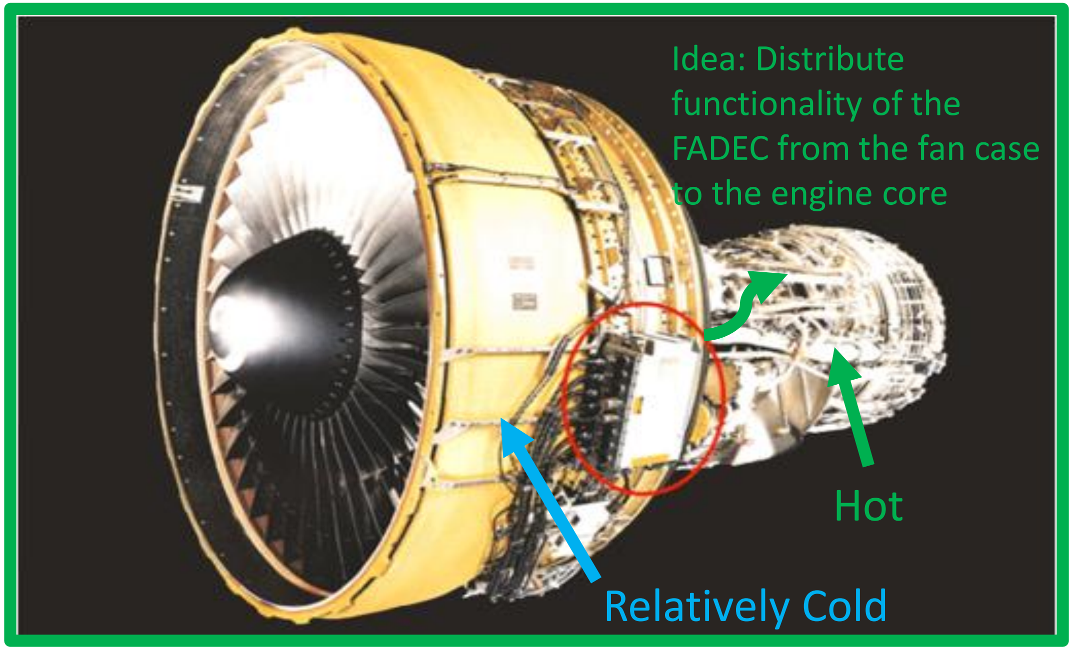
Background: Distributed Engine Control

Current Control Approach

- Centralized architecture performed through a full authority digital engine controller (FADEC)
- Constrains the control system topology and limits capability

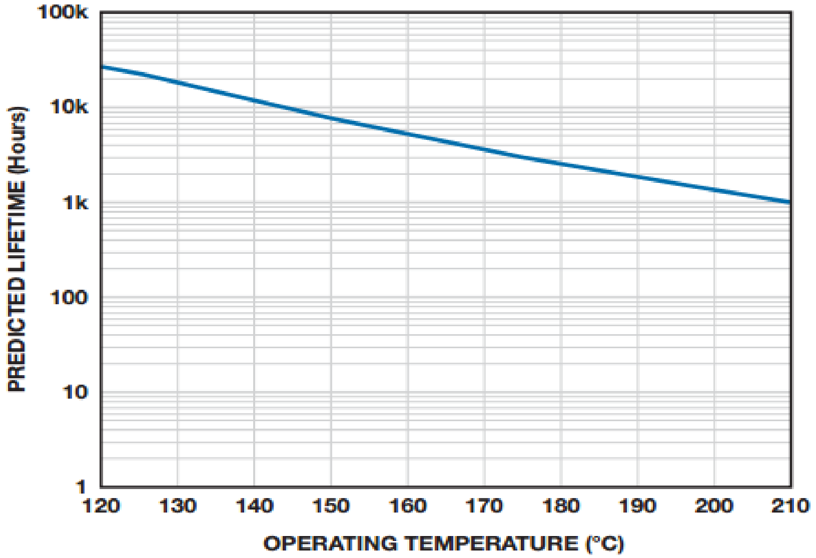
Distributed Engine Control

- Hardware-driven strategy that adds flexibility
- Modularizes the control system and distributes control functions to smart nodes located across the engine
- Utilizes a light-weight digital communication network



- Some Potential Benefits: Reduce weight, reduce volume impact, alleviate obsolescence and certification issues, enable more advanced control

Background: High Temperature Electronics



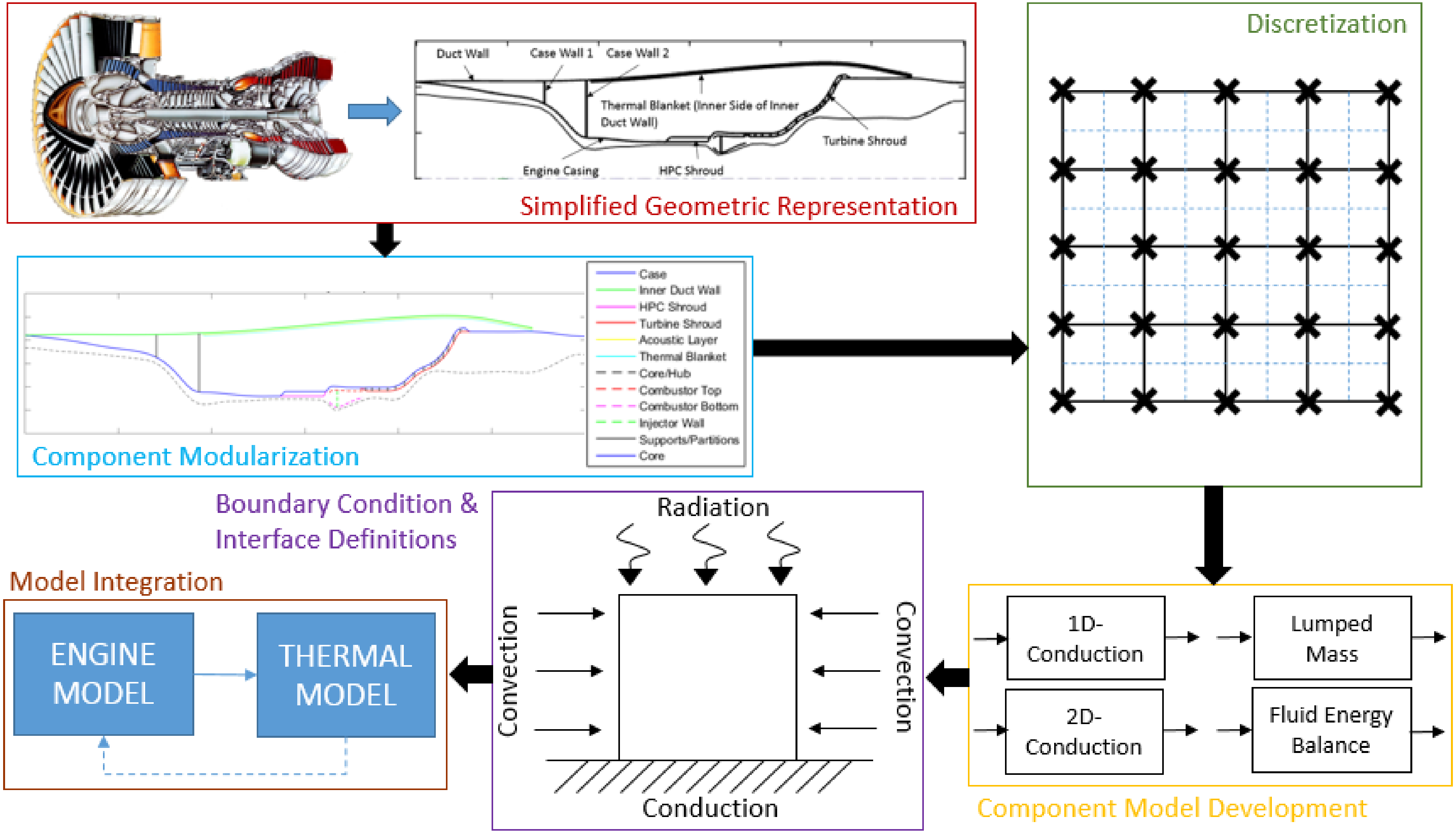
Example of the reliability vs. temperature relationship for an electronic device http://www.analog.com/library/analogdialogue/archives/46-04/high_temp_electronics.pdf

- Desire to mount smart nodes on the engine core
- Challenging thermal environment
  - State-of-art material for internal gas path exceed 1500°C
  - Common consumer electronics operate reliably <70°C, sometimes 150°C
  - Inverse relationship between temperature and electronic reliability
- High-Temp electronics
  - Silicon-On-Insulator (SOI): Up to 300°C (225°C near term)
  - Silicon Carbide: 500°C +

- Important considerations: Max & min temperature (steady-state), rate of change in temperature (dynamic), & temperature cycling (dynamic)
- Objective: Develop a thermal model of the relevant engine structure to estimate the environment in which DEC electronics will be placed + develop re-useable modeling tools + develop capability to use the model and or its results to drive test equipment

“High temperature is relative”

Thermal Modeling Methodology



Simplified Geometric Representation

Component Modularization

Discretization

Component Model Development

Boundary Condition & Interface Definitions

Model Integration

Thermal Modeling Techniques

Structure

- 2-D Finite Difference Method (FDM) - More significant components (engine casing, shrouds, duct wall, etc.)

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p}\nabla \cdot (k\nabla T) \rightarrow \frac{\partial T}{\partial t} = \frac{1}{\rho C_p}\left[\left(\frac{\partial k}{\partial r} + \frac{k}{r}\right)\frac{\partial T}{\partial r} + k\frac{\partial^2 T}{\partial r^2} + \frac{\partial k}{\partial z}\frac{\partial T}{\partial z} + k\frac{\partial^2 T}{\partial z^2}\right]$$

T = temperature, t = time, ρ = density, C_p = heat capacity, k = thermal conductivity,
r = radial direction coordinate, z = axial direction coordinate

  - Model the component as a cylindrical shell of constant radius and thickness
  - Discretized and then solved using a 2-D implicit scheme

- Lumped Capacitance – Less significant components (core components – compressor and turbine blades)

$$\frac{\partial T}{\partial t} = \frac{1}{mC_p}[\underbrace{hA(T_F - T)}_{\text{Convection}} + \underbrace{uA(T_R - T)}_{\text{Radiation}}]$$

m = effective mass, A = surface area, T_F = temperature of convecting fluid, T_R = temperature of radiating body,
h = convection heat transfer coefficient, u = radiation heat transfer coefficient

Thermal Modeling Techniques

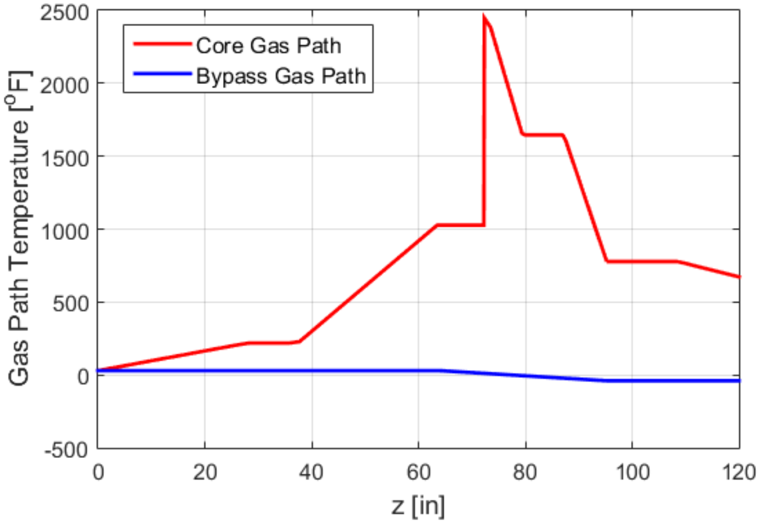
Flow Paths & Voids

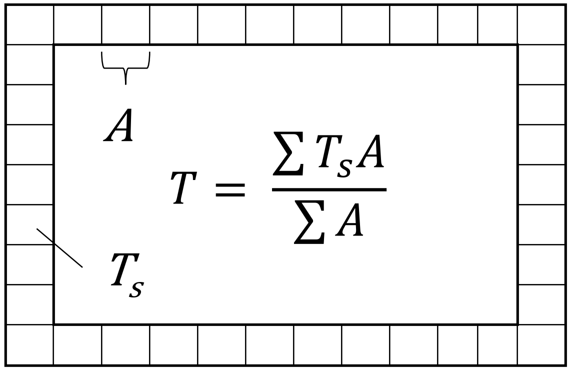
- Engine simulation data – used for gas paths and some bleed flows
- Fluid Energy Balance – used for bleed flows of significant heat transfer and relatively low mass flow

$$Q = \sum_{out}(\dot{m}C_pT) - \sum_{in}(\dot{m}C_pT)$$

T = temperature, C_p = heat capacity,
$\dot{m}$ = mass flow rate, Q = heat

- Average of Surroundings – used for closed volumes with no forced air flow





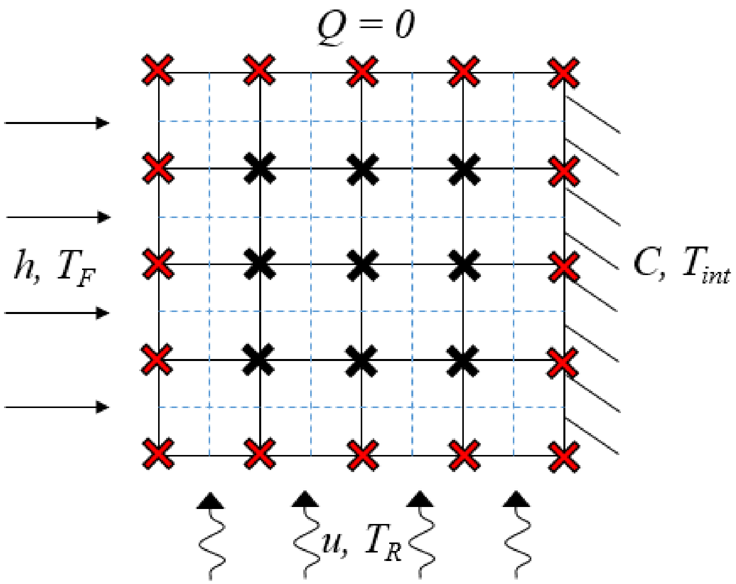
$$T = \frac{\sum T_s A}{\sum A}$$

A = *surface area of element exposed to the enclosed fluid*
T_s = *surface temperature of the element*

Thermal Modeling Techniques

Boundary Conditions

- Conduction
  - Thermal capacitance of each boundary node is computed to enable conduction boundary conditions to be applied at the interface of 2 solid components
- Convection
  - Forced and natural convection are considered
  - Relations used for the coefficient *h* are generic and tunable
    - Tuning variables were set based on guidance from studies conducted at NASA and information found in literature
- Radiation
  - Written in a linear form
  - The coefficient *u* is a strong function of temperature and is updated each time-step of the simulation.
  - Relations for *u* assumes radiation between reflective concentric cylinders
  - Assumed radiation only occurs between parallel surfaces

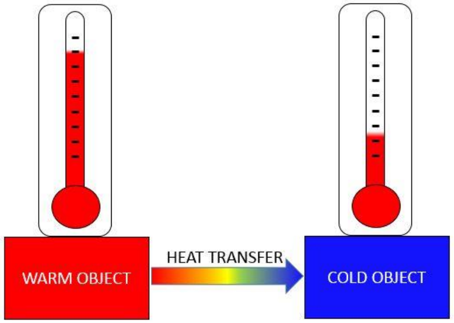


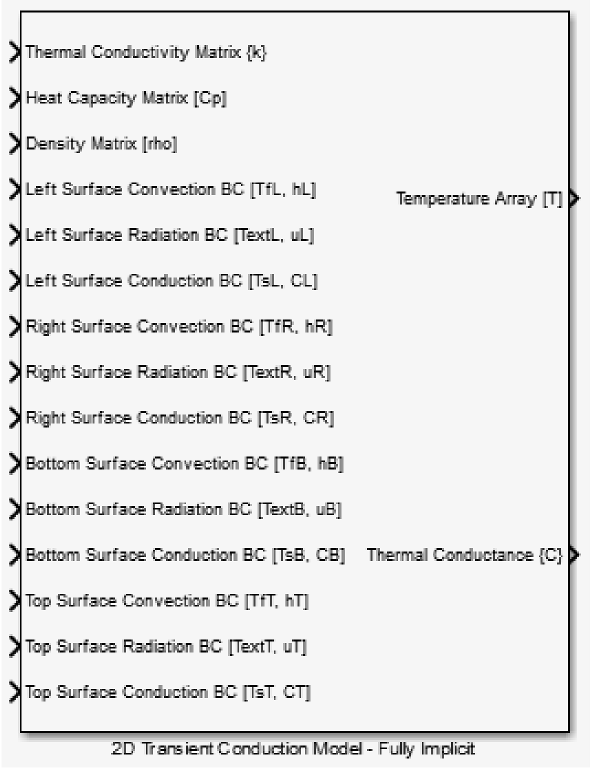
Q = heat
h = convection heat transfer coefficient
T_F = fluid temperature
u = radiation heat transfer coefficient
T_R = temperature of radiating body
C = thermal capacitance
T_{int} = temperature at the interface between 2 solids

Thermal Modeling Techniques

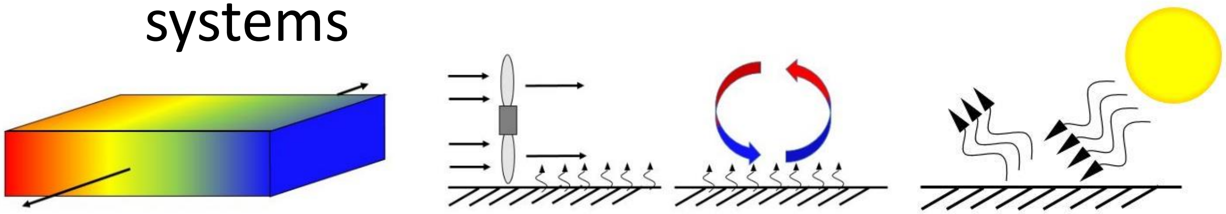
Thermal System Analysis Toolbox (TSAT)

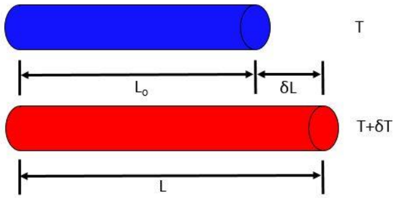
- Library of tools developed in the MATLAB/Simulink environment
- Topics modeled
    - Conduction
    - Convection
    - Radiation
    - Deformation
    - Air Properties
    - Fluid Heat Transfer
    - General Tools
- Provides building blocks for building up and modeling dynamic thermal systems




Thermal Conductivity Matrix {k}
Heat Capacity Matrix [Cp]
Density Matrix [rho]
Left Surface Convection BC [TfL, hL]
Left Surface Radiation BC [TextL, uL]
Left Surface Conduction BC [TsL, CL]
Right Surface Convection BC [TfR, hR]
Right Surface Radiation BC [TextR, uR]
Right Surface Conduction BC [TsR, CR]
Bottom Surface Convection BC [TfB, hB]
Bottom Surface Radiation BC [TextB, uB]
Bottom Surface Conduction BC [TsB, CB]
Top Surface Convection BC [TfT, hT]
Top Surface Radiation BC [TextT, uT]
Top Surface Conduction BC [TsT, CT]
Temperature Array [T]
Thermal Conductance {C}

2D Transient Conduction Model - Fully Implicit



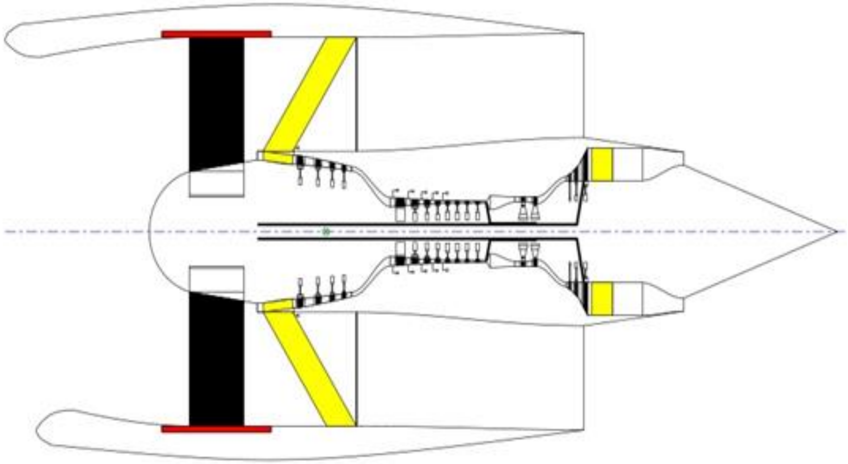


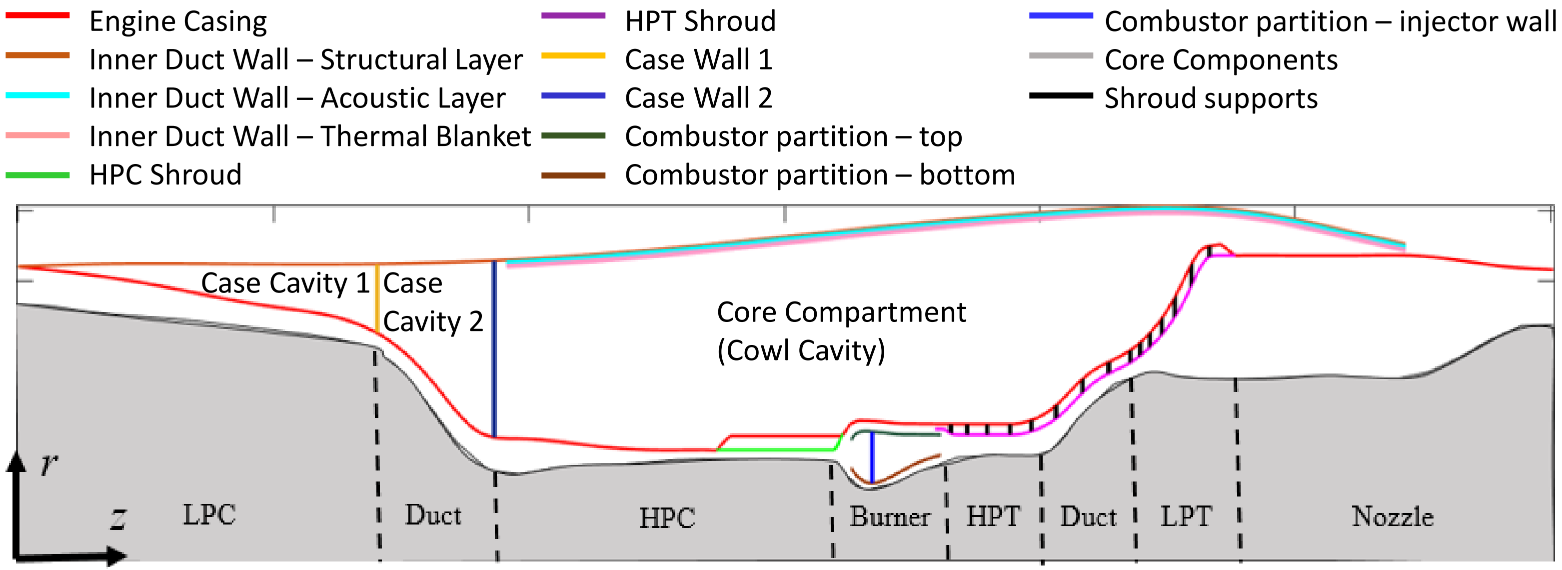
Download Link: https://github.com/nasa/TSAT

Application: The Engine

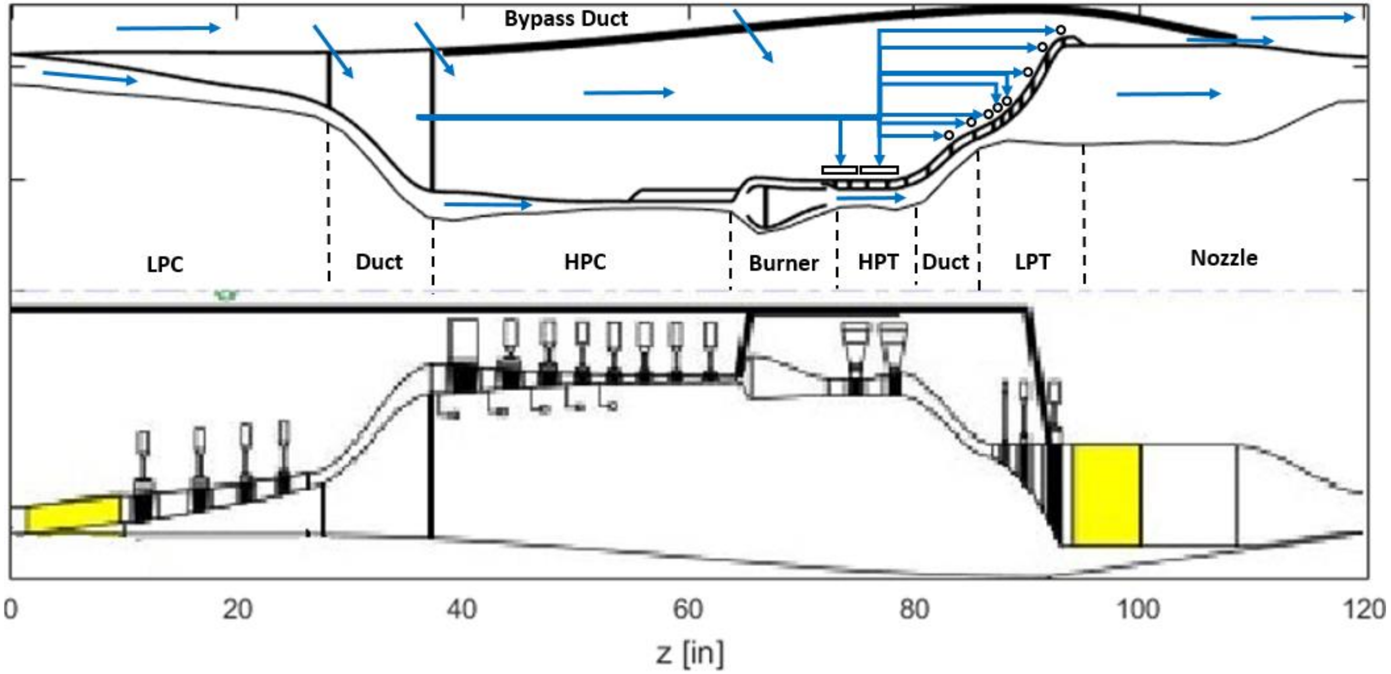
Advanced Geared Turbofan 30,000lb$_f$ (AGTF30)

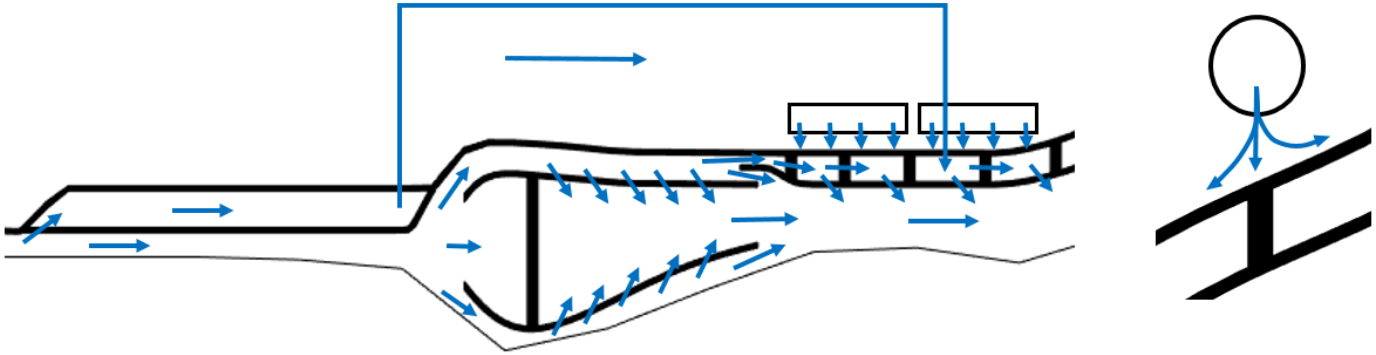
- Based on the NASA N+3 NPSS reference engine
- 3rd generation geared turbofan
- Features a compact gas turbine (CGT) and a variable area fan nozzle
- Capable of producing 30,000lb$_f$ of thrust at the sea-level static condition





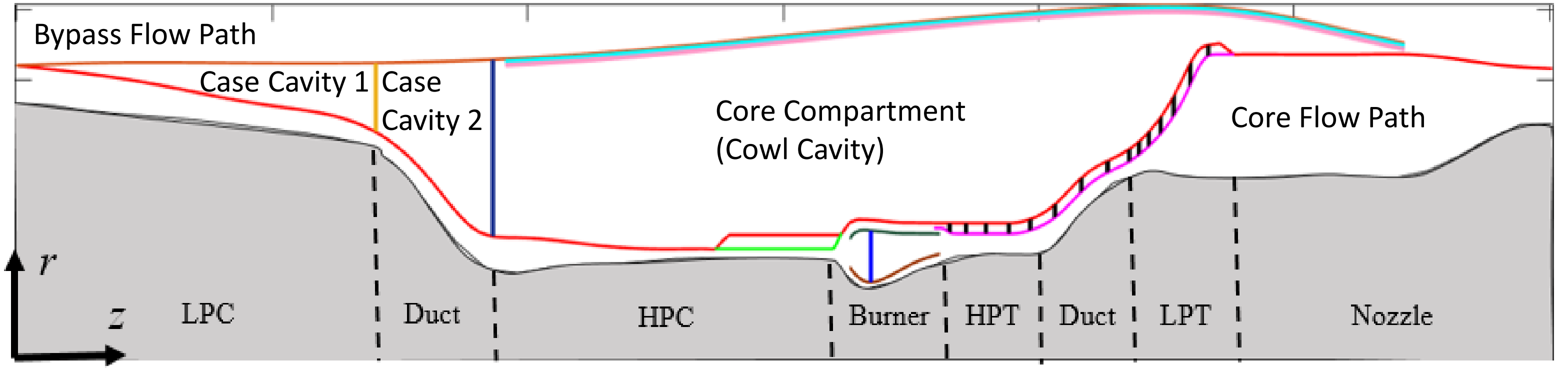
Application: The Engine Air Flow





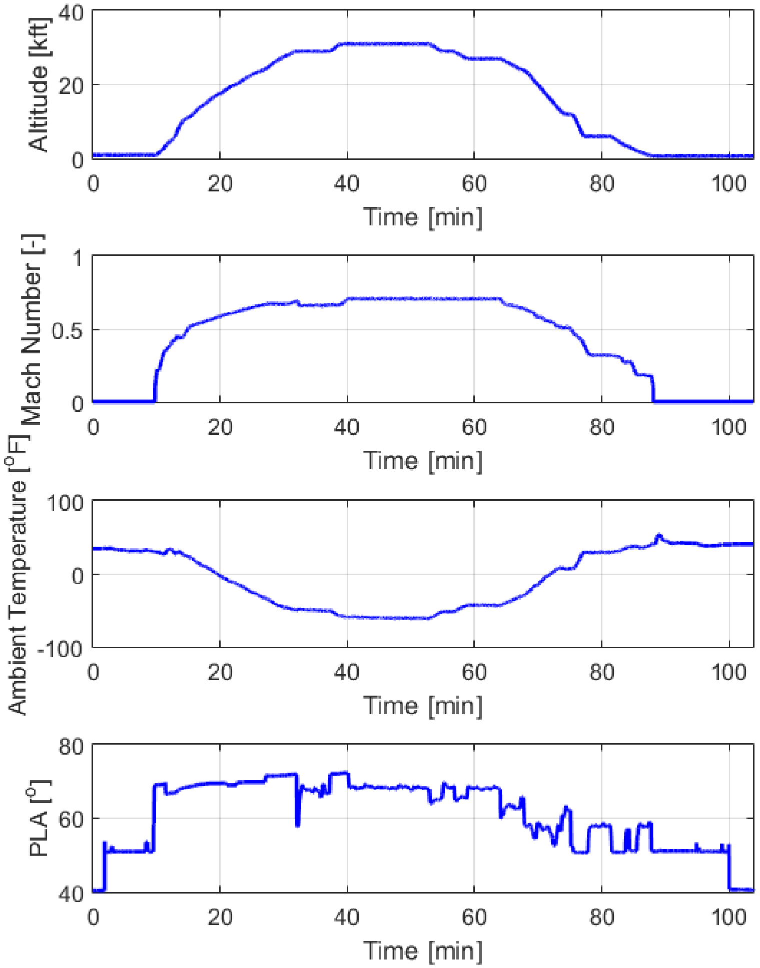
Application: Modeling

- Structures
  - All components except the “core components” were modeled with 2-D FDM
    - Geometry was approximated as a cylindrical shell of the components average radius and thickness
    - Various levels of discretization were investigated
  - Core components utilized a lumped capacitance model
- Important cavities and voids
  - Bypass flow path, core flow path, and case cavity 2 temperatures were driven by the engine model simulation
  - Case cavity 1 temperature was approximated as the average of its surrounding structure
  - Core compartment temperature was approximated using the fluid energy balance method
- Boundary conditions and interfaces between models were defined



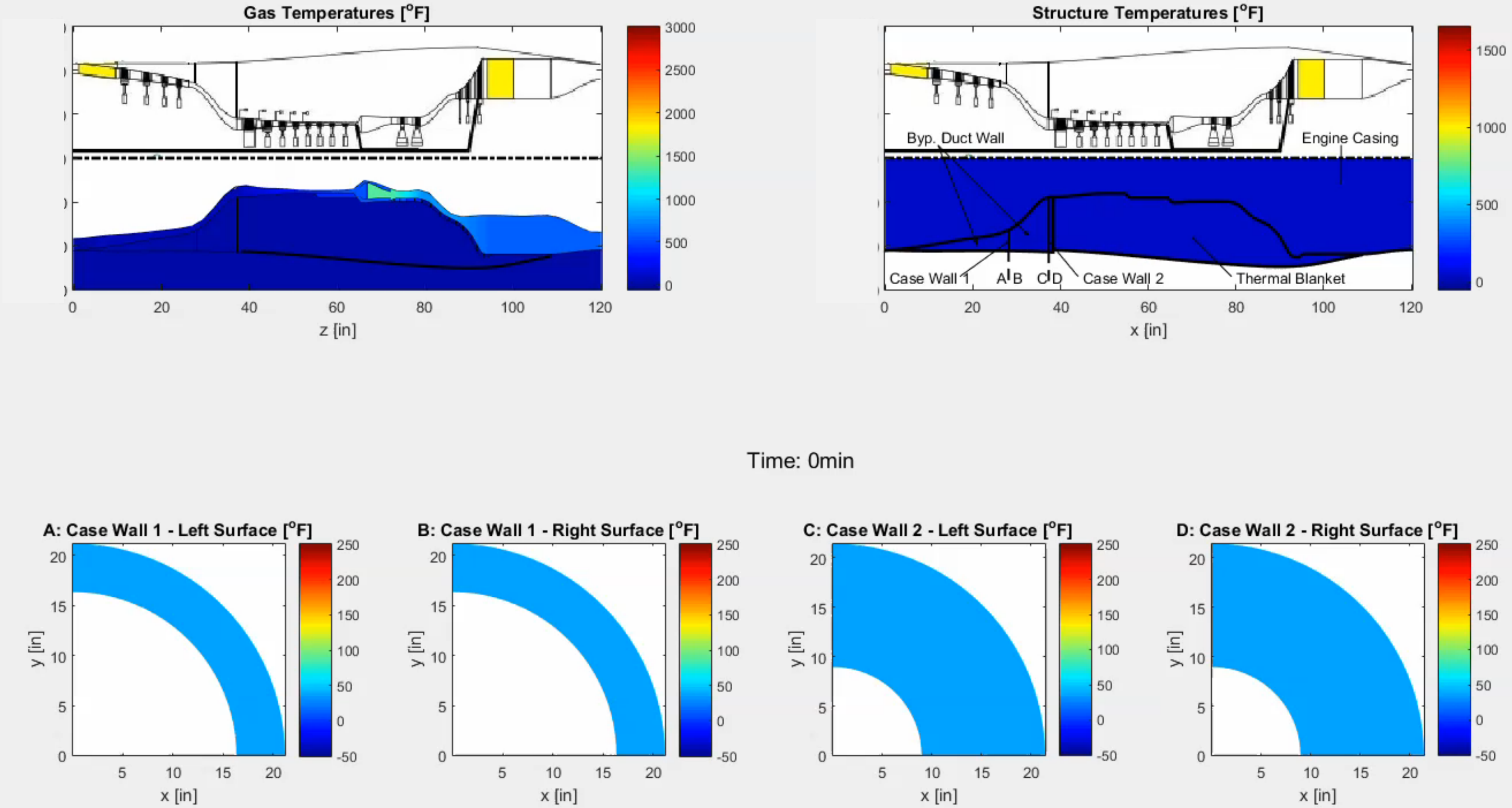
Application: Flight Profile

- Flight profile constructed from real data
- The starting and ending destinations are unknown but is representative of a ~250 mi flight
    - Cleveland, Ohio to Washington D.C. or Las Vegas, Nevada to Los Angeles, California
- At the start of the simulation all structures are initialized at ambient temperature
- After the flight, the thermal simulation is extended to investigate heat soak back (modeling details are not provided here for the sake of time – see the paper)



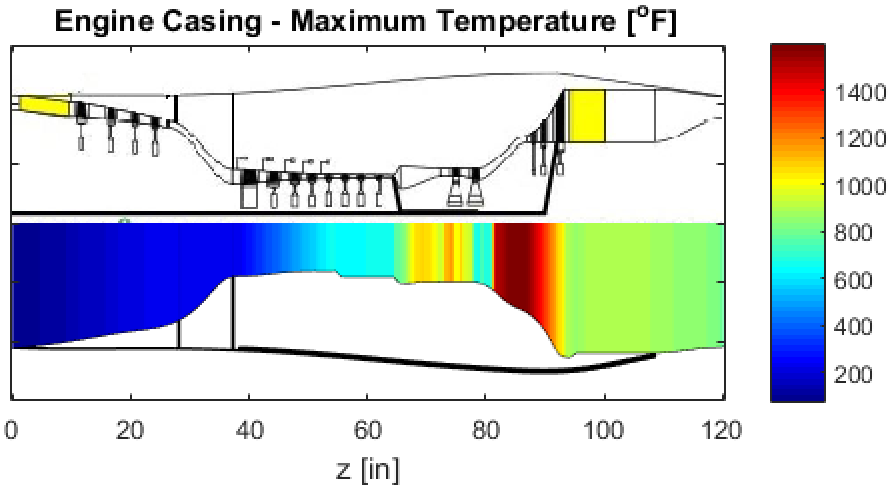
PLA = power lever angle

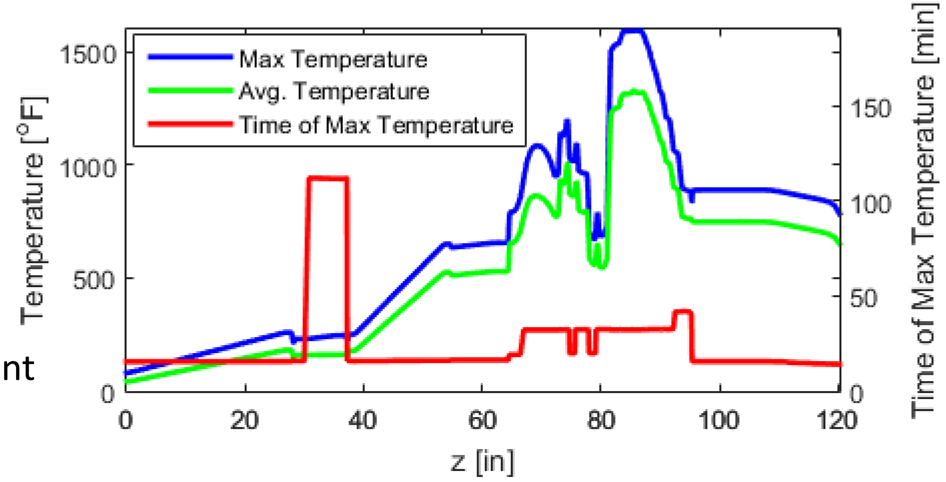
Application: Results



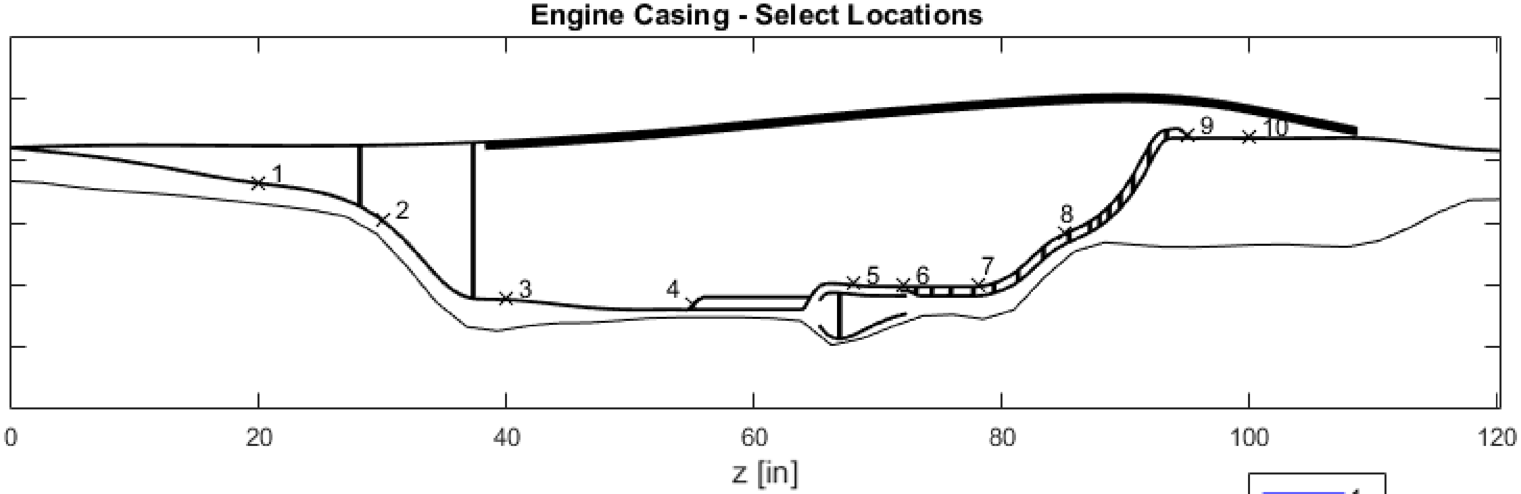
Application: Results

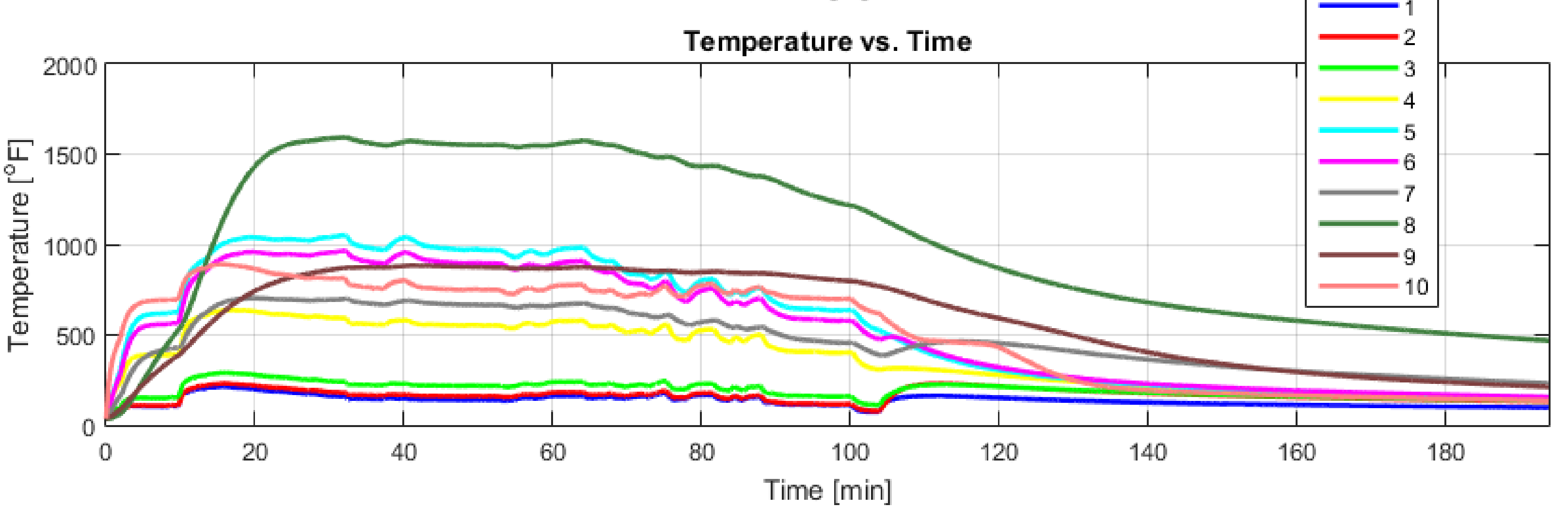
- Compartments
  - Case Cavity 1: Up to 125˚F
  - Case Cavity 2: Up to 155 ˚F
  - Core Compartment (Cowl Cavity): Up to 650 ˚F (400 ˚F upstream of the inter-turbine duct)
- Structure
  - Engine Casing: Up to 1580 ˚F (1100 ˚F outside the inter-turbine duct)
  - Inner Duct Wall (Thermal Blanket): Up to 600 ˚F (350 ˚F upstream of the inter-turbine duct)
  - Case Wall 1: Up to 220 ˚F
  - Case Wall 2: Up to 220 ˚F
- Observations
  - Rate of change in temperature
    - Compartments: -2.5 ˚F/sec – 2.5 ˚F/sec
    - Structures: -2.5 ˚F/sec - 5 ˚F/sec
  - Maximum temperatures occurred at different parts of the engine during different times including: the cold startup of the engine, during climb, during cruise, and during heat soak back





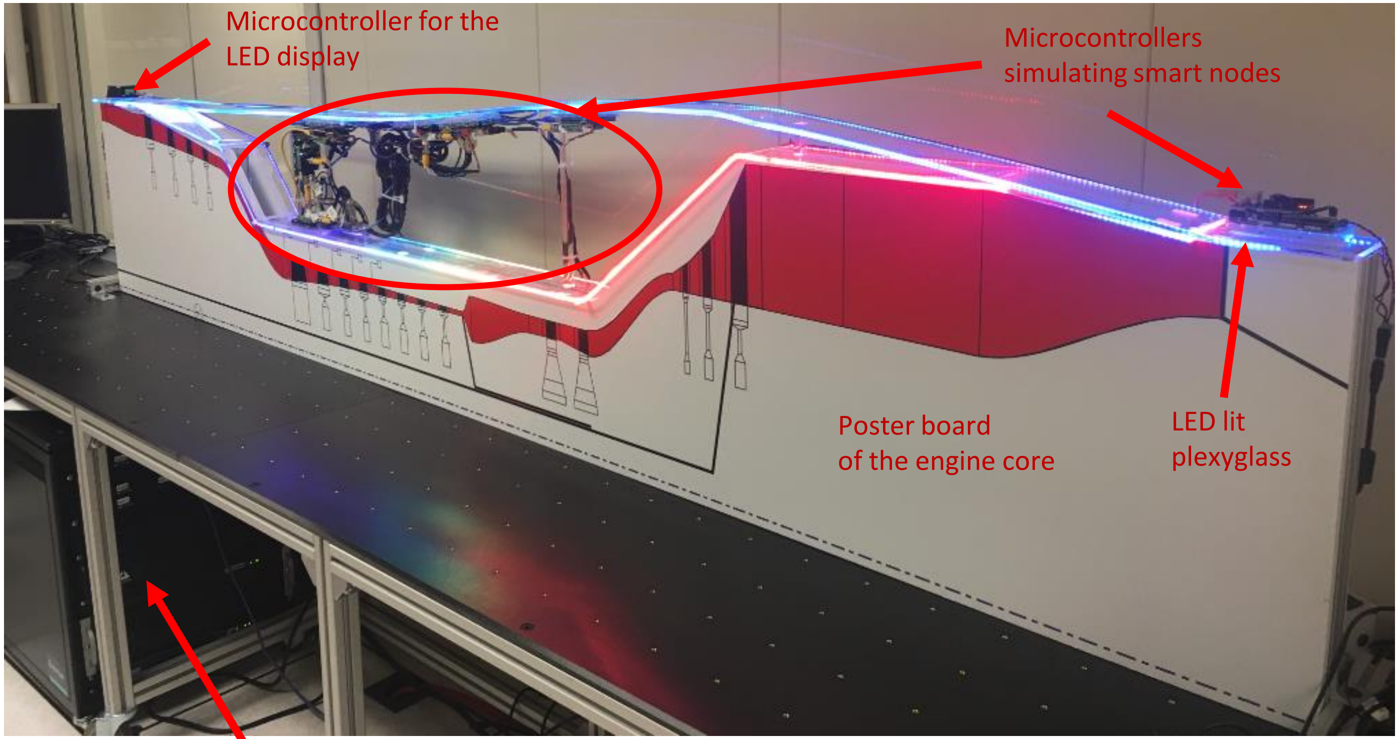
Application: Results


Engine Casing - Select Locations


Temperature vs. Time

Real-Time Capabilities

- Model runs faster than real-time
- Migrated to the hardware-in-the-loop (HIL) system known as the Decentralized Engine Control System Simulator (DECSS)
- Integrated in a multi-model simulation including a physical network and simulated smart nodes
- Used the model to drive a real-time, full-size LED display
  - Illustrates the ability to interact with test equipment



Microcontroller for the LED display

Microcontrollers simulating smart nodes

Poster board of the engine core

LED lit plexyglass

DECSS

Summary

- Motivation for high level thermal modeling pertaining to distributed engine control has been discussed
- A thermal modeling methodology for gas turbine engines has been proposed
- An application of modeling methodology has been illustrated
- Results from the application have been presented and discussed
- Real-time capabilities have been demonstrated with eye toward hardware testing

Acknowledgements

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- The Distributed Engine Control Working Group (DECWG®) for providing input and guidance related to this work

Questions?

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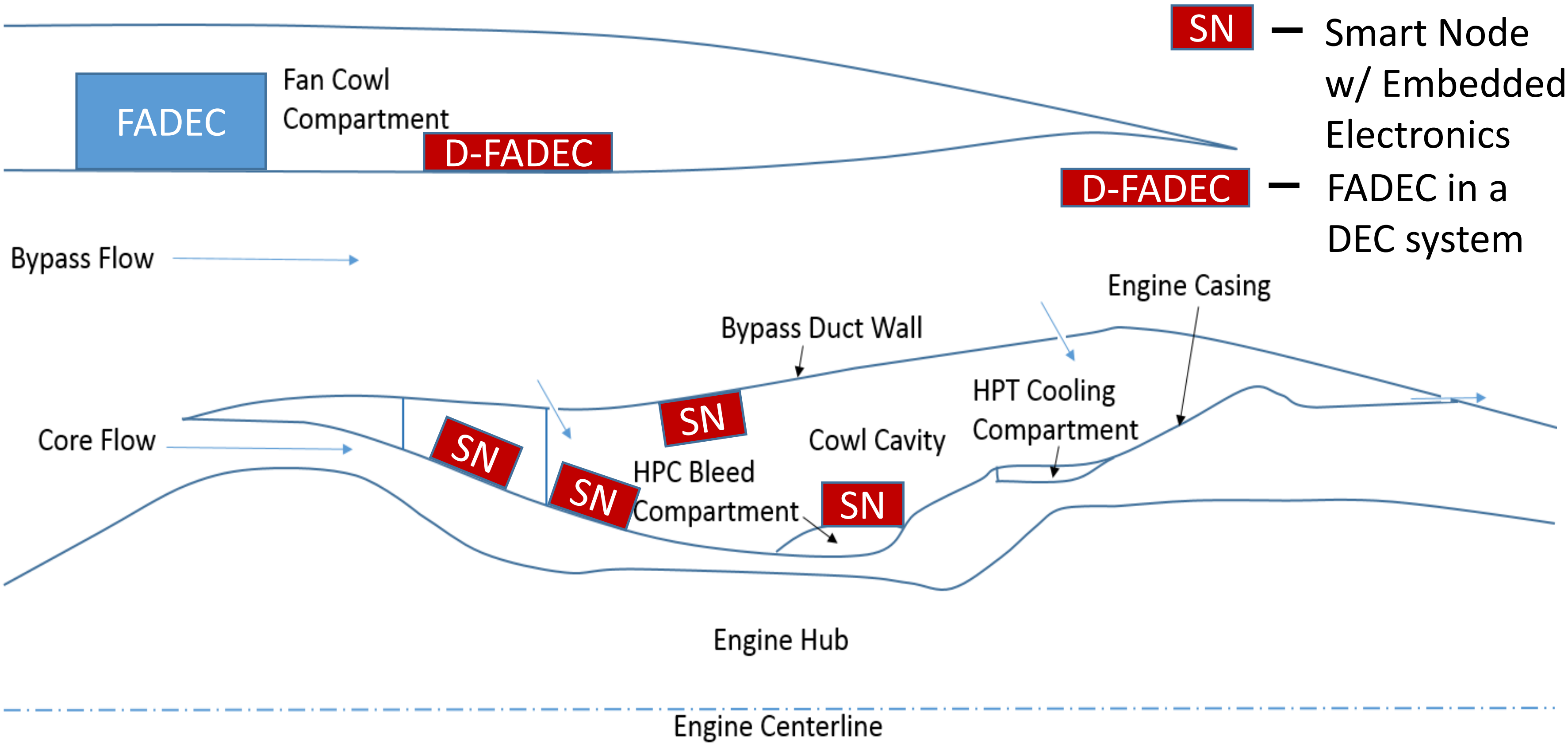
- George Thomas – george.l.thomas@nasa.gov

TSAT Link:

https://github.com/nasa/TSAT

EXTRA SLIDES

Background: Distributed Engine Control



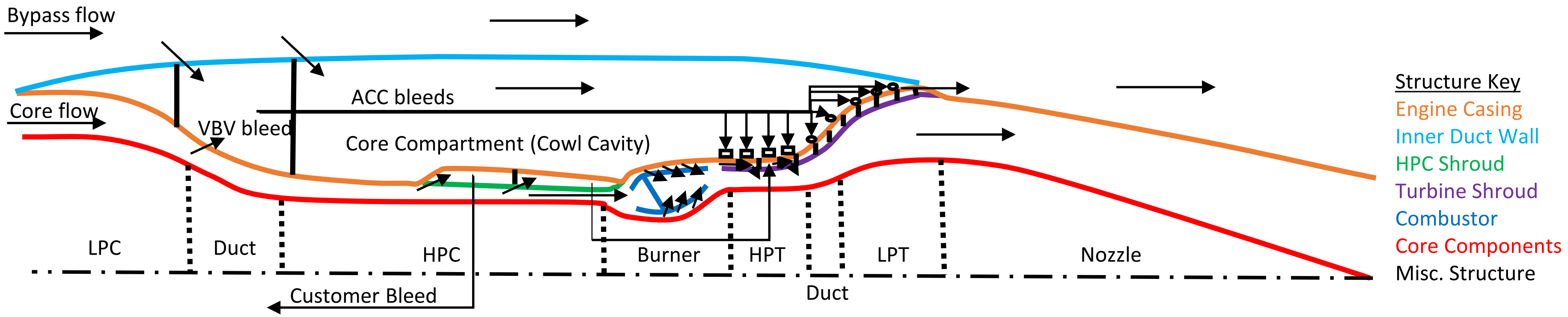
SN – Smart Node w/ Embedded Electronics

D-FADEC – FADEC in a DEC system

Where can we mount hardware?

- SN mounting surfaces could include those exposed to the cowl cavity or case compartments (engine casing, bypass duct wall, & various supports structures)

Thermal Modeling Methodology



What part(s) of the engine are we interested in modeling?

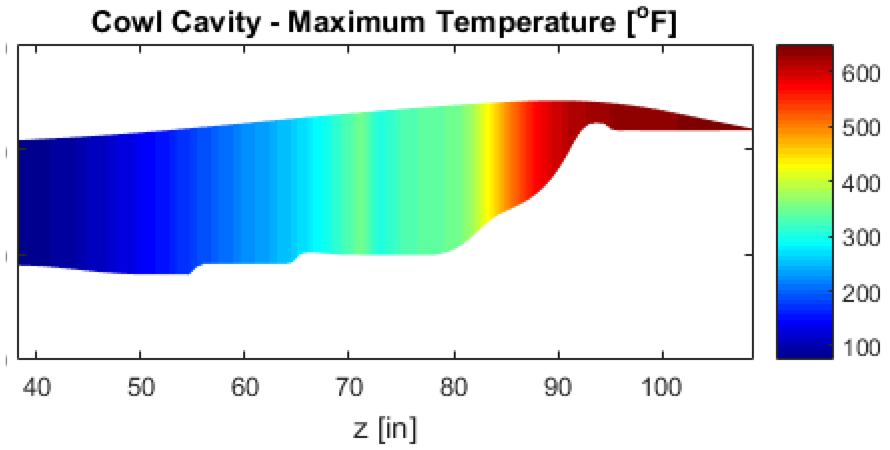
- Any potential mounting structure for a smart node
- Any compartment in which a smart node could be mounted
- Any structure or flow path that could have significant implications on the thermal environment of a potential mounting locations

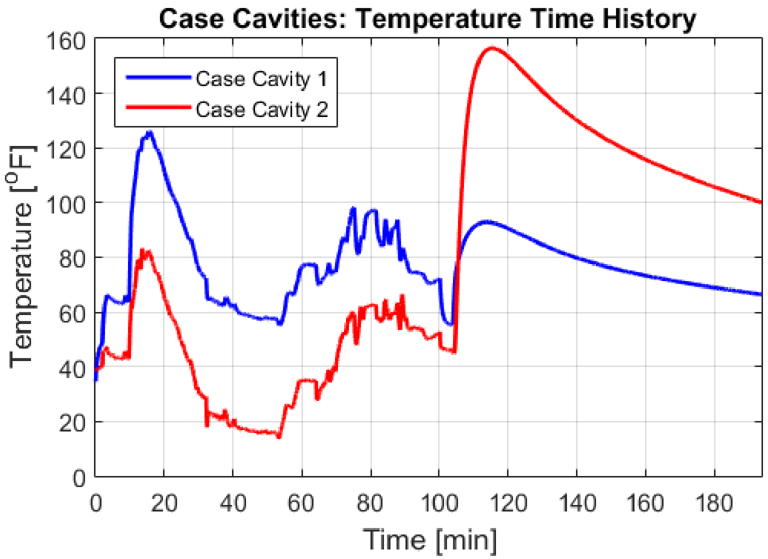
Needs?

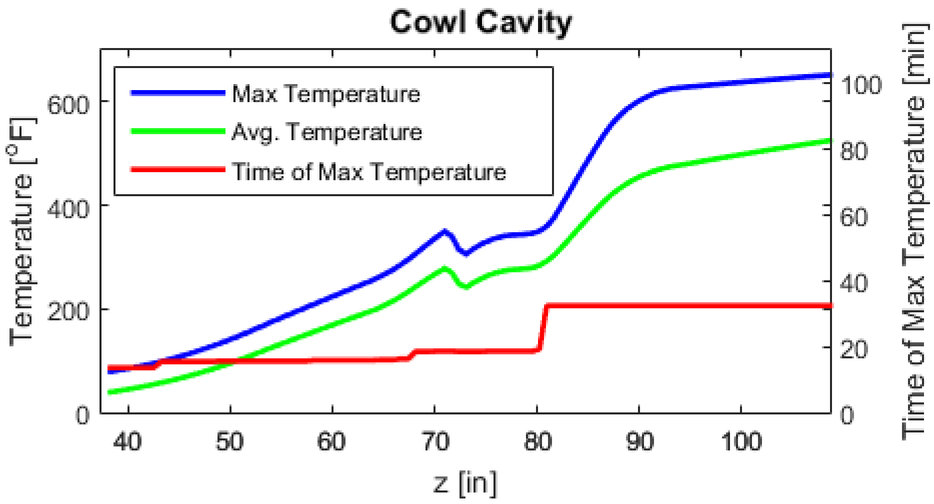
- Geometry/dimensions, secondary air system, other heat transfer/cooling mechanisms inherent in the design

Application: Results

- Max T: 125˚F during take-off (case cavity 1), 155 ˚F during heat soak (case cavity 2), 400 ˚F during climb (applicable portion of the cowl cavity)
- Max Increasing dT/dt: 1 ˚F/sec (case cavity 1 & 2), 2.5 ˚F/sec (applicable portion of the cowl cavity)
- Max Decreasing dT/dt: 0.5 ˚F/sec (case cavity 1), 2 ˚F/sec (case cavity 2), 2.5 ˚F/sec (applicable portion of the cowl cavity)
- Observations
  - Temperature rises several hundred degrees through the cowl cavity (core compartment)
  - Case cavity 1 shows dampening effects comparted to the temperature response of case cavity 2

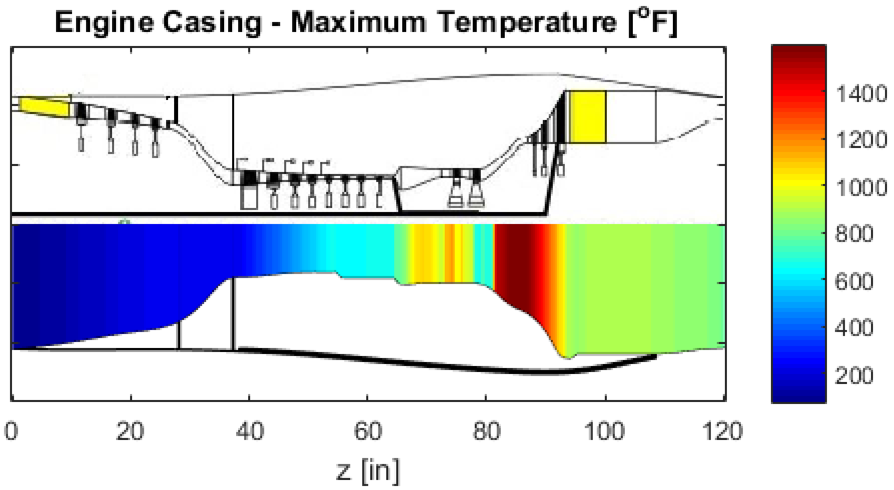


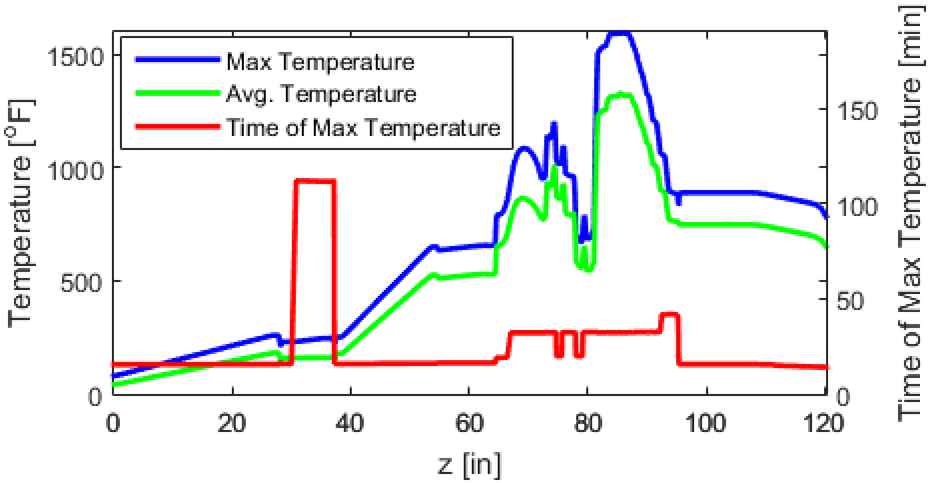




Application: Results

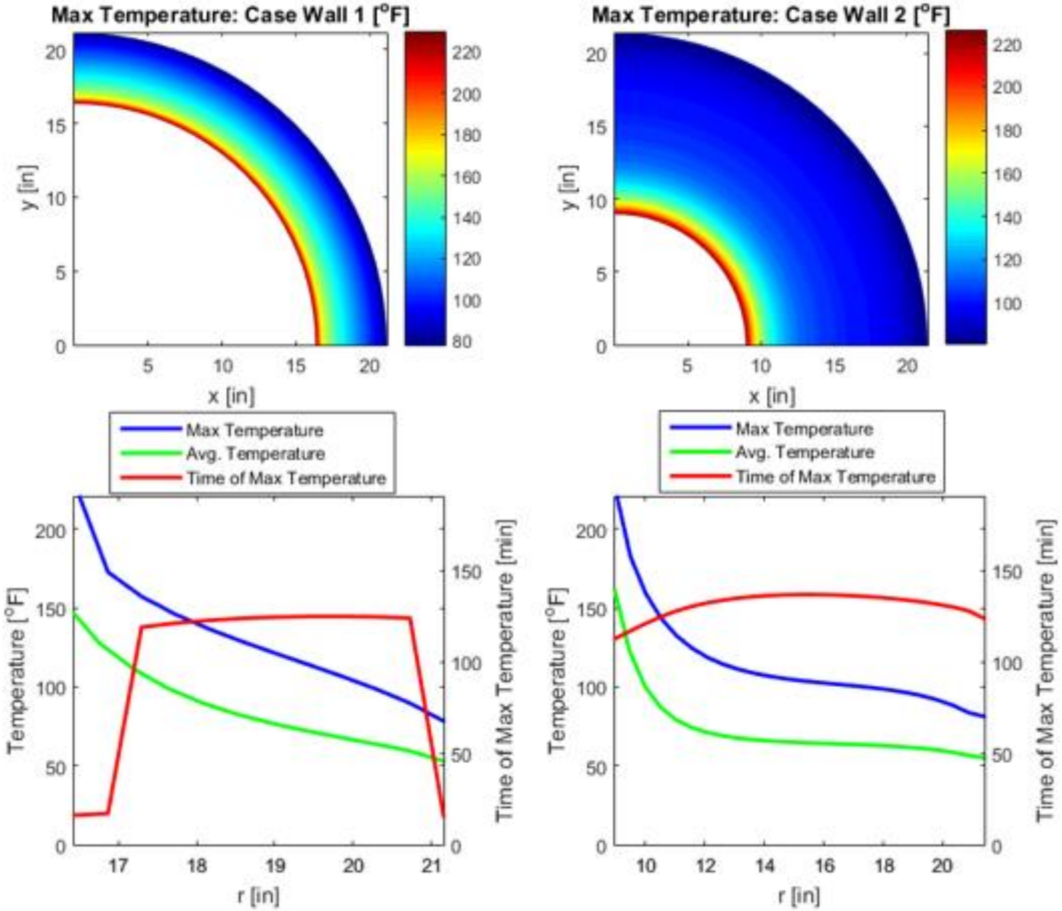
- Max T: ~1580 ˚F (~1100 ˚F neglecting inter-turbine duct)
- Max Increasing dT/dt: 5 ˚F/sec (neglecting nozzle)
- Max Decreasing dT/dt: 2.5 ˚F/sec (neglecting nozzle)
- Observations:
  - Max temperature occurs in the inter-turbine duct region due high temperatures from the aggressive cycle design and lack of active cooling
  - Max temperatures for different locations are shown to occur during climb, cruise, and heat soak





Application: Results

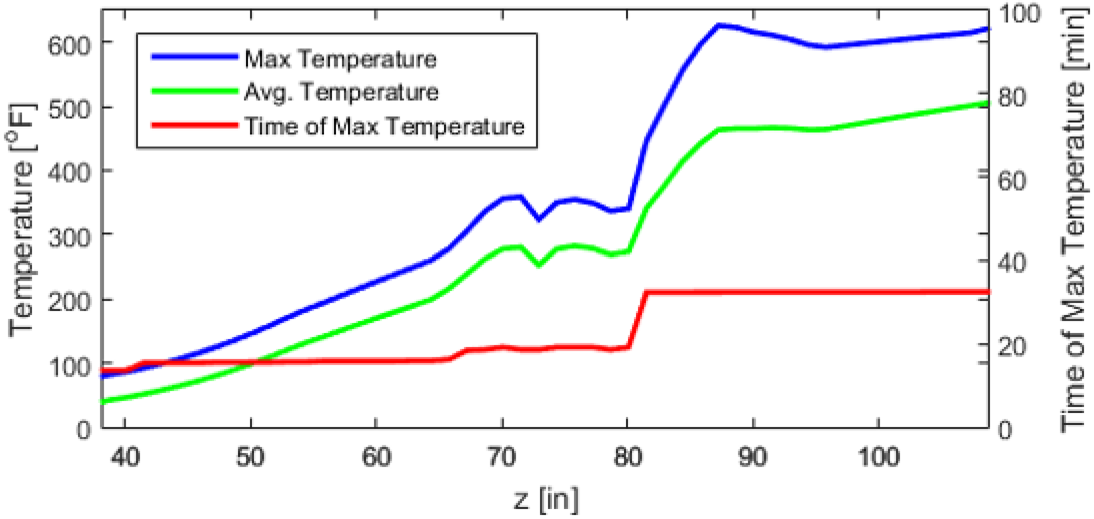
- Max T: ~220 ˚F
- Max Increasing dT/dt: ~1.3 ˚F/sec (at engine case), ~0.3 ˚F/sec (away from the engine case)
- Max Decreasing dT/dt: ~0.7 ˚F/sec (at engine case), ~0.1 ˚F/sec (away from the engine case)
- Observations:
  - Max temperature occur during heat soak, and to a lesser extent take-off



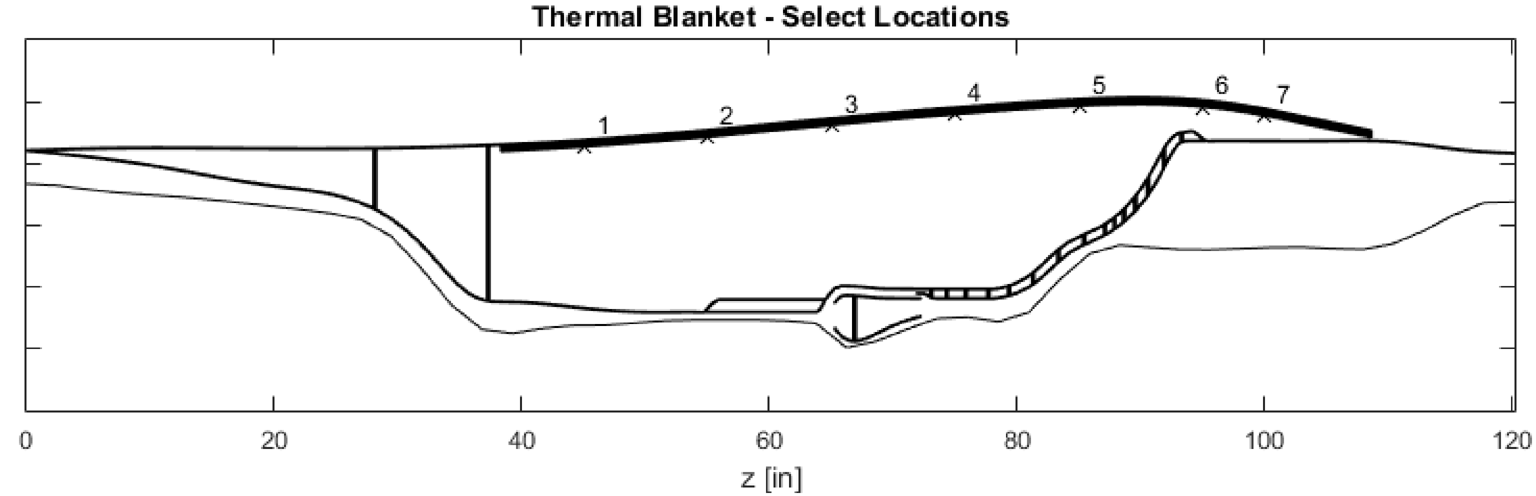
Application: Results

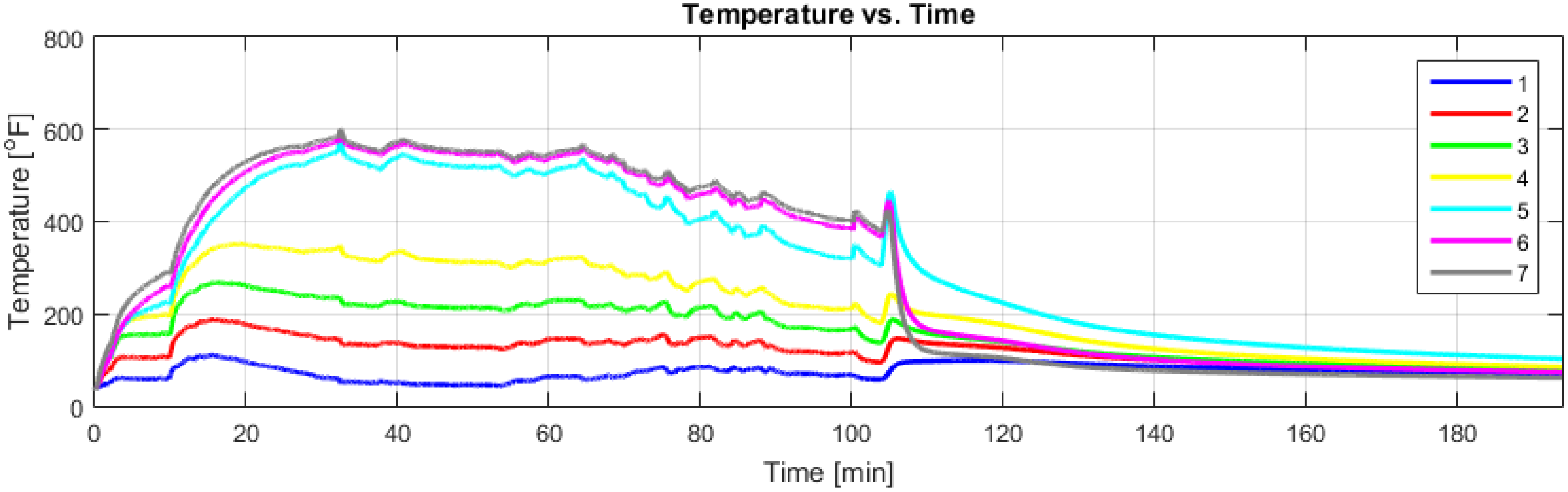
- Max T: ~600 ˚F (~350 ˚F for the region upstream of the inter-turbine duct)
- Max Increasing dT/dt: ~2 ˚F/sec
- Max Decreasing dT/dt: ~1.5 ˚F/sec
- Observations:
  - Max temperatures reached during climb to shortly after reaching cruise

Inner Bypass Duct Wall – Thermal Blanket

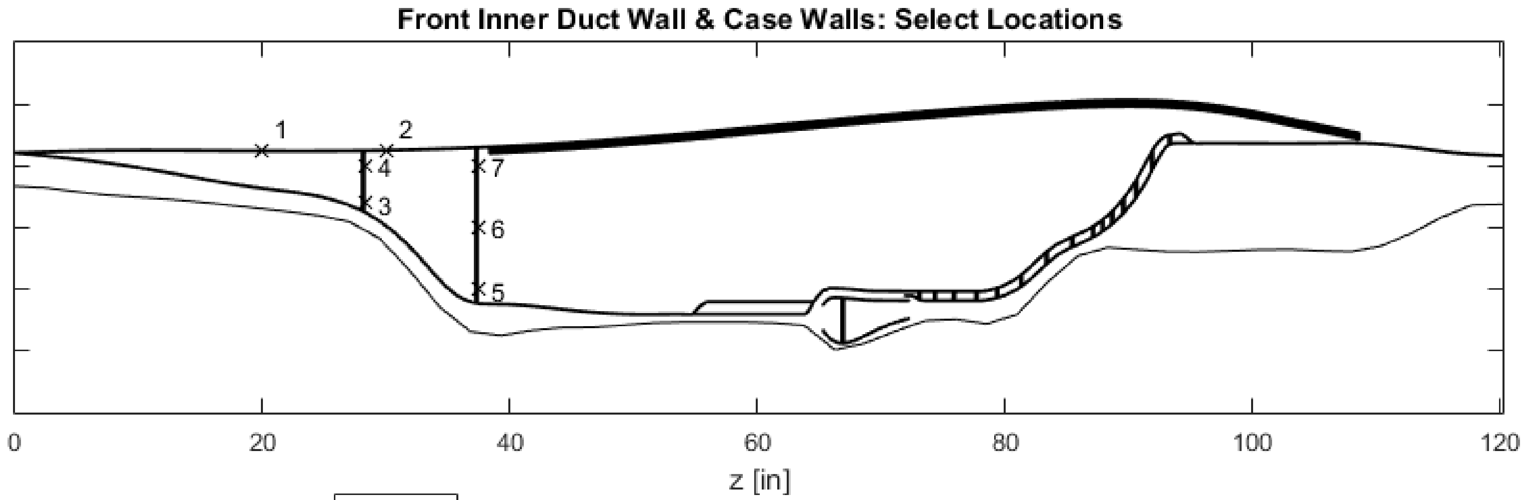


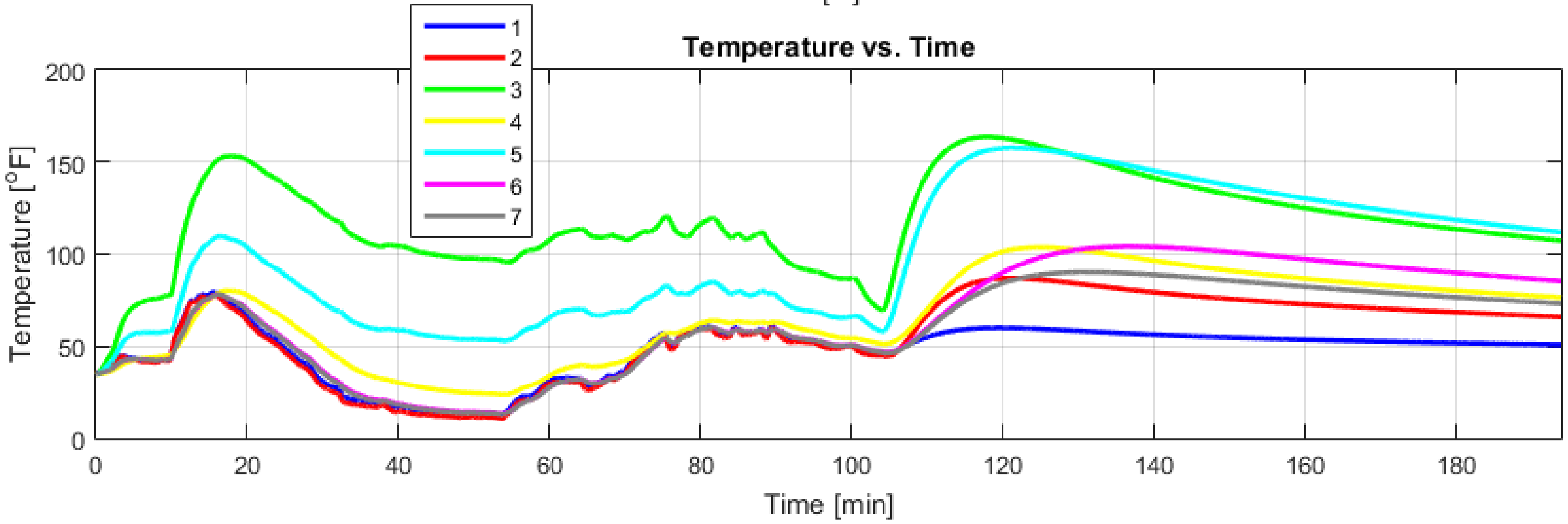
Application: Results



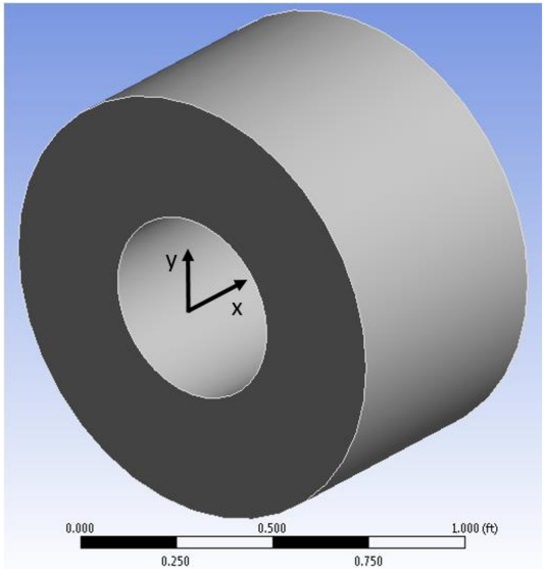


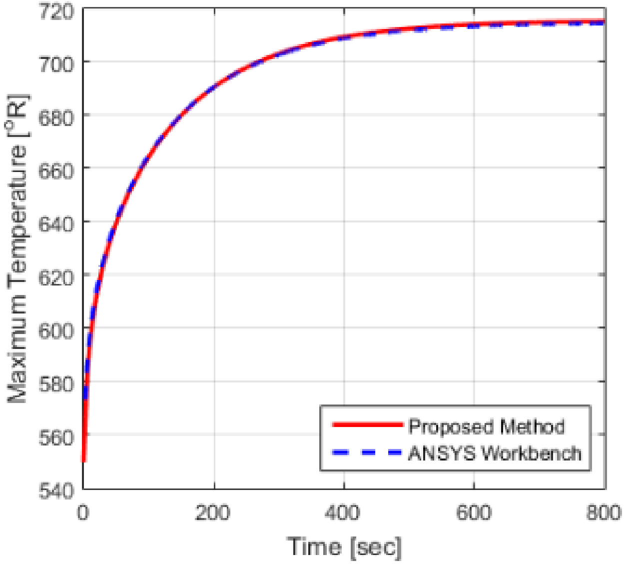
Application: Results

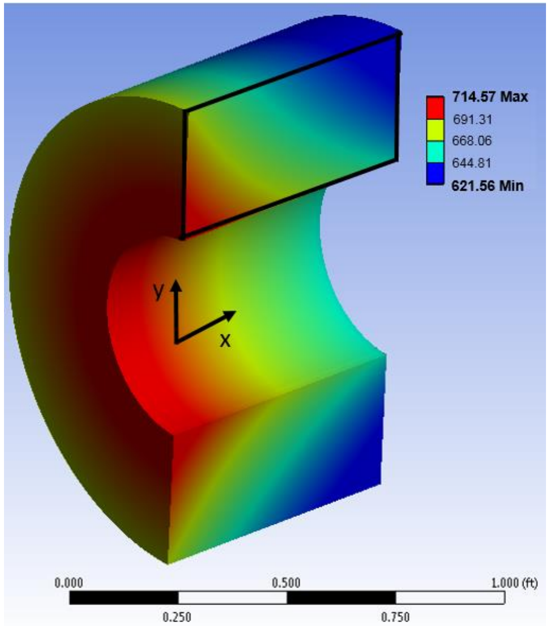

Front Inner Duct Wall & Case Walls: Select Locations

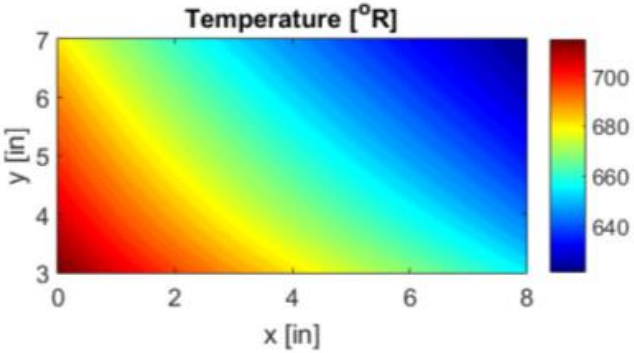

Temperature vs. Time

Extra Slides: ANSYS Verification Example









Proposed Method →

ANSYS Workbench ↑