



Introduction to Dynamic Propulsion System Modeling for Control Design, Analysis, and Simulation

Overview

Jonathan Litt, NASA Glenn Research Center

Propulsion and Energy Forum

August 19, 2019



AGENDA

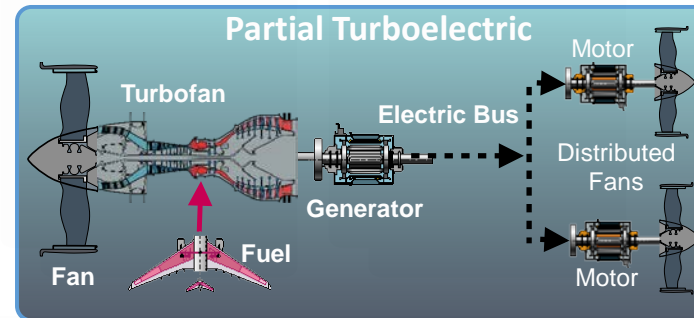
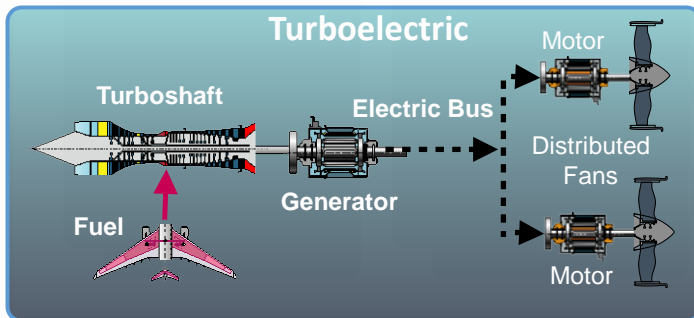
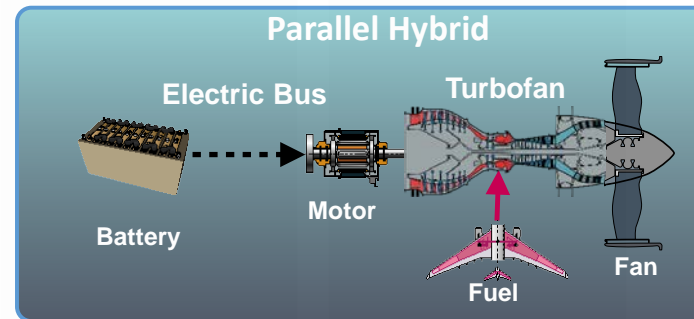
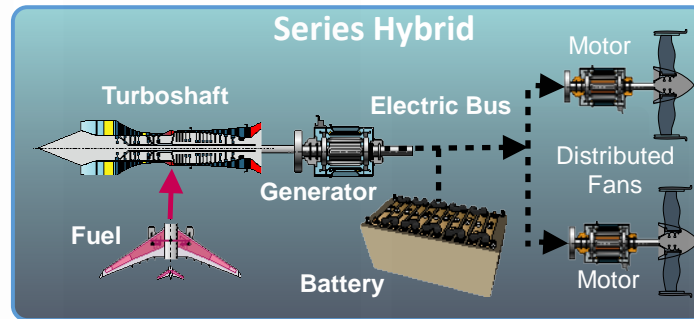
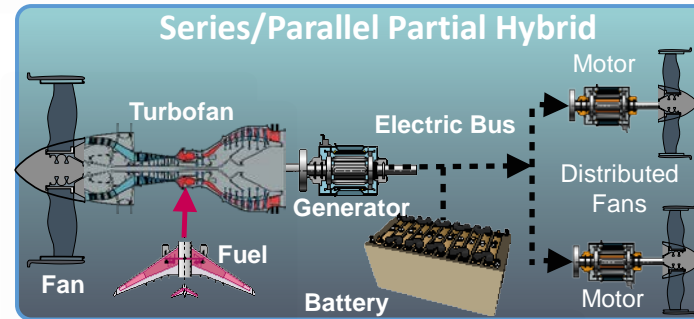
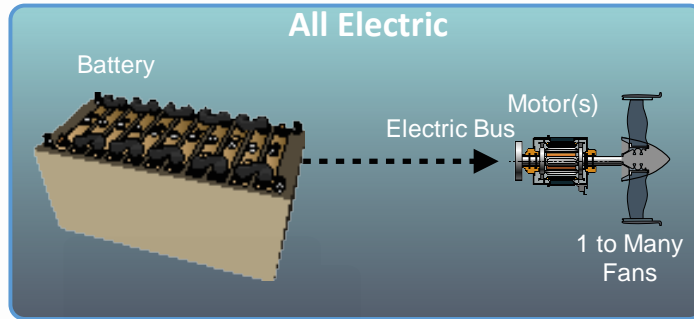
- Overview – Jonathan Litt
- Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)—Jeffryes Chapman
- Electrical Modeling and Thermal Analysis Toolbox (EMTAT)—Mark Bell
- Single-Aisle Turboelectric Aircraft with an Aft Boundary Layer Propulsor (STARC-ABL)—Joseph Connolly
- Thermal Systems Analysis Toolbox (TSAT)—Jonathan Kratz



Overview

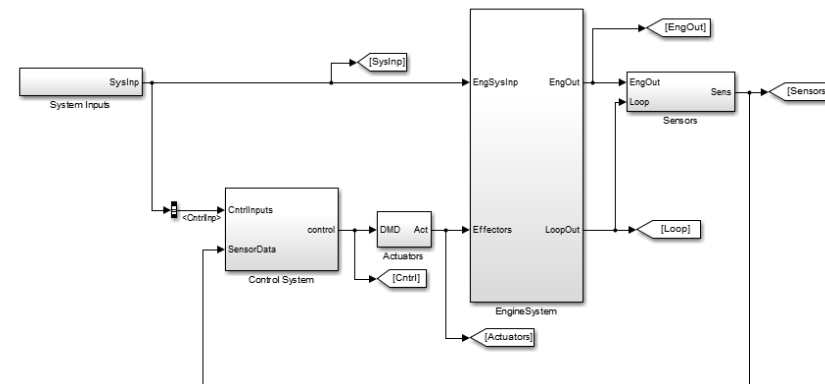
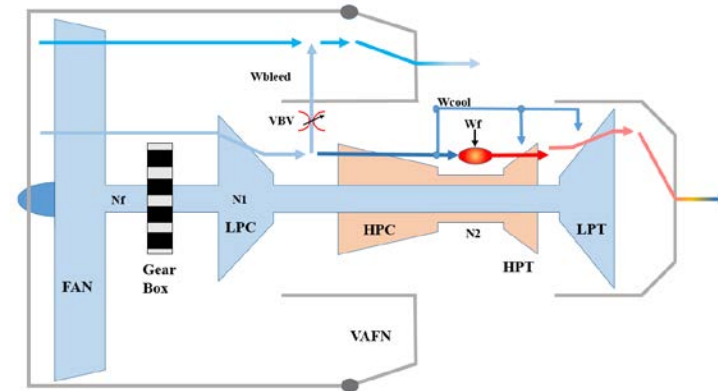
- Electrified Aircraft Propulsion (EAP) is rapidly becoming an area of great interest to the transportation community
- A dynamic modeling and transient simulation capability is important for control design and analysis, and the development of coordination strategies
- NASA is developing tools that can model the dynamic interaction of the power system and the turbomachinery—including thermal effects—at a time scale appropriate for control design
- All codes are open source, created in MATLAB™/ Simulink™, and free to download and use

EAP Architectures



T-MATS—Jeffryes Chapman

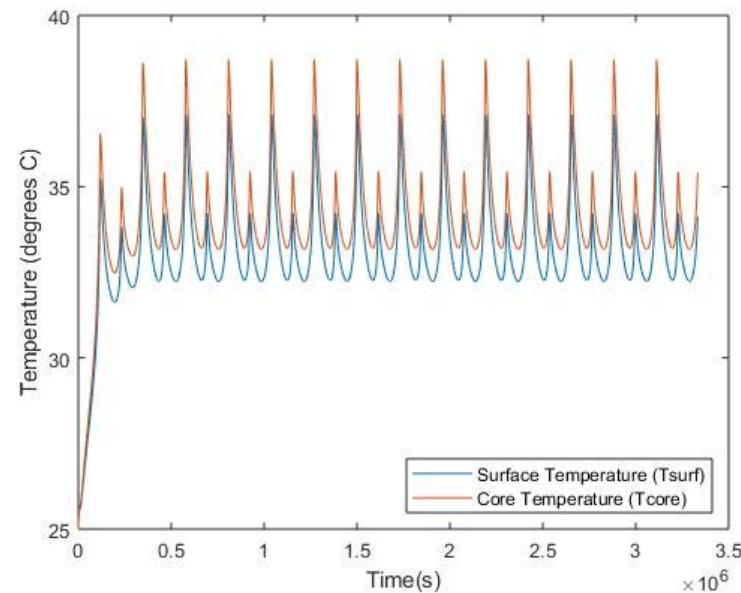
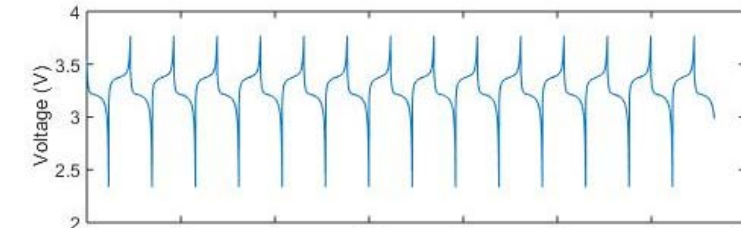
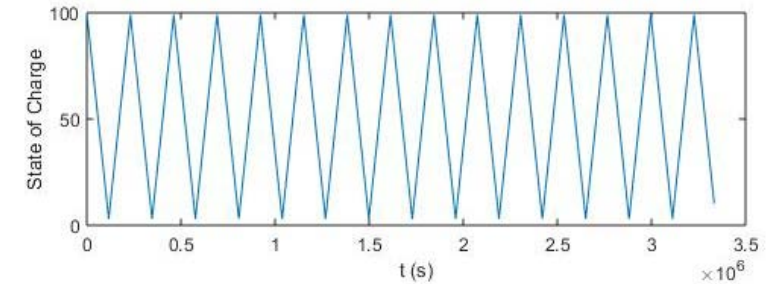
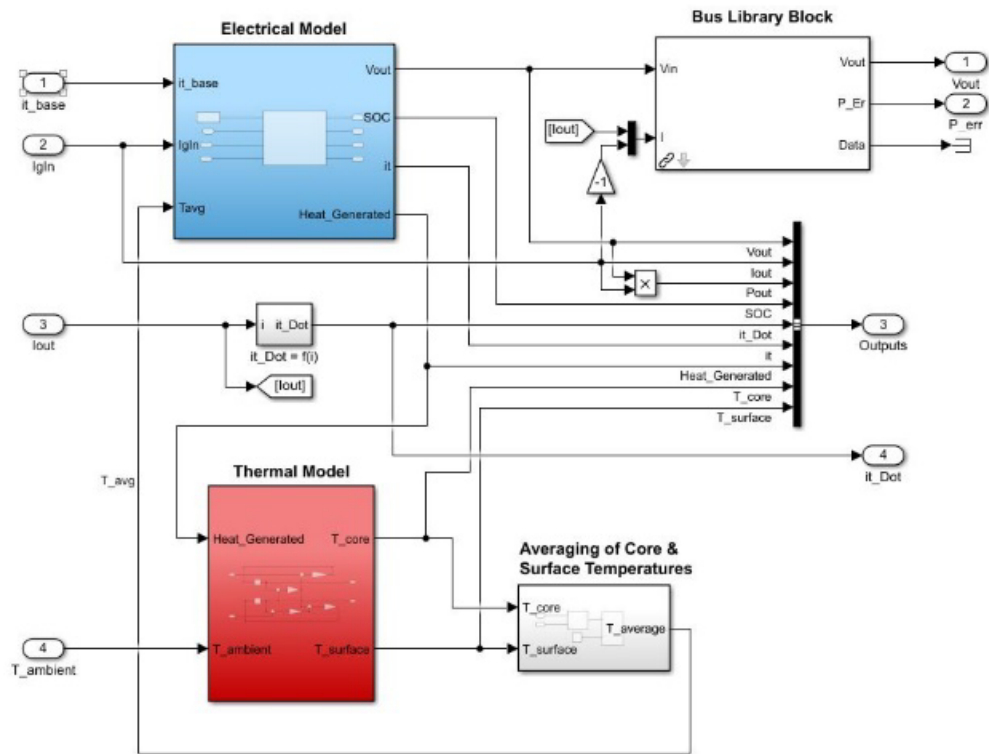
- Modular thermodynamic modeling framework for building dynamic simulations
- Designed for easy creation of custom Component Level Models (CLM) of jet engines
- Although originally intended to simulate turbomachinery, it has been used for other applications, such as fuel cell modeling





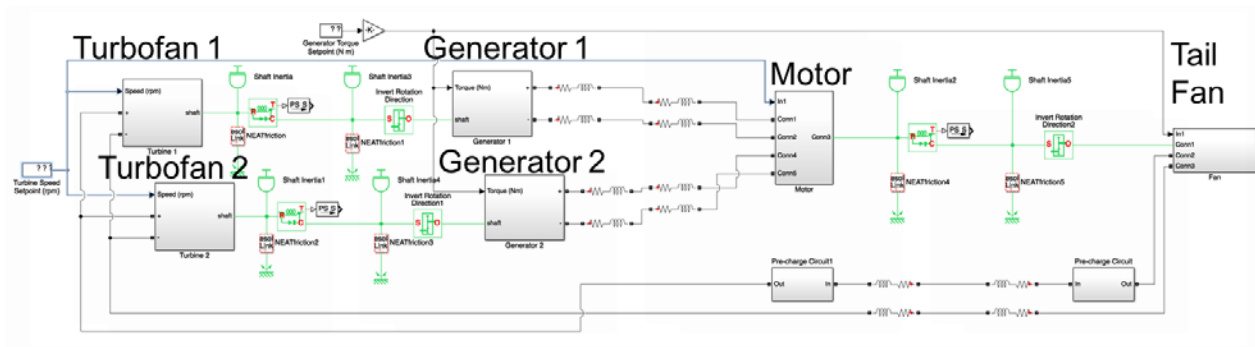
EMTAT—Mark Bell

- Power Flow/Physics-based Electrical/Thermal modeling package (to be released)
- Compatible with T-MATS



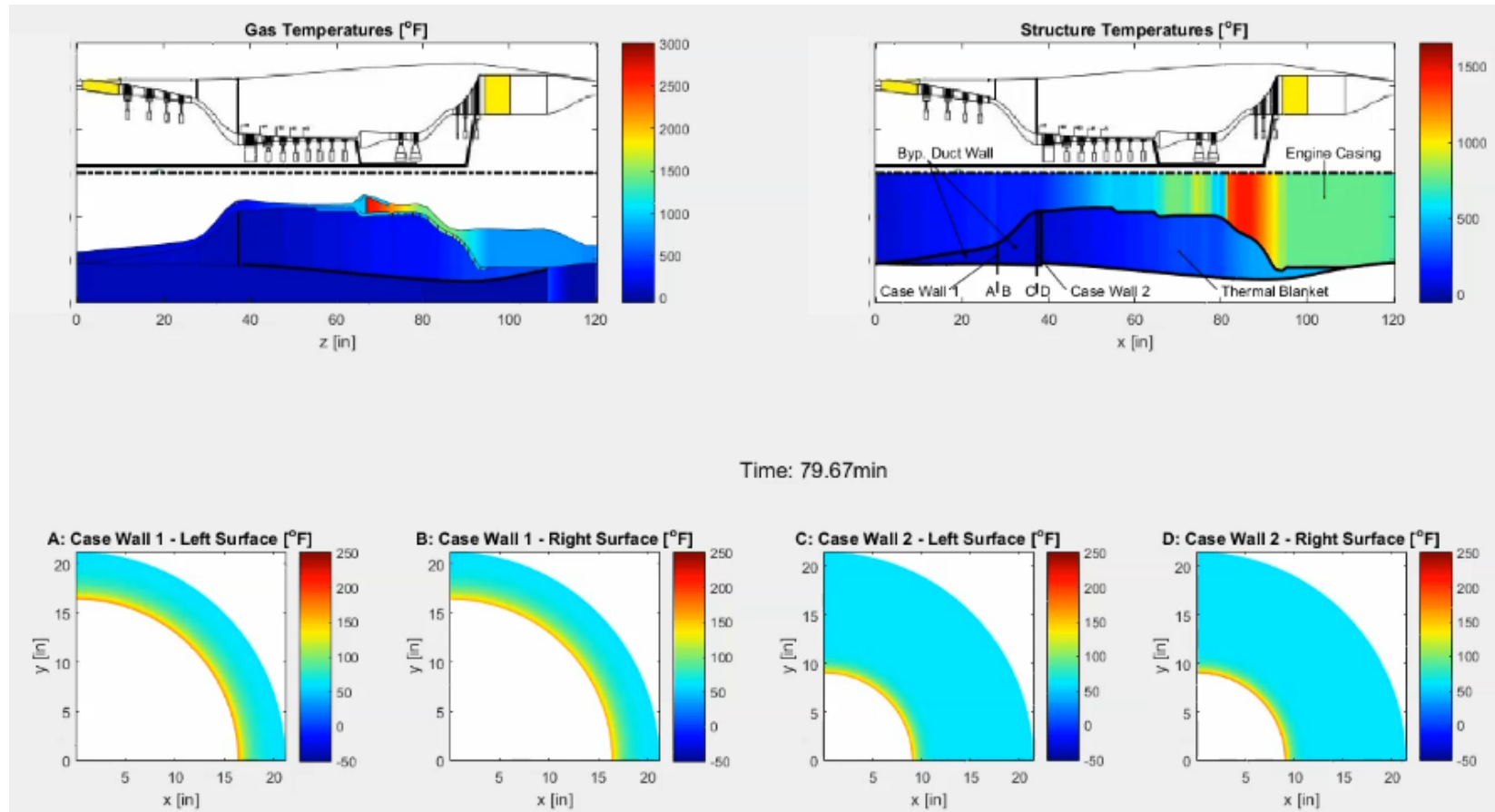
STARC-ABL—Joseph Connolly

- Turboelectric aircraft with two underwing turbofan engines and one electrically-driven tail fan
- Simulink-based modeling tools are used to create a dynamic simulation of the electrified propulsion system



TSAT—Jonathan Kratz

- Used for the modeling and analysis of dynamic heat transfer





Introduction to Dynamic Propulsion System Modeling for Control Design, Analysis, and Simulation

Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

**Jeffryes W. Chapmann, NASA Glenn Research
Center**

Propulsion and Energy Forum

August 19, 2019



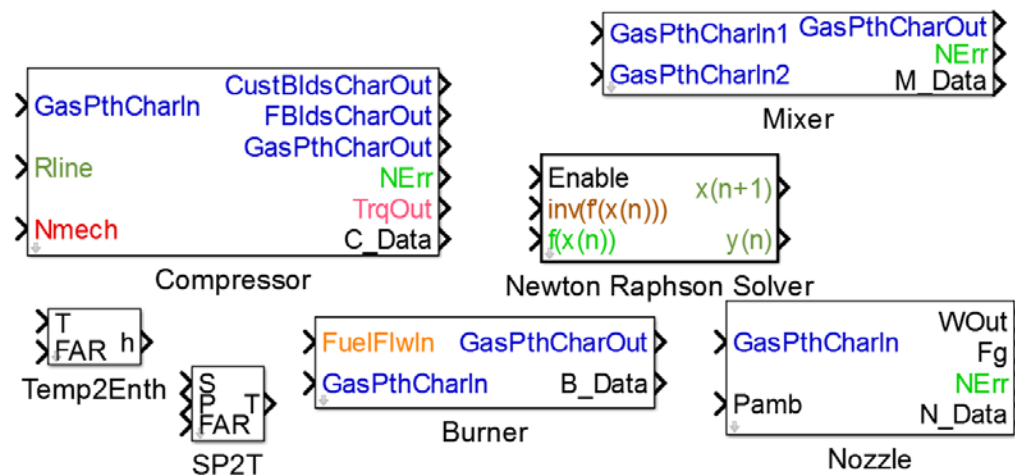
Background

- AGTF30, Advanced Geared Turbofan 30,000 lbf
 - Gas turbine simulation
 - Based on next generation geared turbofan technology
 - Completely developed within MATLAB/Simulink/T-MATS
 - Steady-state and dynamic operation
 - Control system ready
- Purpose
 - Provide a ready made software platform for advanced gas turbine research.



Modeling Platform

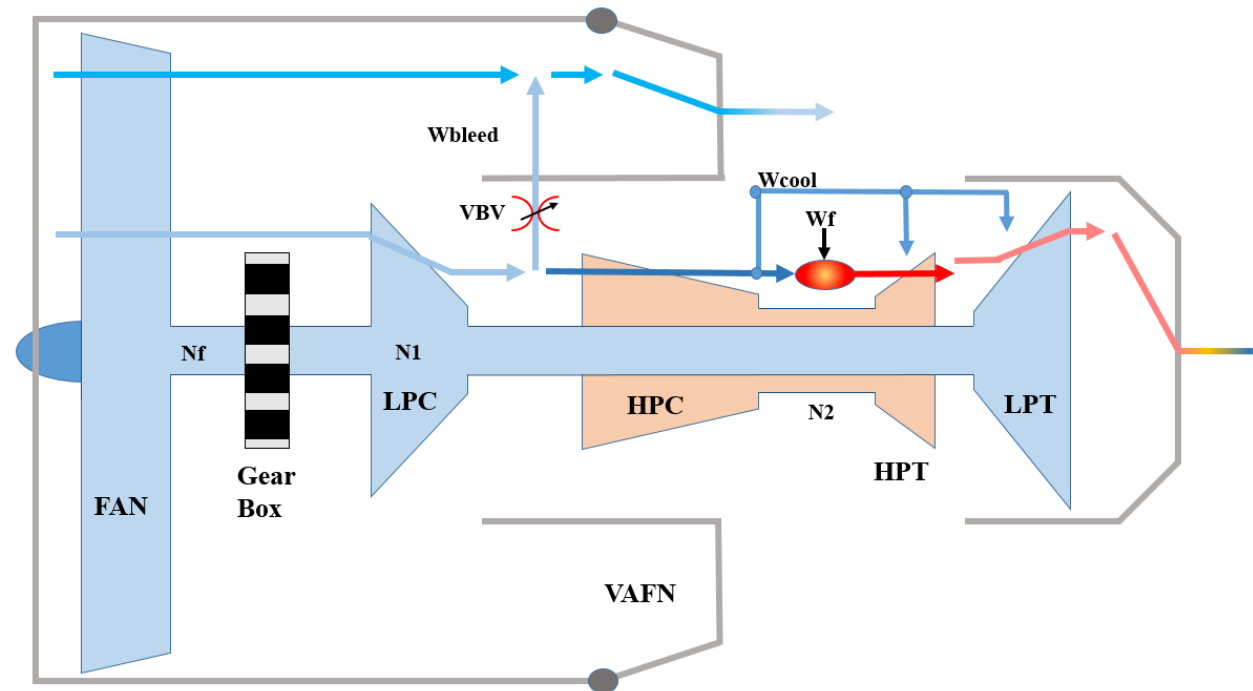
- The AGTF30 was created using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
 - Modular thermodynamic modeling framework created by NASA
 - Built on top of MATLAB/Simulink
 - Package highlights:
 - General thermodynamic simulation design framework
 - Variable input system solvers
 - Advanced turbo-machinery block sets
 - Control system block sets
 - Non-proprietary, free of export restriction and open source with 4500+ downloads, <https://github.com/nasa/T-MATS/releases>





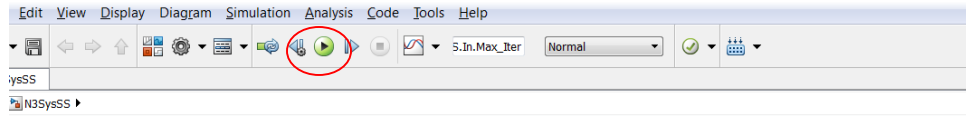
Engine Model Description

- **Advanced Geared Turbofan features**
 - Variable area fan nozzle (VAFN)
 - Dual spool with low pressure shaft connected to fan via a gear box
- **Performance**
 - BPR = 24, OPR = 50, TIT = 3000, TSFC = 0.46 at cruise
 - 30,000 lbf takeoff thrust
- **Control Effectors: VAFN, fuel flow (W_f), and variable bleed valve (VBV)**

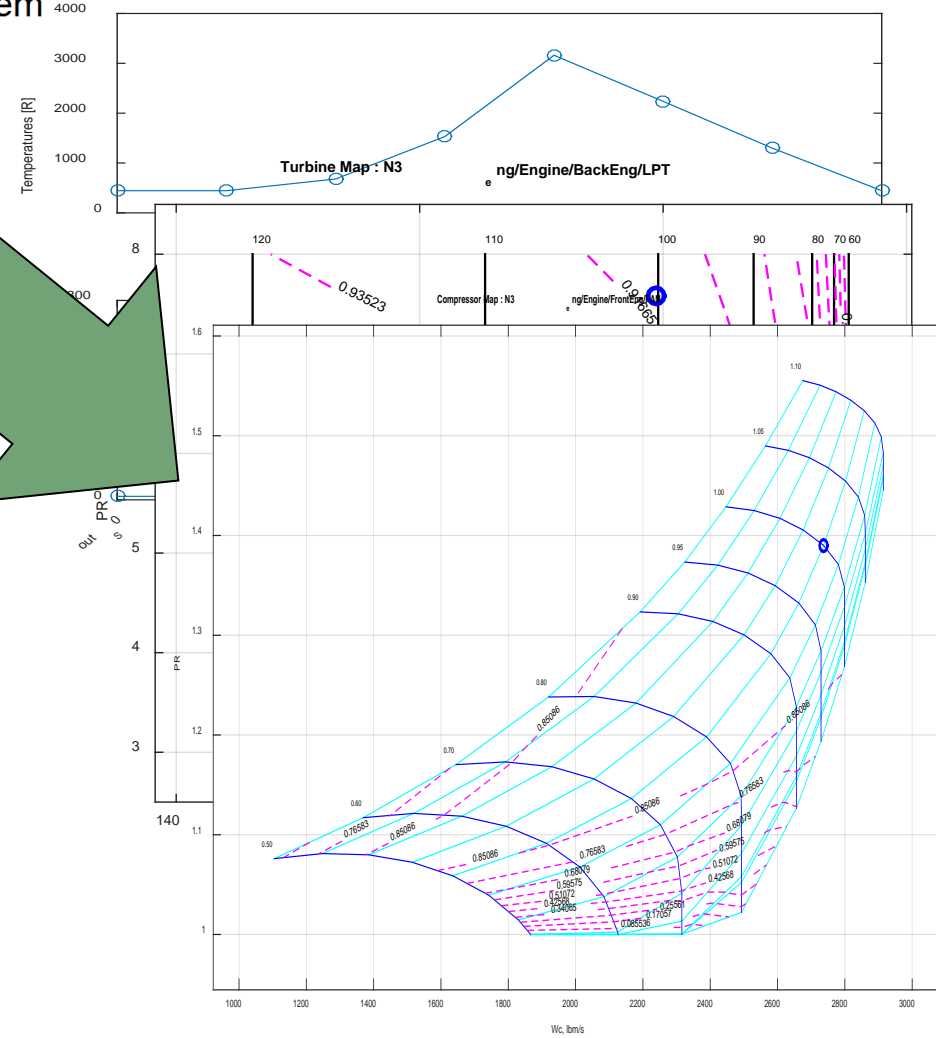
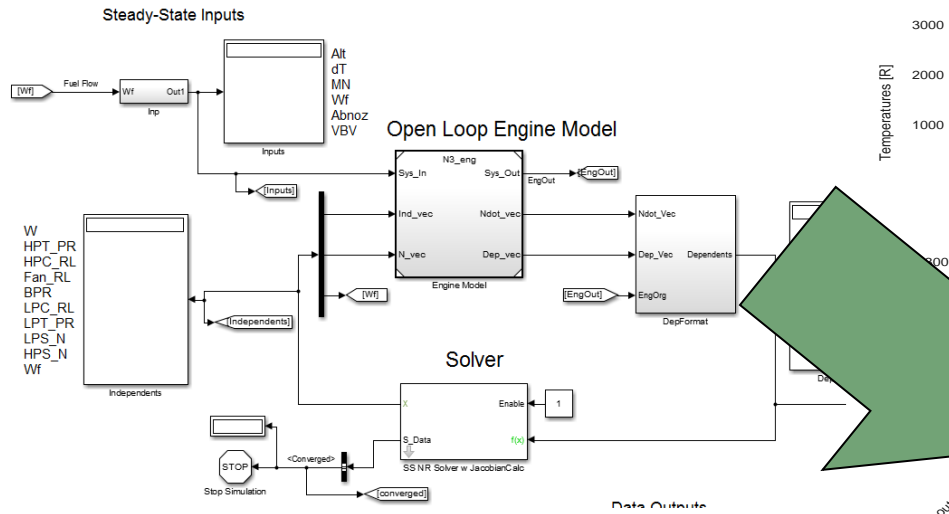




Running the Model



N+3 Steady-State Geared TurboFan System

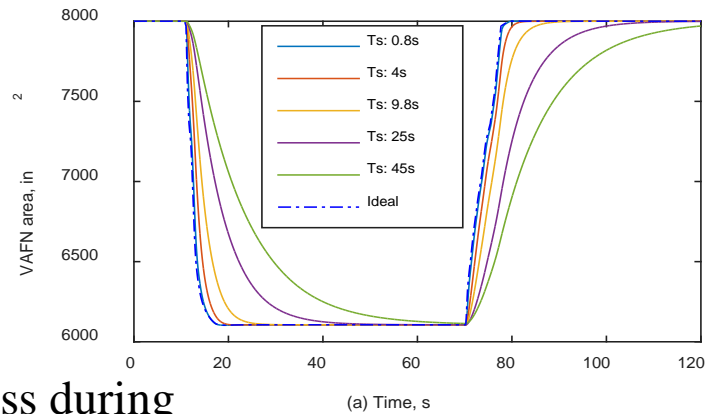


Run simulation to generate representative performance data.

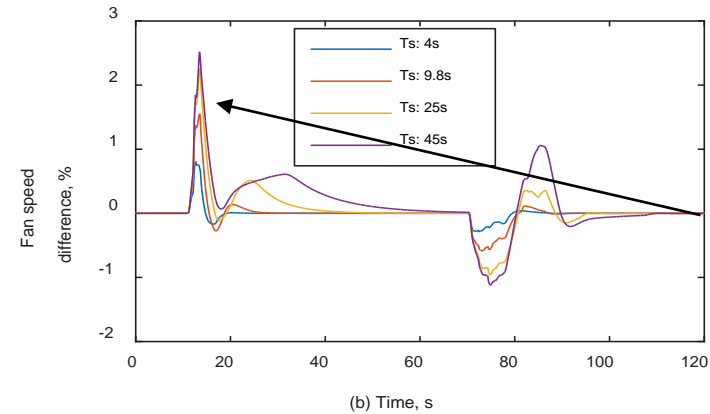
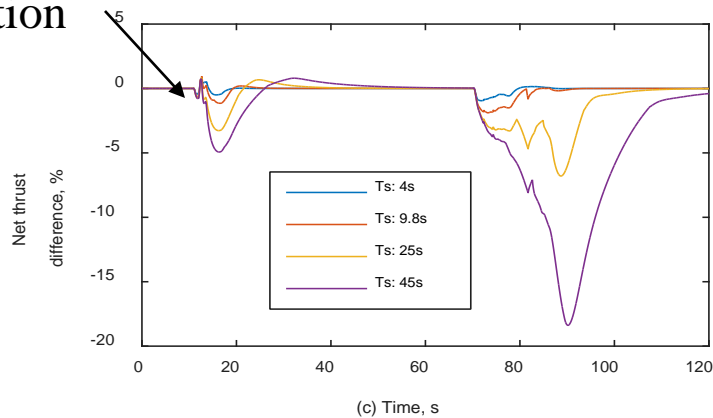


Example research: VAFN response study

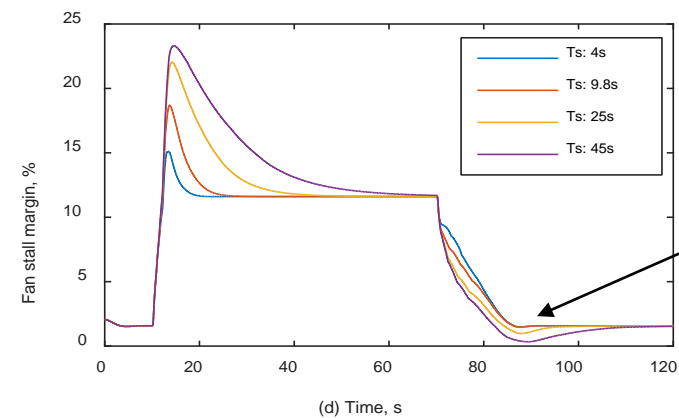
- The AGTF30 was used for a simple study to find the minimum settling time requirement for a hypothetical shape memory alloy actuator.



Thrust loss during acceleration



Increase in fan speed during acceleration



Stall margin positive at all points



Acknowledgments

Funding for this work was provided by NASA Advanced Air Transport Technology (AATT) project and NASA Transformational Tools and Technologies (TTT) project

Links



AGTF30:

<https://www.grc.nasa.gov/WWW/cdtb/software/agtf30.html>

AGTF30: github location:

<https://github.com/nasa/AGTF30>

T-MATS:

<https://www.grc.nasa.gov/WWW/cdtb/software/t-mats.html>

Publication :

Chapman, J. W., Litt, J. S., "Control Design for an Advanced Geared Turbofan Engine," AIAA-2017-4820, Propulsion and Energy Forum, Atlanta, GA, June 10-12, 2017.

<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011210.pdf>



Introduction to Dynamic Propulsion System Modeling for Control Design, Analysis, and Simulation

Electrical Modeling and Thermal Analysis Toolbox (EMTAT)

Mark Bell, PE
Vantage Partners, LLC

Propulsion and Energy Forum
August 19, 2019





EMTAT - Definition

- The Electrical Modeling and Thermal Analysis Toolbox (EMTAT) is a set of Simulink libraries designed to simulate a variety of power electronic devices, using both physics-based and power flow calculations. EMTAT is designed to interface with T-MATS as a complementary set of library blocks.
- Due to the relatively slow time step of ~1 ms in most T-MATS simulations, the electronic devices can be assumed to be operating at steady state. Steady state operation allows the electrical performance calculations to be simplified, with all of the high speed transients captured as an efficiency loss. Note - This does not replace high speed, high fidelity electronic simulation tools such as SPICE. However, since EMTAT simulates at least 25x real time, it is more useful for model-based control methods.





EMTAT - Operation

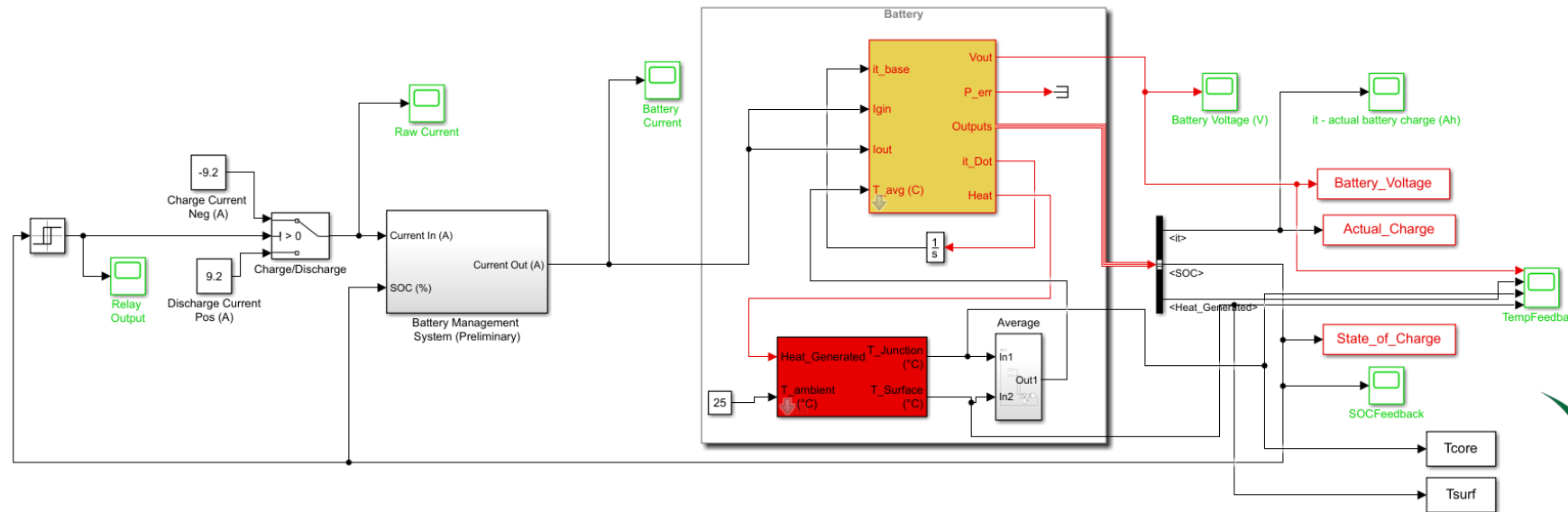
- Steady state operation of electrical components, while smoothing out the high speed electrical transients, still demonstrates system dynamics in operation. Physics-based models also allow for realistic heat outputs and thermal rises to be calculated, with the associated performance impacts.





EMTAT – Temperature Feedback

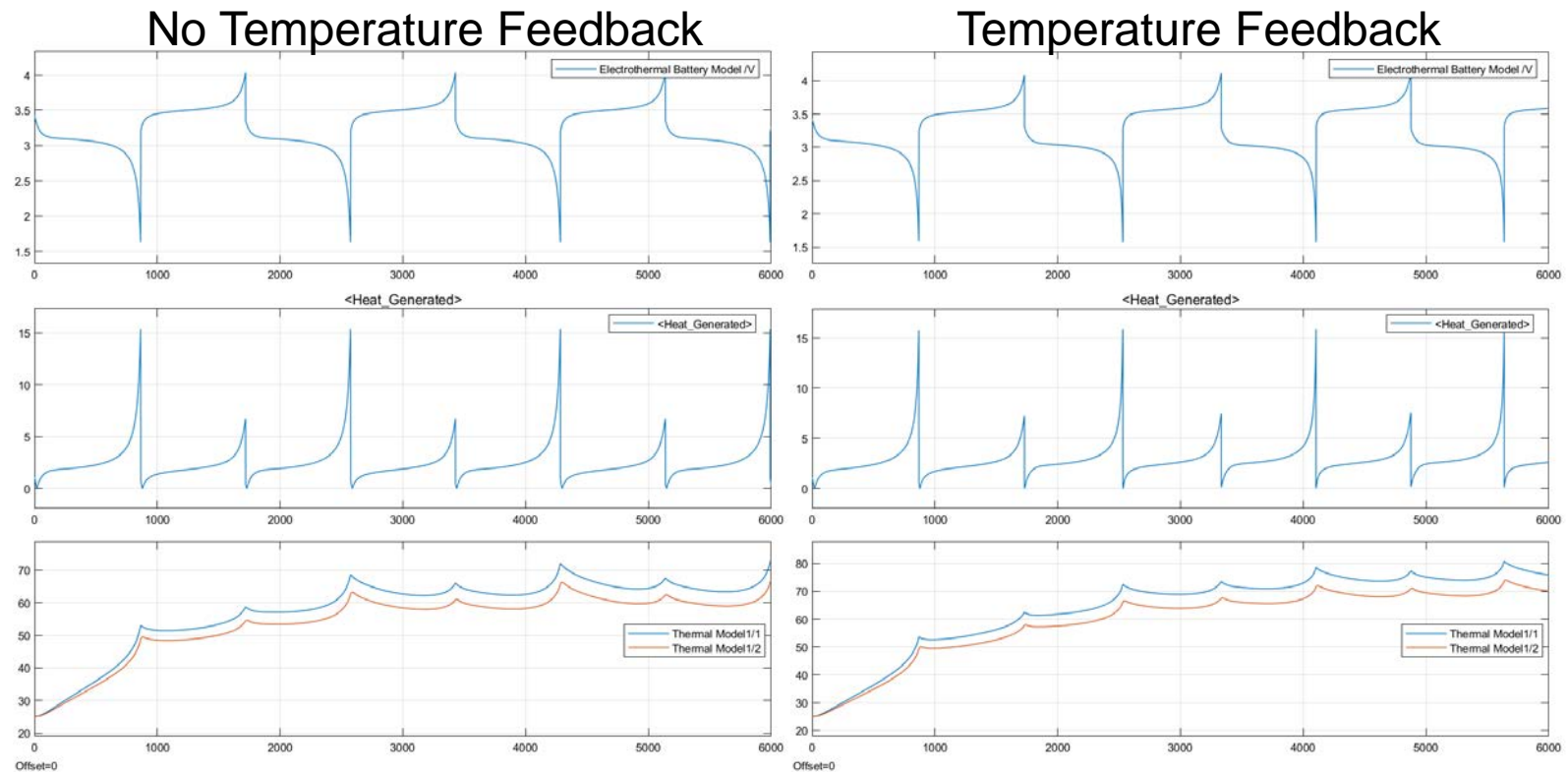
- Temperature feedback allows users to see the performance changes associated with changing temperatures in the parts. Shown here is a simple battery charge/discharge simulation, using the physics based battery block and the heat to temperature block for temperature feedback. By overriding the average temperature input with a constant, we can instead disable temperature feedback.





EMTAT – Temperature Feedback

- As can be seen here, the increased internal temperatures leads to increased heat generation and faster discharge cycles.
- Internal temperatures affect physical component properties as specified by manufacturer data sheets.



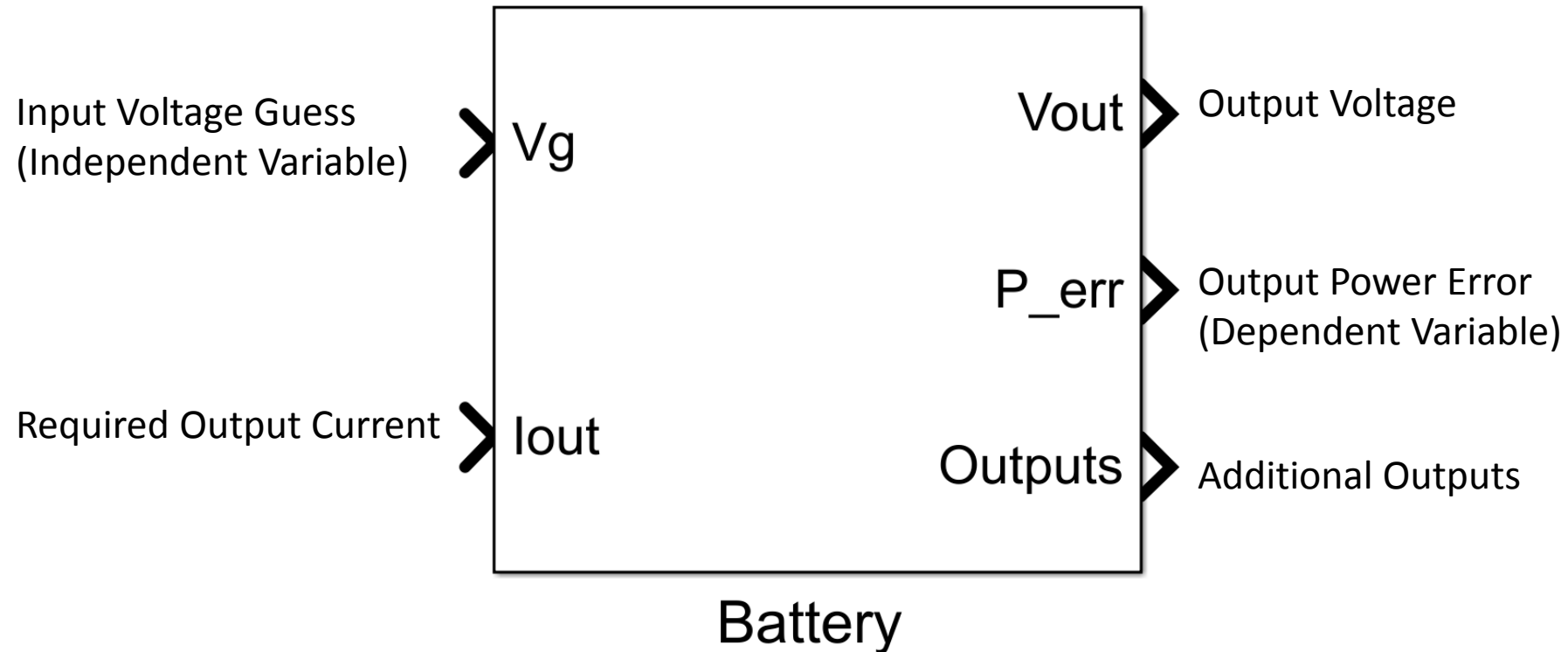


APPENDIX – EMTAT Component Overview

Component	Library (Power Flow/Physics Based)	Temperature Output	Thermal Feedback
Battery (Li+)	PF + PB	Y	Y
DC Boost Converter	PF + PB	Y	Y
DC Buck Converter	PF + PB	Y	Y
Inverter/Rectifier	PF + PB	Y	Y
Electric Motor/Generator (PMSM)	PF + PB	Y	Y
Resistor	PF + PB	Y	Y
Current Limiting Resistor	PF + PB	Y	Y
Transmission Line	PF		
Super Capacitor	PF		
AC Transformer	PF		

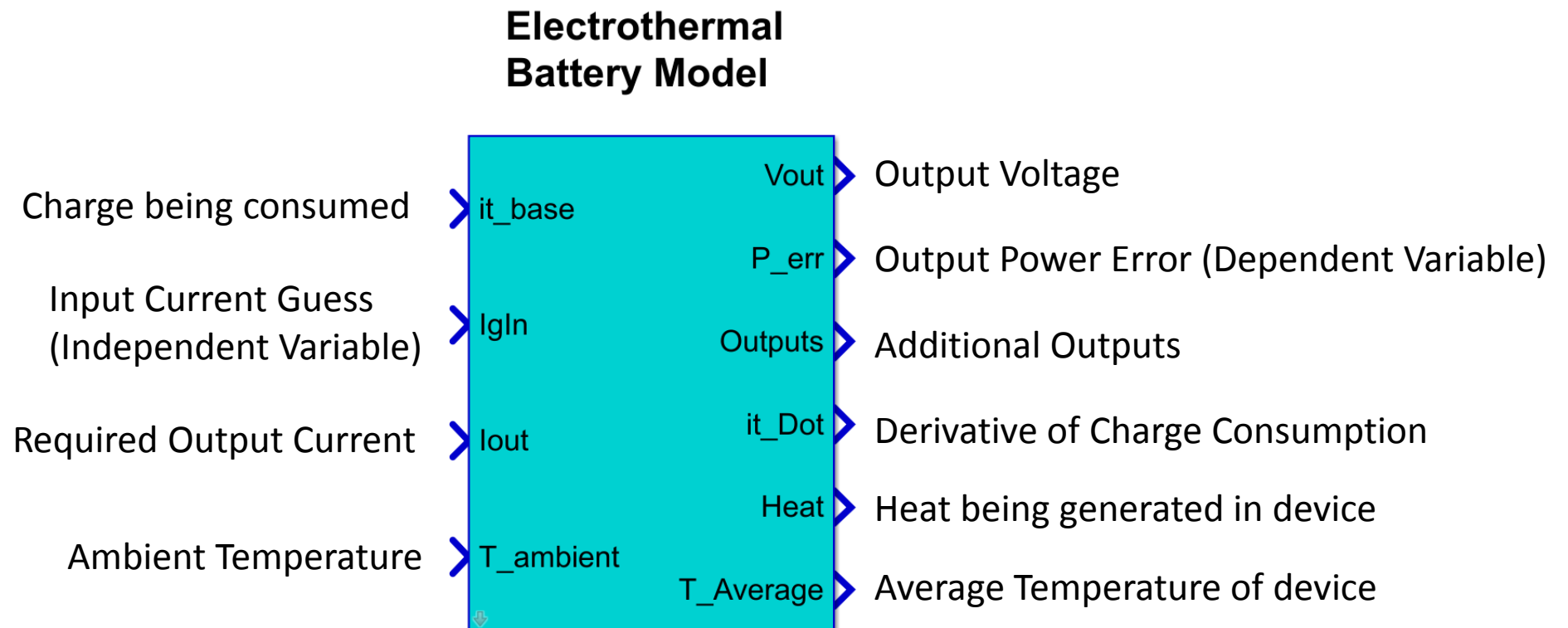
Battery – Power Flow

This block takes in a nominal voltage input. It contains a slack bus and a battery impedance to provide basic battery behavior.



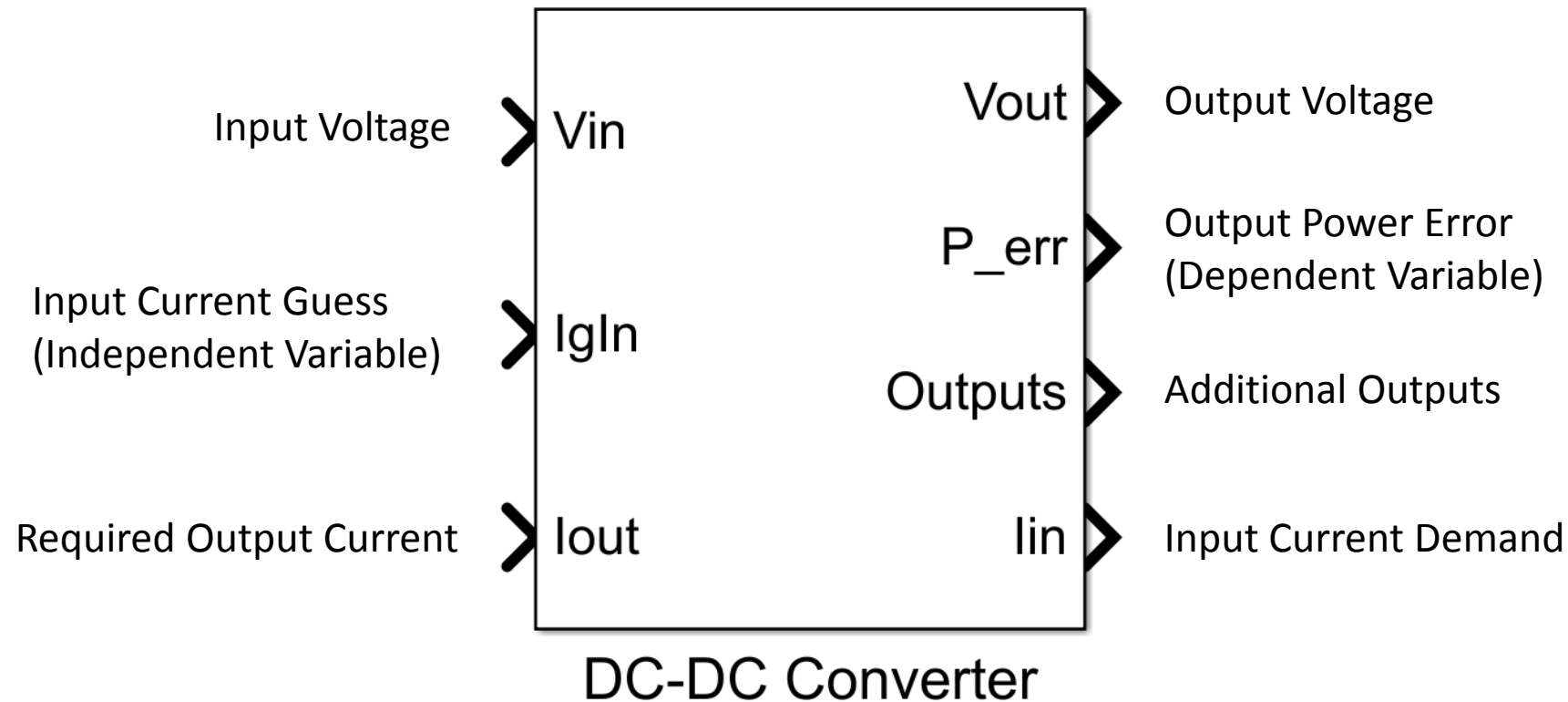
Battery – Physics Based

This block represents a physics-based battery model. The output voltage is a function of the current drawn from the battery, and the time integral of the current drawn from the battery. The block requires an integrator to calculate charge consumption. This block uses the waste heat generated due to inefficiencies to calculate internal temperatures and performance changes due to temperature changes.



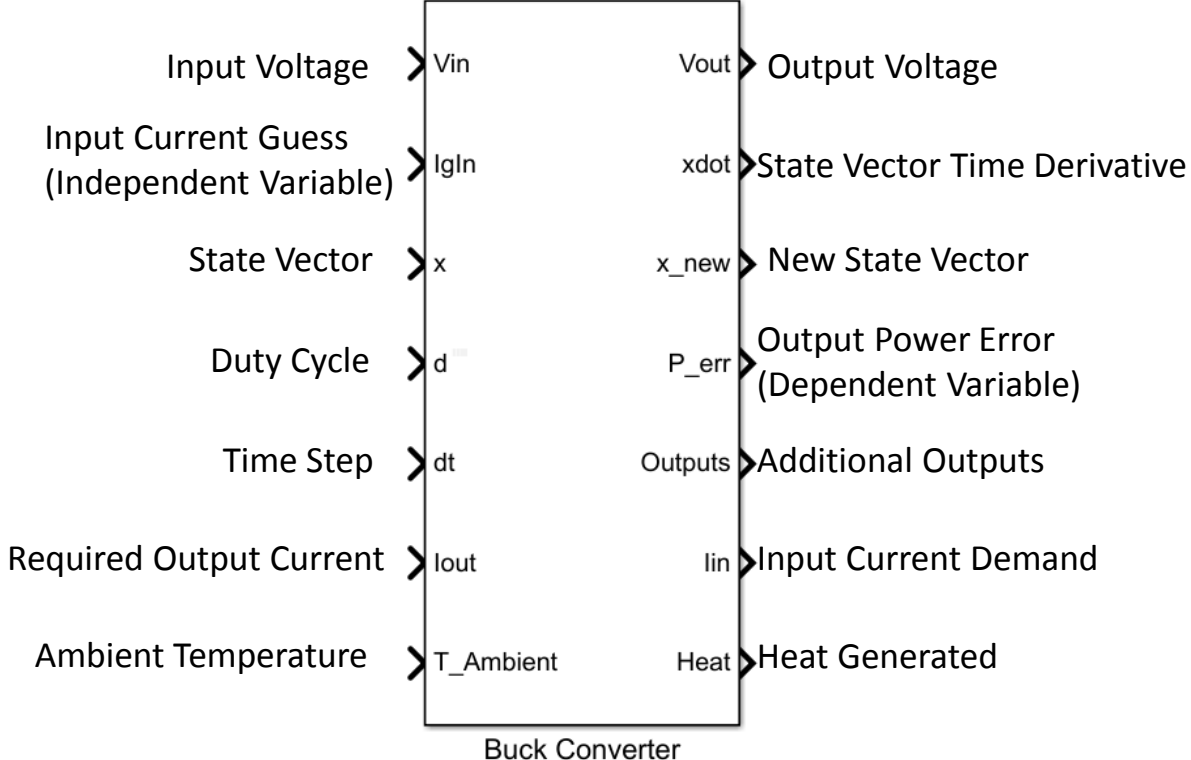
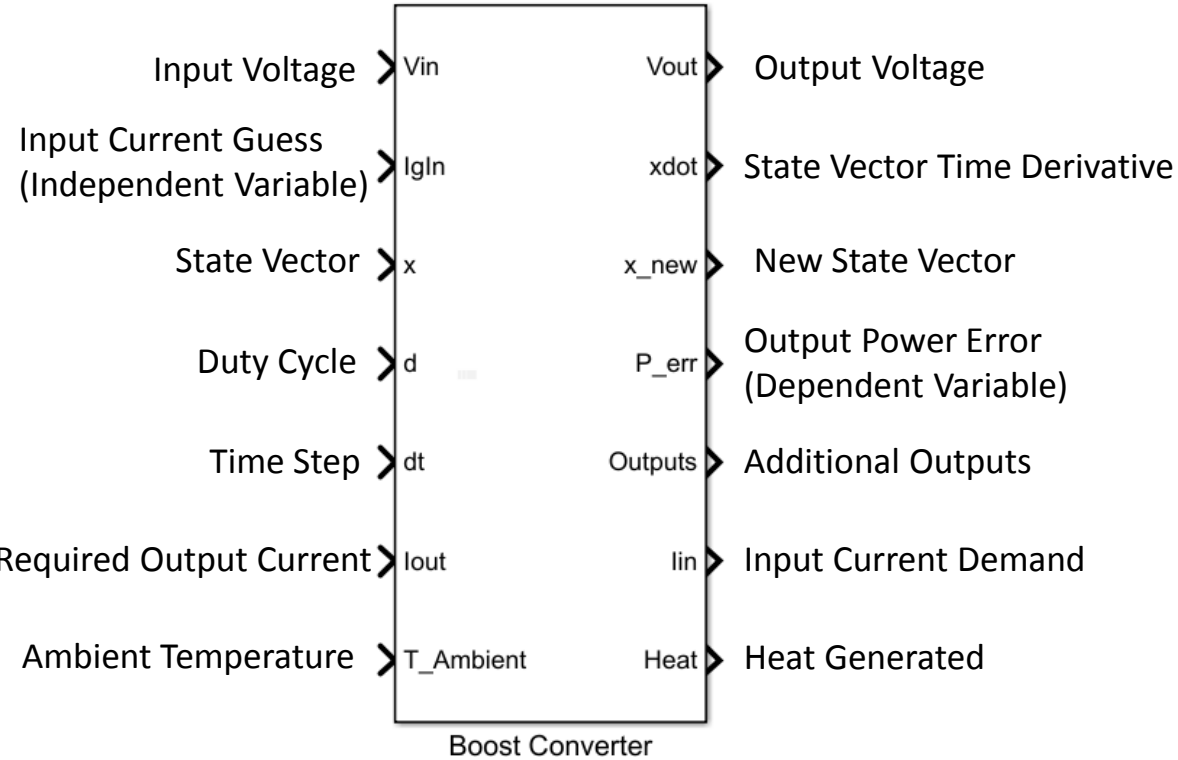
DC-DC Voltage Converter – Power Flow

This block represents a generic DC-DC converter controlled to produce a constant output voltage (either a buck, boost, buck-boost, Cuk, etc.). The converter's efficiency is defined via a lookup table that is a function of input voltage and current. The input current is solved for, such that the power in equals the power out.



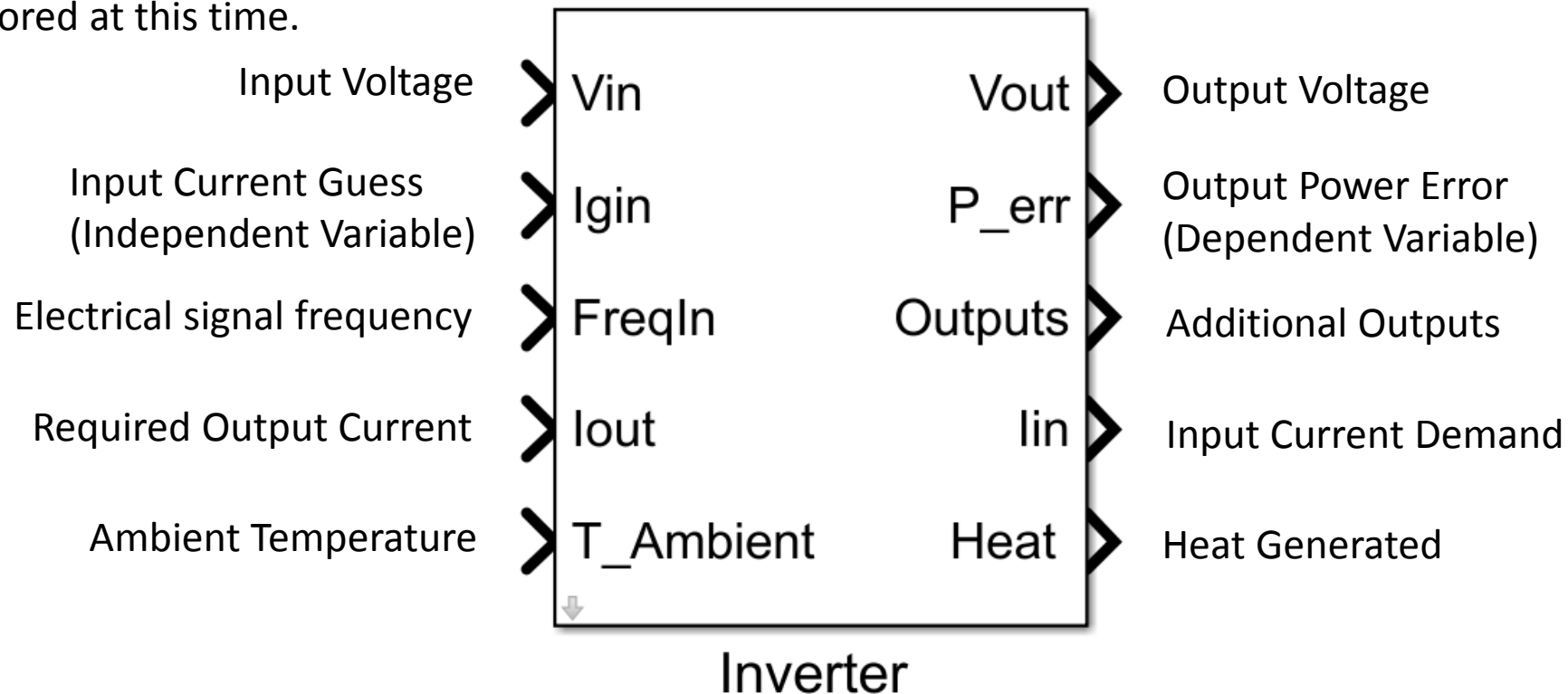
DC-DC Voltage Converters – Physics Based

These blocks represent generic DC-DC Buck and Boost converters, controlled to produce a constant output voltage. The converter efficiencies are determined by the physical characteristics of the parts that create the devices. These blocks use the waste heat generated due to inefficiencies to calculate internal temperatures and performance changes due to temperature changes.



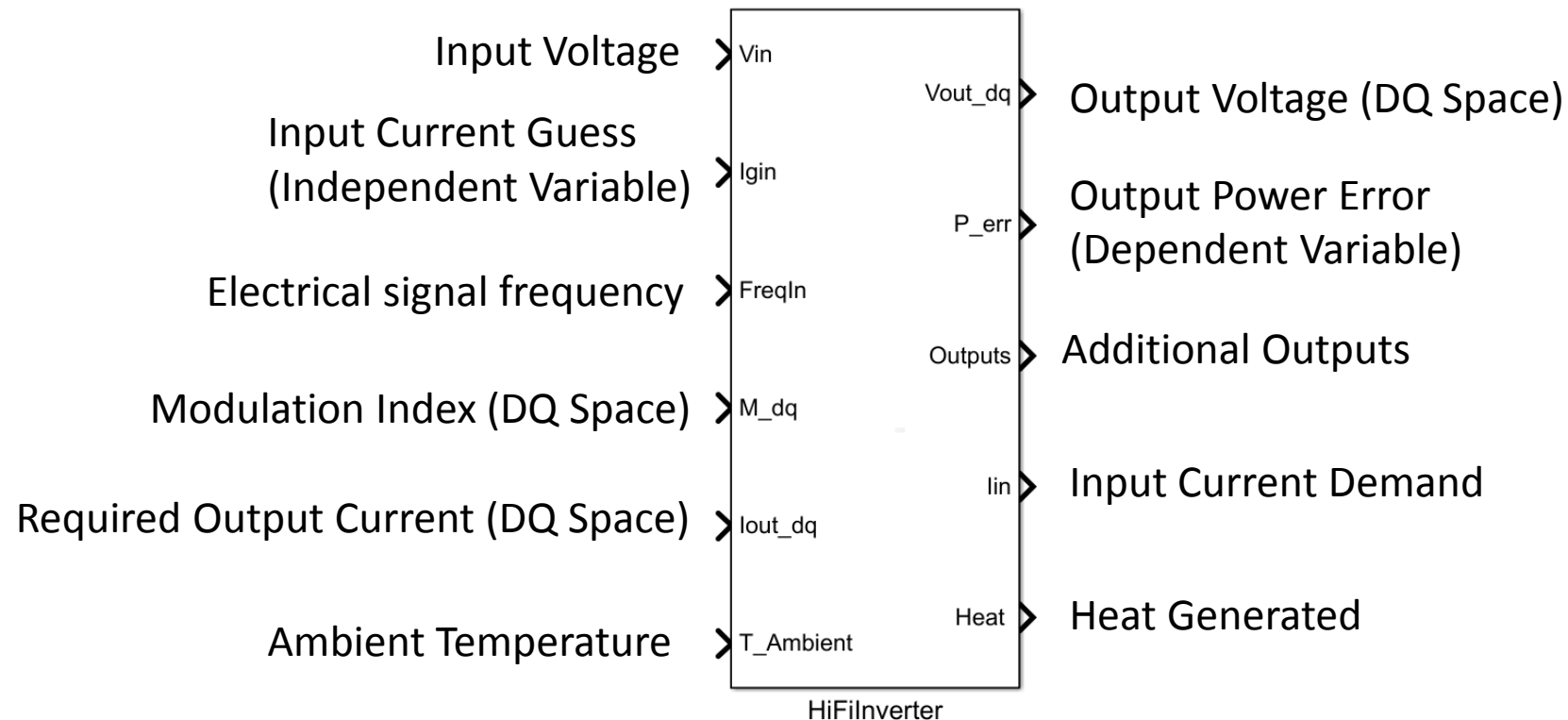
AC-DC/DC-AC Voltage Converter – Power Flow

This block represents a DC-to-AC inverter or AC-DC rectifier, depending on the polarity of the output current. V_{in} is DC, V_{out} is AC. This block assumes that the Required Output Current is in a per phase amplitude format, and the required input current is scaled up for total current in a 3 phase system. The block produces an output voltage that scales with input frequency according to the flux constant, $Hz_to_V_M$. The load is assumed to have no inductance, and so we are assumed to operate with unity power factor. Converter efficiency is specified via a lookup table that is a function of output voltage and output current. Heat generated due to efficiency losses is calculated, and Ambient Temperature and any heating effects are ignored at this time.



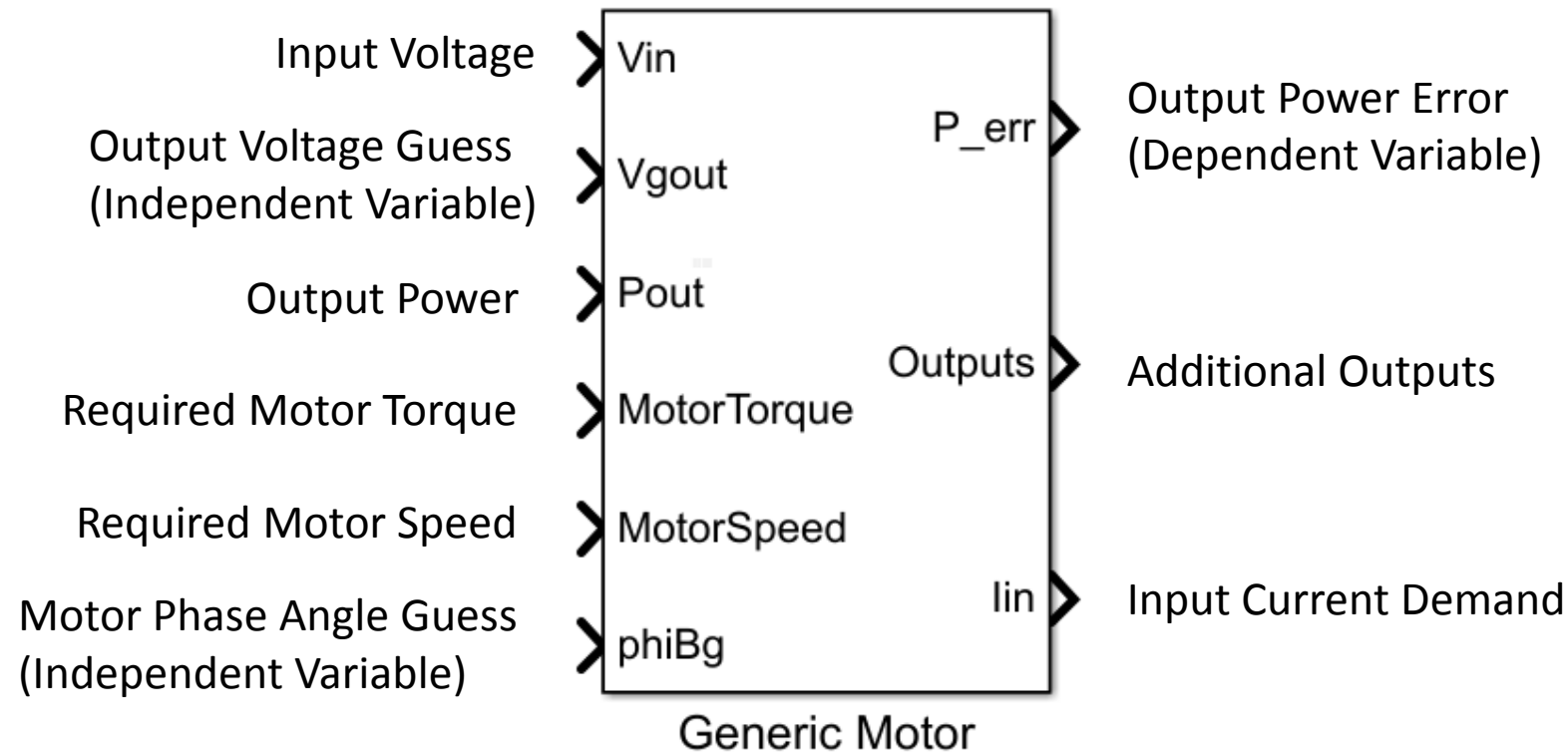
AC-DC/DC-AC Voltage Converter – Physics Based

This block represents a generic, 3-phase, multi-level inverter whose AC side is modeled in d-q space. The inverter is composed of submodules whose characteristics are then lumped together into positive and negative "arms," (given by R_{arm} , C_{arm} , and L_{arm}) which are above and below each AC phase. The arm voltages are also lumped together. The arm circuit parameters and switch/switching parameters are specified in the block mask. Note that the arm resistance is meant to include the switch on-resistance as well as other resistances. If the required output current is negative, then this block acts as a rectifier. V_{in} is always DC, V_{out_dq} is always in DQ Space. This block uses the waste heat generated due to inefficiencies to calculate internal temperatures and performance changes due to temperature changes.



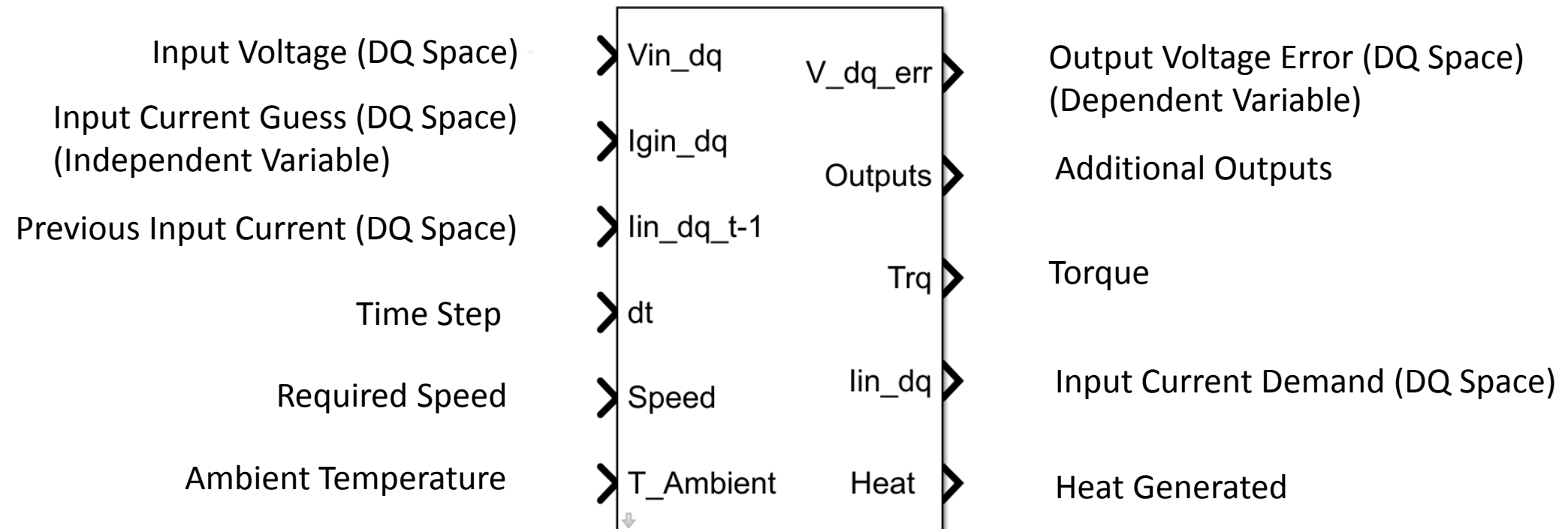
Electric Motor/Generator – Power Flow

This block represents a generic AC motor with a standard resistive impedance of 0.01 Ohms and an efficiency table input.



Electric Motor/Generator – Physics Based

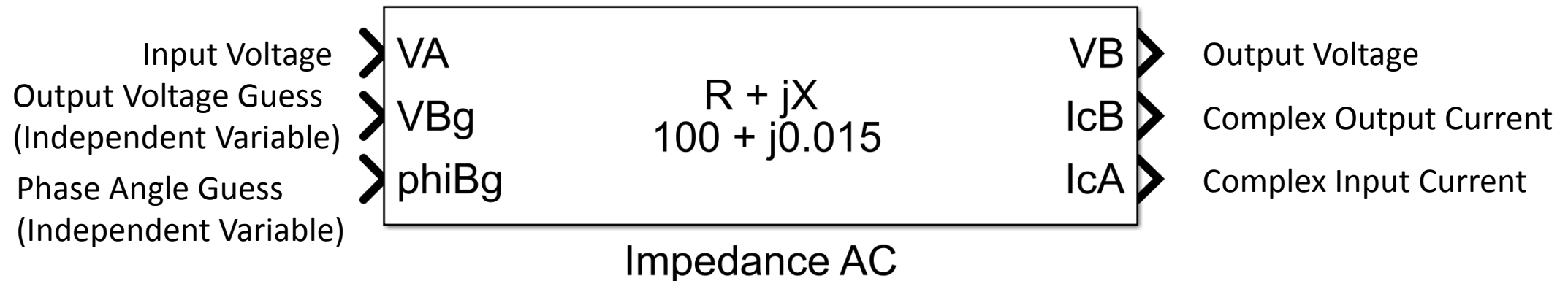
This block represents a generic synchronous motor whose electrical performance is calculated in dq0 space. The motor's dynamic impedance is simulated in terms of dq input voltage and current. dq current is intended to be a solver independent, and the previous value of dq current and the simulation time step are used to compute the inductor dynamic voltage (motor electrical transients). Note the electrical parameters are two-phase equivalents, so must be computed from the appropriate phase values. This block uses the waste heat generated due to inefficiencies to calculate internal temperatures and performance changes due to temperature changes.



PhysicsBasedSynchronousMotor

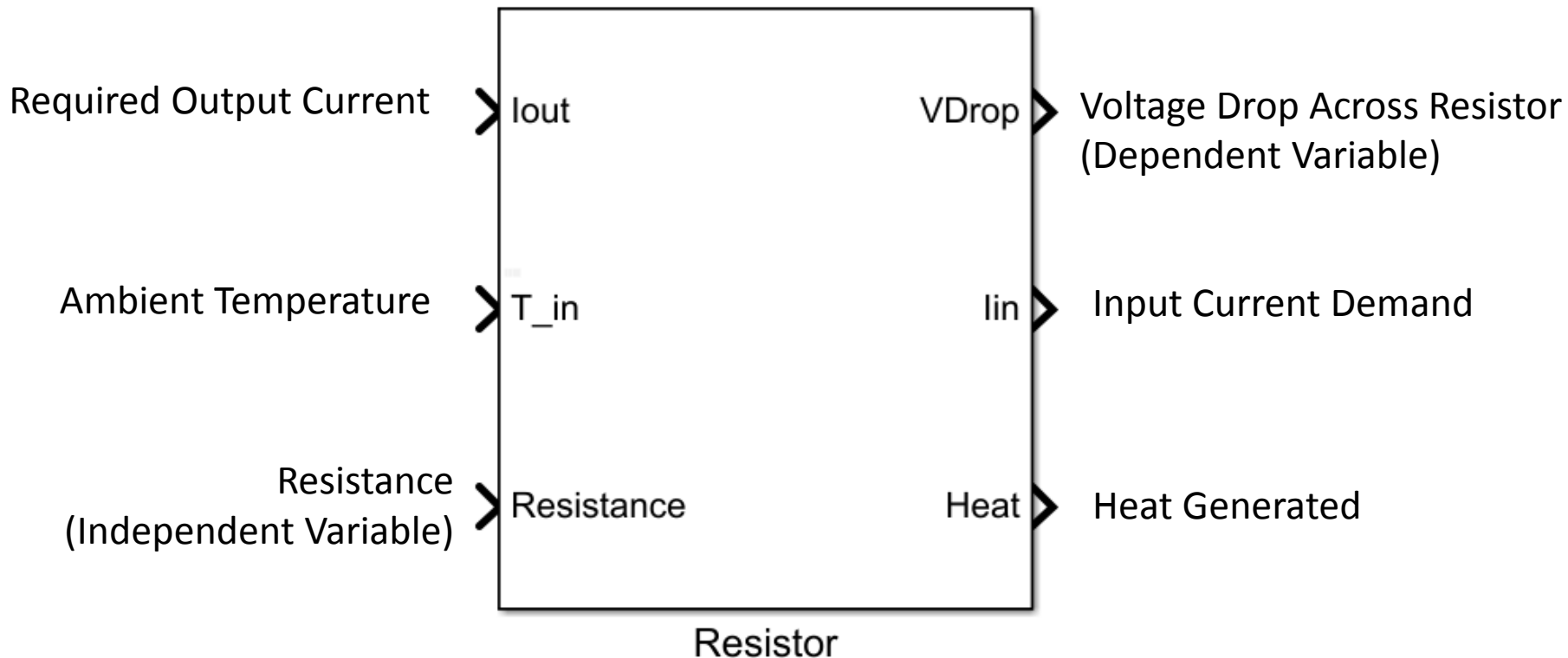
Resistor – Power Flow

The impedance component offers the basis of any line by allowing any impedance to be defined manually. The component is created using an upstream voltage input, then solving for the downstream voltage.



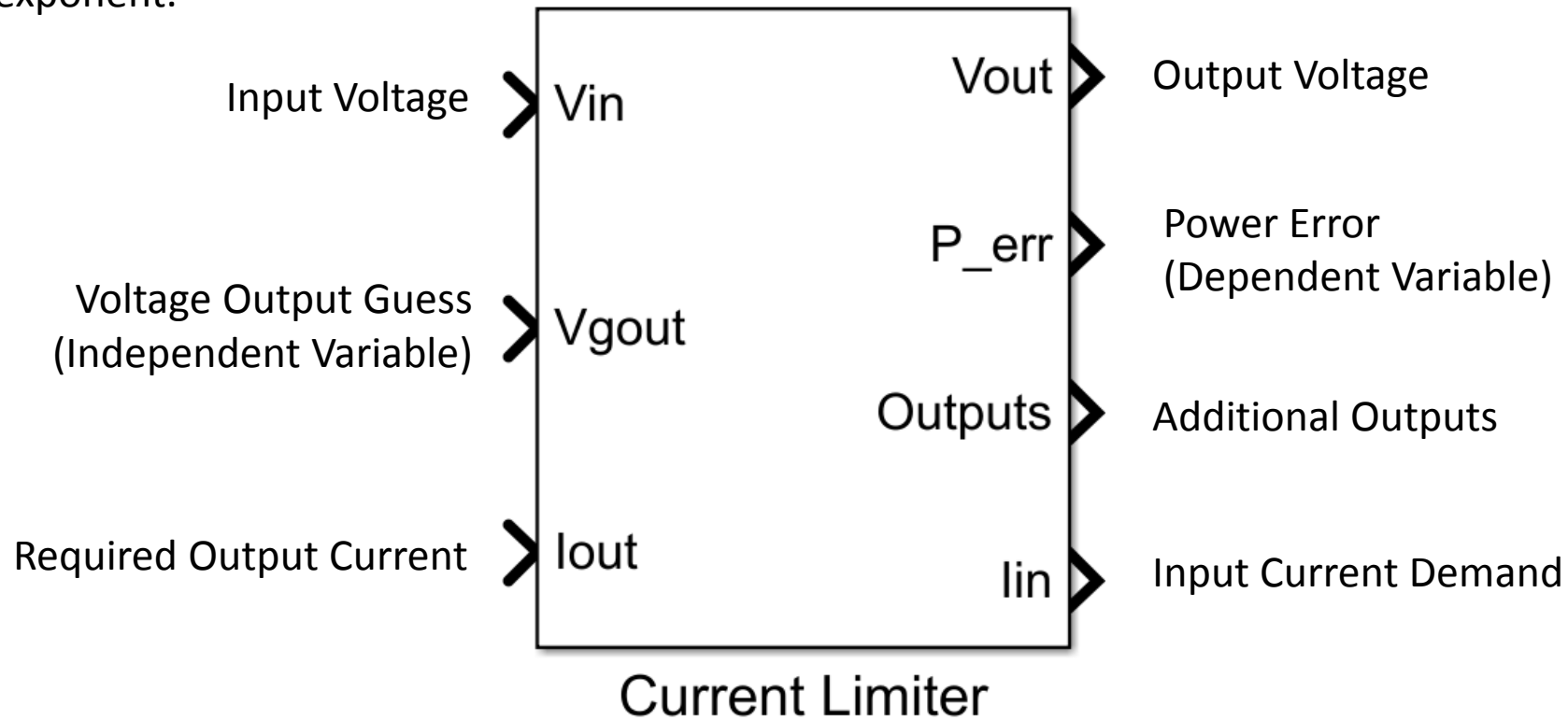
Resistor – Physics Based

This block is a current based resistor, adjusting the resistance to achieve the desired voltage drop at a given current. There will be added a minimum resistance, to simulate the ability of a controller to use a PWM signal on a switch to increase the effective resistance, but there is still a minimum resistance of the device itself. This block may be used in a variety of ways to create Current Limiting Resistors, Basic Resistors, Power Bleed Resistors, etc. This block uses the waste heat generated to calculate internal temperatures and performance changes due to temperature changes.



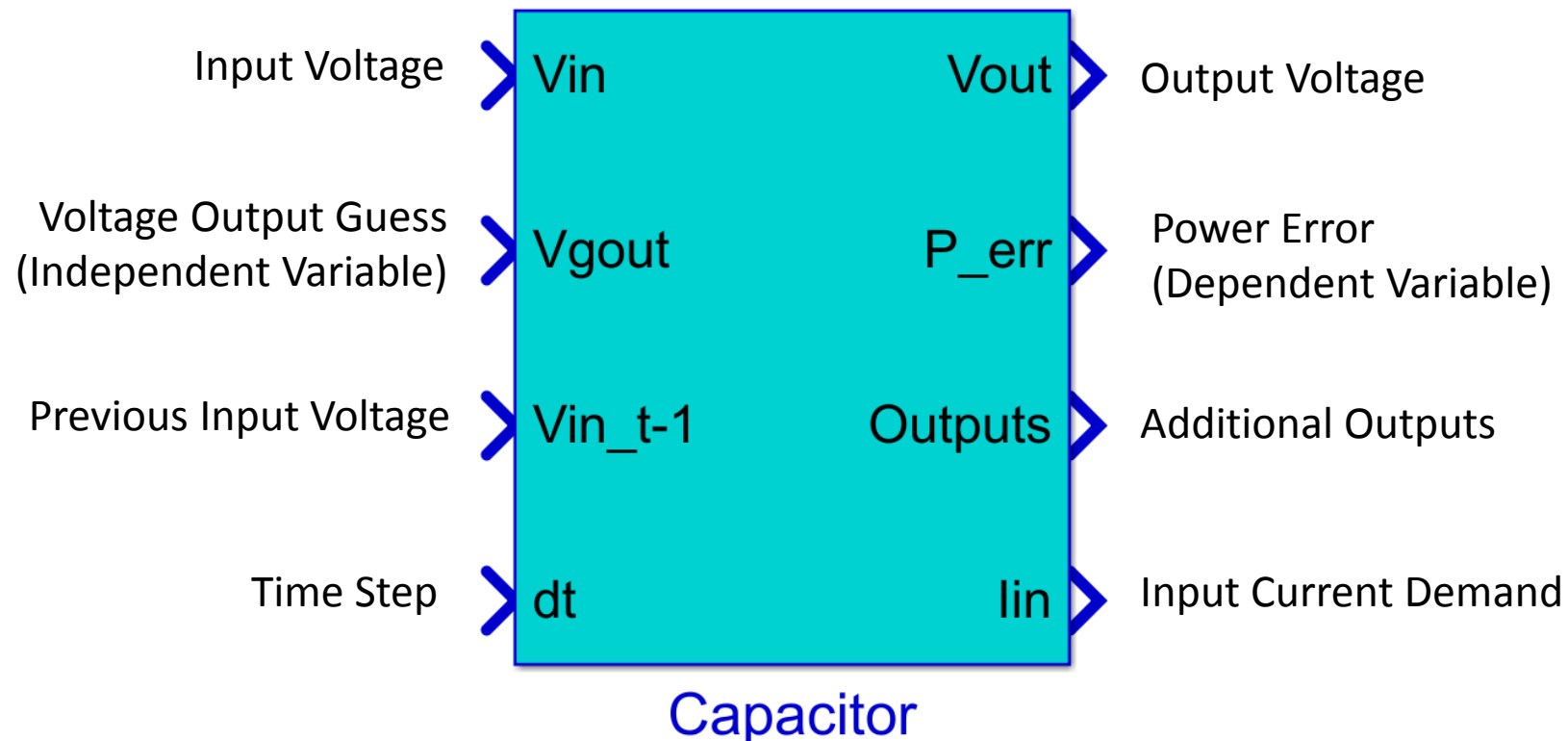
Current Limiting Resistor – Power Flow

This block represents a generic current limiting device. If the current through this device is within the upper/lower limits, this device's impedance will be the "On Resistance." Otherwise the impedance will be the "HiZ Resistance." If current is close to the bounds, the impedance will be somewhere in between (the R vs I characteristic is sigmoidal.) You can adjust the roll off of the characteristic via the rolloff_M parameter, which is the base of the sigmoid function's exponent.



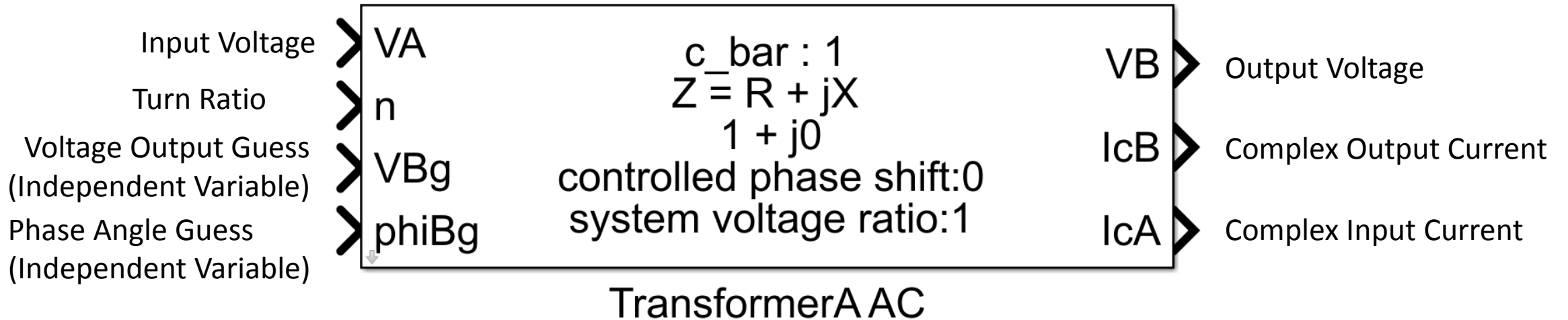
Capacitor – Power Flow

This block represents a capacitor, with a specified capacitance (C_M , in Farads), equivalent series resistance (ESR_M , in Ohms), and constant leakage current (I_{Leak_M} , in Amps).



AC Transformer – Power Flow

This block represents an AC Transformer, with a specified resistance (R_M , in Ohms), reactance (X_M , in Ohms), controlled phase shift (α_M), and system voltage ratio (b_M).





Introduction to Dynamic Propulsion System Modeling for Control Design, Analysis, and Simulation

Partial Turbo-Electric Propulsion System

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Acknowledgments

Donald Simon
Amy Chicatelli

NASA Glenn Research Center



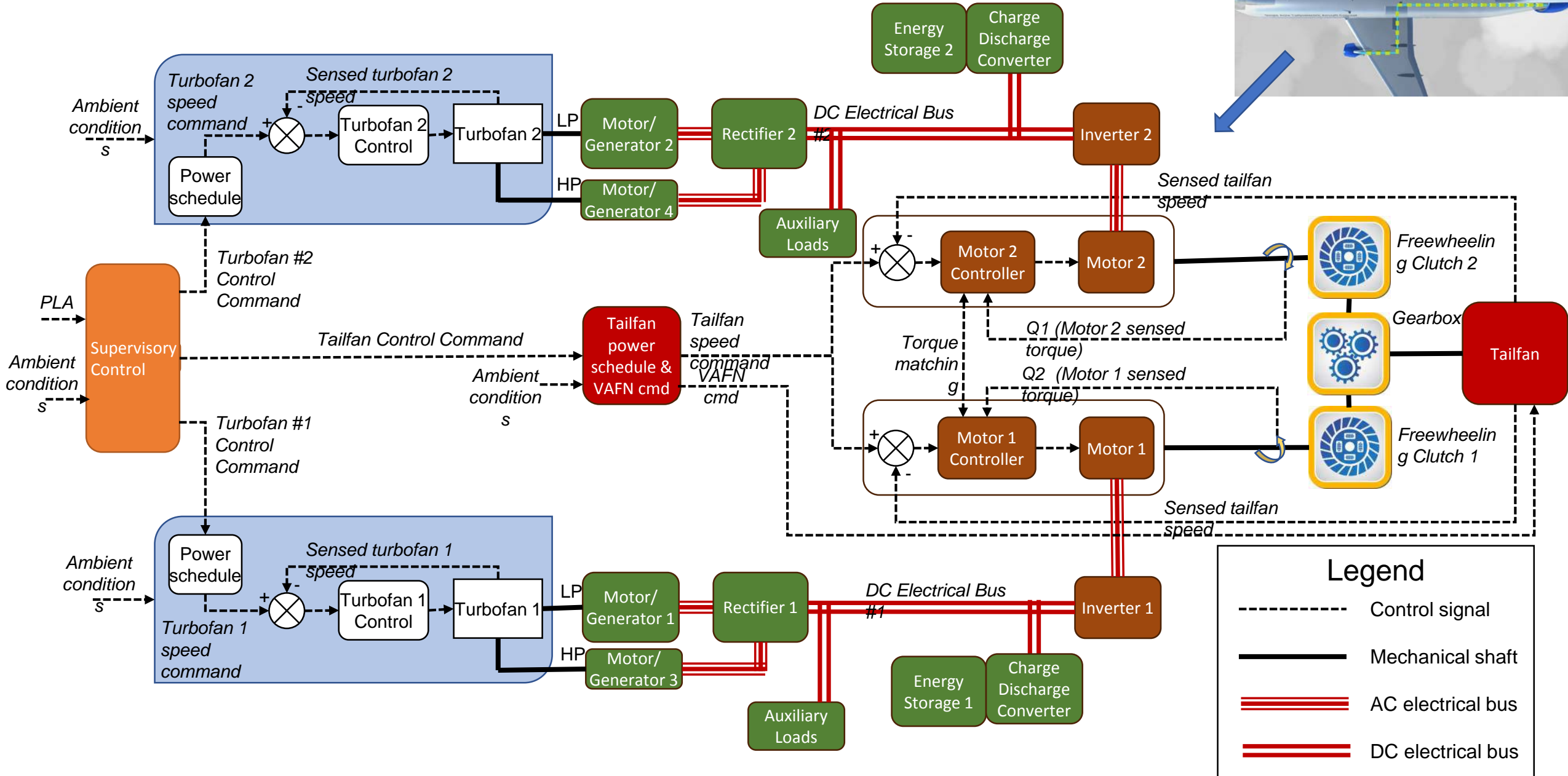
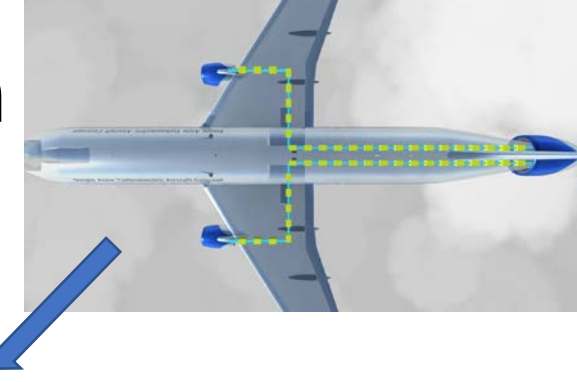
Introduction

- The dominant source of emissions in the aviation market today is from aircraft larger than the regional transport class
- Turbine engine must produce a local thrust in addition to supplying power to an electrical generator for distributed thrust using a tail fan.
 - Enables boundary layer ingestion benefits
- It is important to verify that the engine itself does not incur a significant efficiency penalty or performance degradation while maintaining lifecycle operability expectations



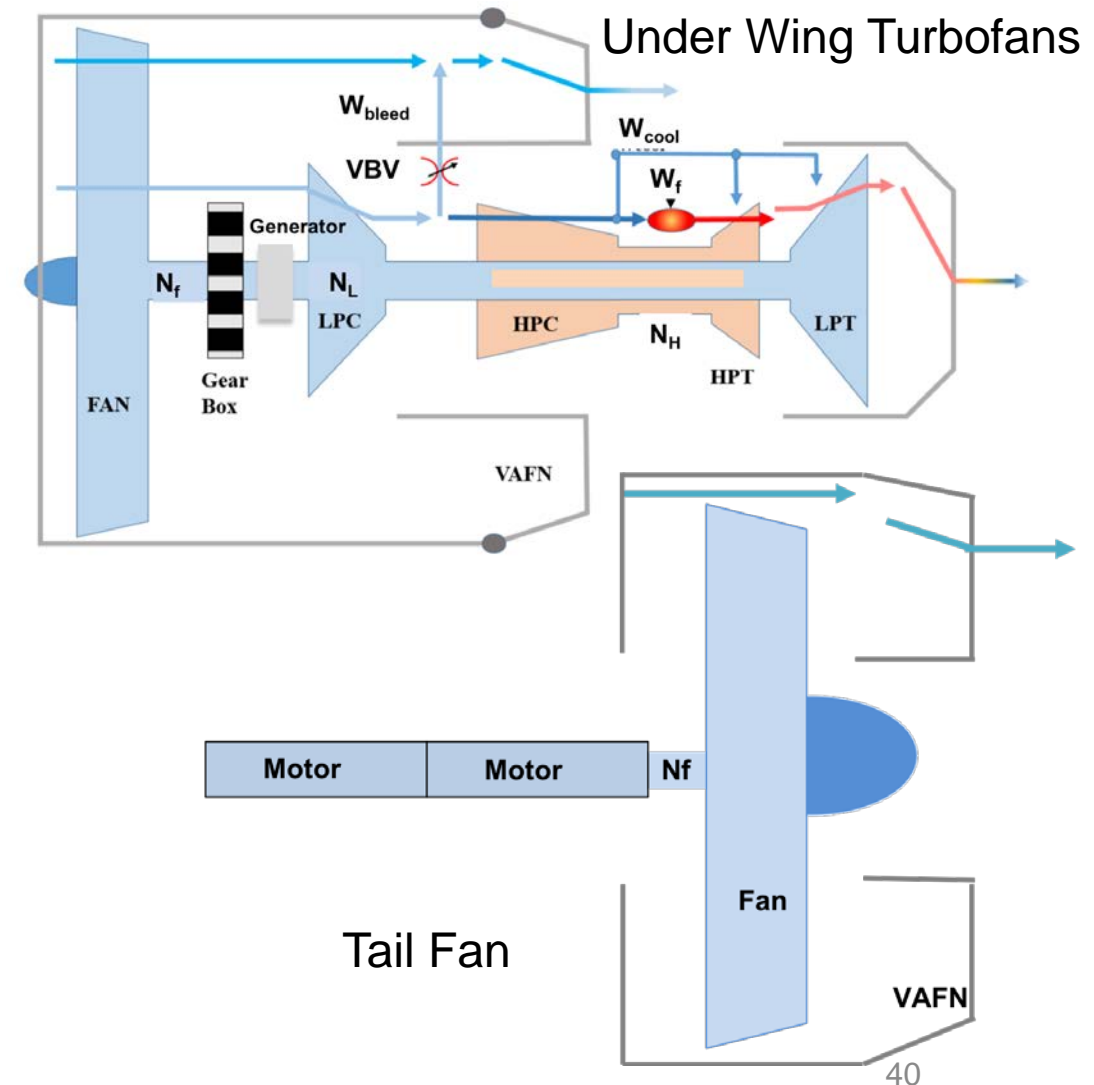
- NASA's initial concept vehicle the Single-aisle Turboelectric Aircraft - Aft Boundary Layer (STARC-ABL)
- The aircraft size accommodates 150 passengers
- Cruise: 0.78 Mach, Range: 3,500nmi

STARC-ABL Propulsion System Block Diagram



Propulsion System Modeling

- The under wing turbofans are geared with an open loop control schedule for the VBV and VAFN
- The tail fan boundary layer effect is modeled based on data obtained from CFD results
 - These are currently being updated
 - The tail fan also has a scheduled VAFN
- Two propulsion system models have been developed:
 - A steady state design model was first developed using the Numerical Propulsion System Simulation (NPSS).
 - A dynamic model was developed using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS).





Introduction to Dynamic Propulsion System Modeling for Control Design, Analysis, and Simulation

Thermal Systems Analysis Toolbox (TSAT) Overview

**Jonathan Kratz
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Outline

Summary

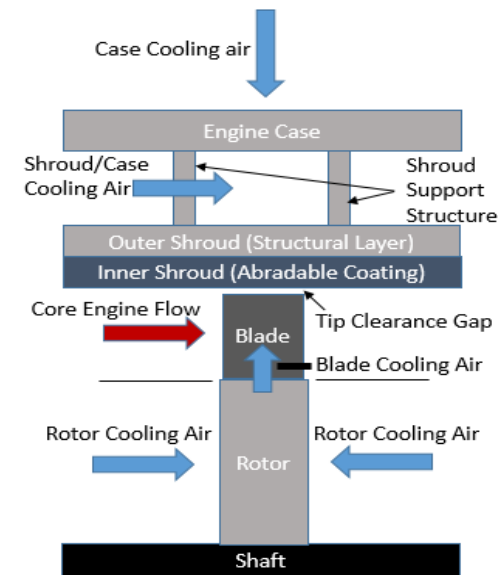
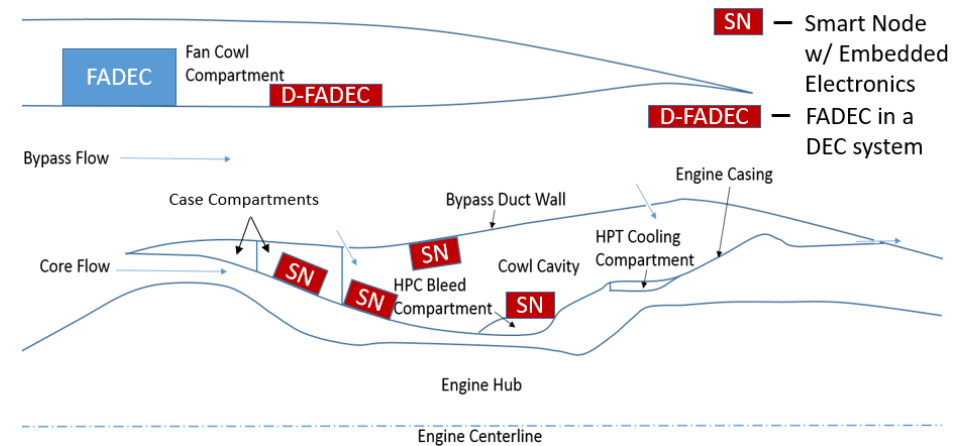
The Thermal Systems Analysis Toolbox (TSAT) is an open source software package developed at NASA. It is a MATLAB/Simulink based modeling tool that was developed for modeling and analysis of dynamic heat transfer. This presentation will provide an overview of the software and illustrate its usage through applications.

Organization

- Background/Motivation
- What is TSAT?
- Example Demos
- Other Example Applications
- Questions

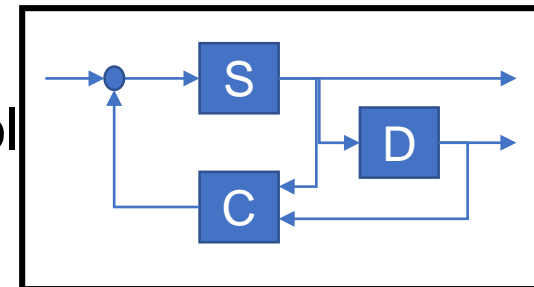
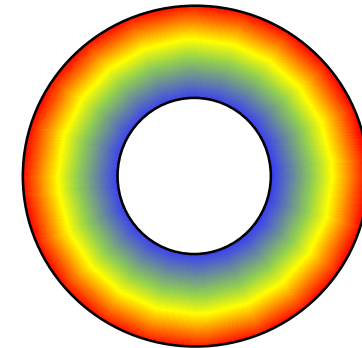
Background/Motivation

- TSAT was created as a bi-product of modeling and analysis efforts in the areas of:
 - Thermal environment characterization of a gas turbine engine for distributed engine control application
 - High pressure turbine tip clearance control
- Distributed Engine Control
 - Desire to mount control system components with embedded electronics on the engine core
 - There is a need to characterize the thermal environment to understand the implications it has on component and system design
- Turbine Tip Clearance
 - Tip clearance varies through the course of a flight, in part due to thermal loading that evokes expansion of the turbine components
 - Thermal modeling is needed to capture the physics of the tip clearance problem



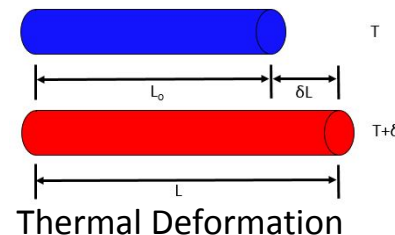
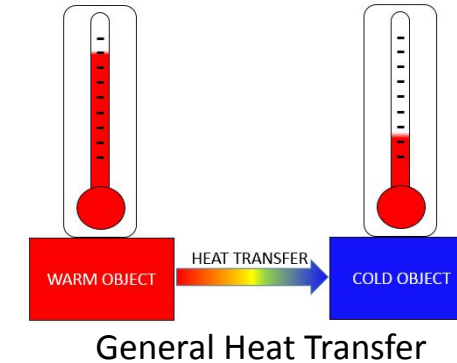
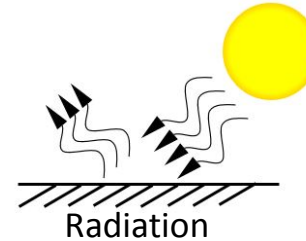
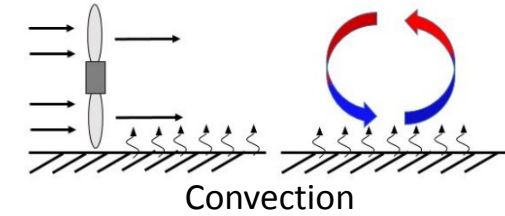
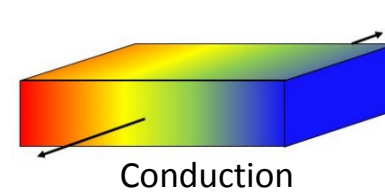
What is TSAT?

- An open source software package available on the NASA Github website:
<https://github.com/nasa/TSAT/releases>
- Coded and applied in the MATLAB/Simulink® environment
- Provides building blocks for constructing models of various systems that involve the transfer of heat
- Meant for modeling heat transfer, particularly those including 0-D, 1-D, and 2-D planar and cylindrical structures
- Suited for system level modeling
- Capable for use in dynamic analysis and control design
- Flexible and modular modeling tools



Scope of TSAT

- Simulink Library with blocks categorized into the following sub-libraries/ topics
 - Conduction
 - Convection
 - Radiation
 - General Heat Transfer
 - Thermal Deformation
 - Air Properties
 - General Tools (utilities)
- MATLAB functions to facilitate model creation



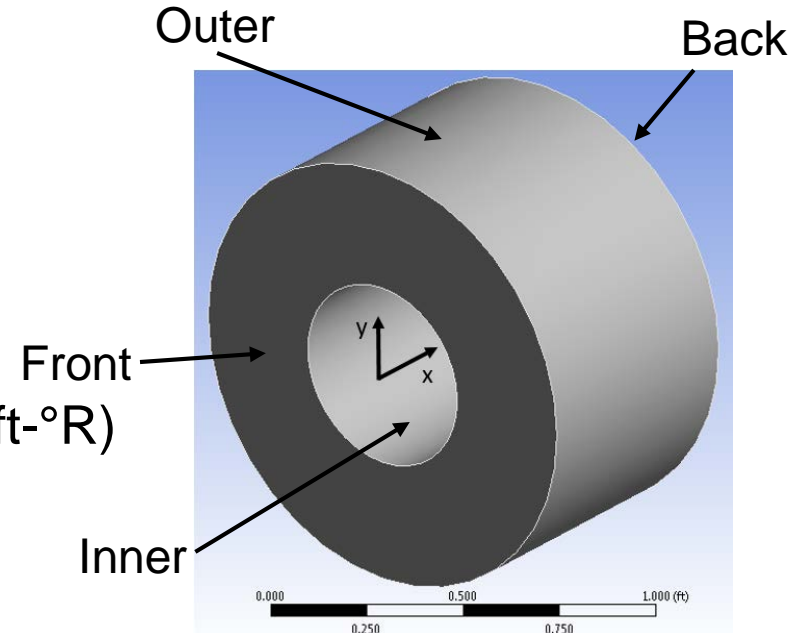
Application: Cylinder with Convection

Cylindrical shell parameters

- Inner radius = 3in
- Outer radius = 7in
- Length = 8in
- Uniform initial temperature of 550 °R
- Thermal conductivity of 0.0328 Btu/(sec-ft-°R)
- Heat capacity of 6.92 Btu/(slug-°R)
- Density of 5.24 slug/ft³.

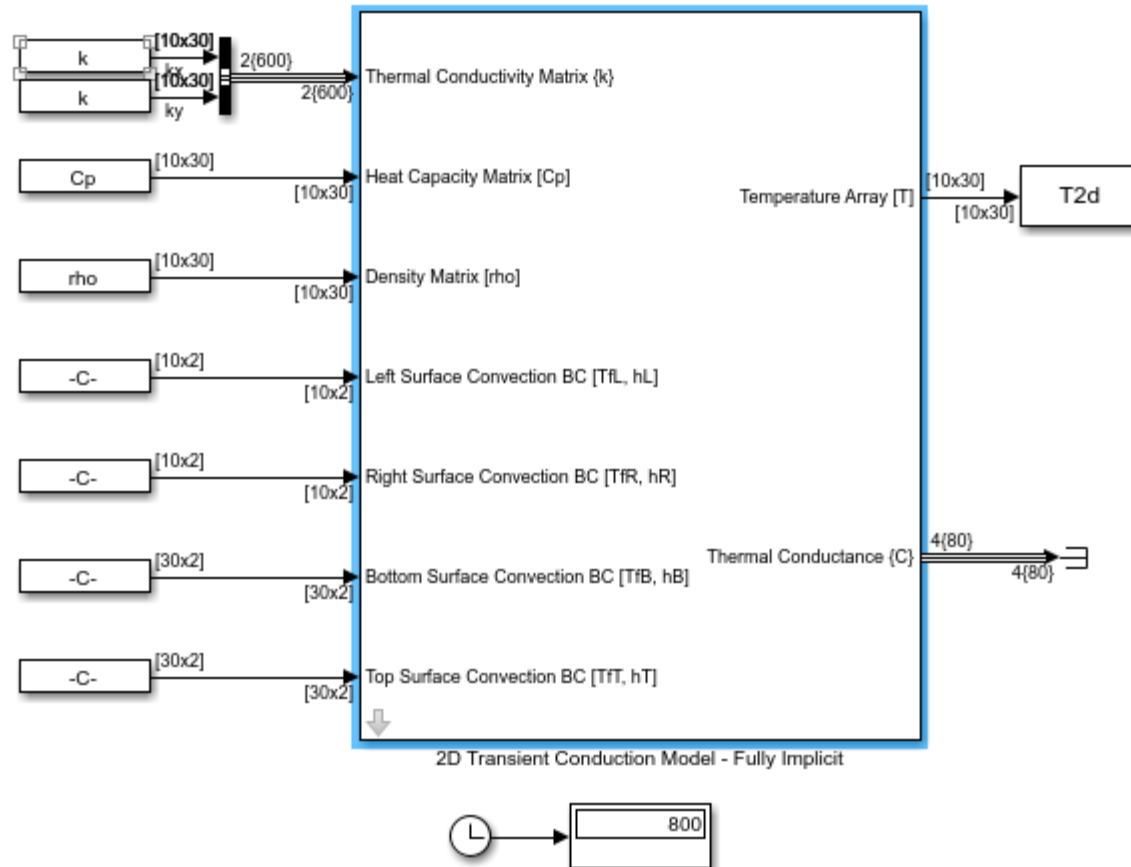
Boundary Conditions

- Convective load on all surfaces with convective heat transfer coefficient of 0.03 Btu/(sec-ft²-°R)
- Fluid in contact with the front and inner surface is 850 °R and the fluid in contact with the back and outer surface is 550 °R.





Application: Cylinder with Convection



Parameters

General Parameters

T0_M - Initial temperature array [mx1]
T0

dt_M - Time step [1x1]
dt

Geometry

x_M - Discretized spatial domain in x-direction (node locations) [nx1]
x

y_M - Discretized spatial domain in r- or y-direction (node locations) [myn]
y

shape_M - Shape in r- or y-direction

Planar in both directions
 Planar in x-direction, Axi-symmetric in y-direction
 Axi-Symmetric in x-direction, Planar in y-direction

Active Left Boundary Conditions

convL_M - Convection
 radL_M - Radiation
 condL_M - Conduction

Active Right Boundary Conditions

convR_M - Convection
 radR_M - Radiation
 condR_M - Conduction

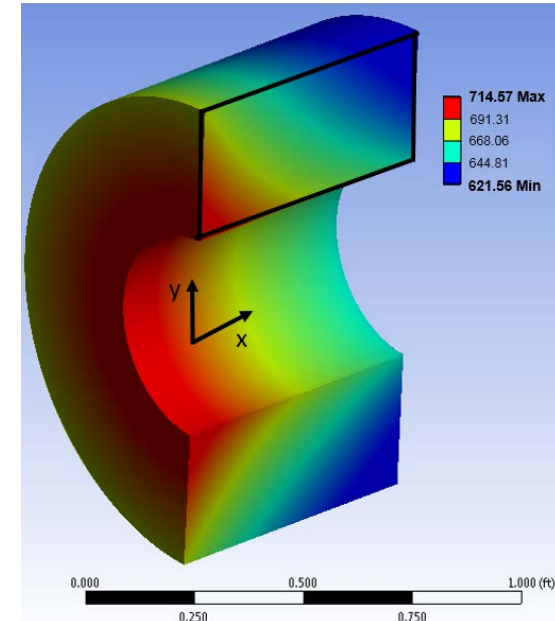
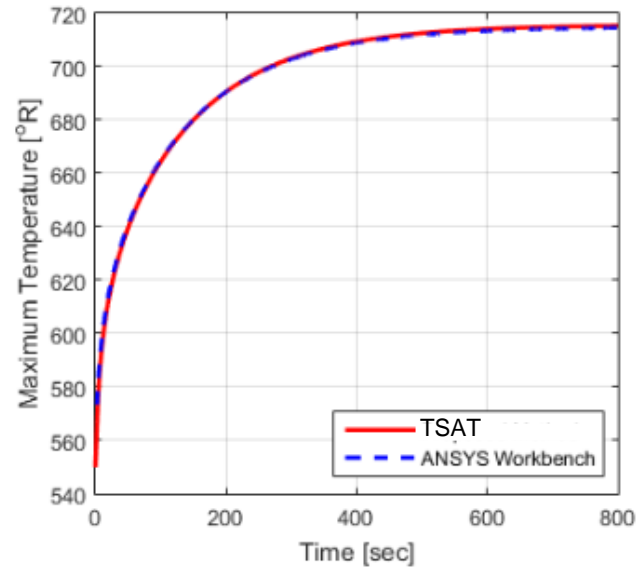
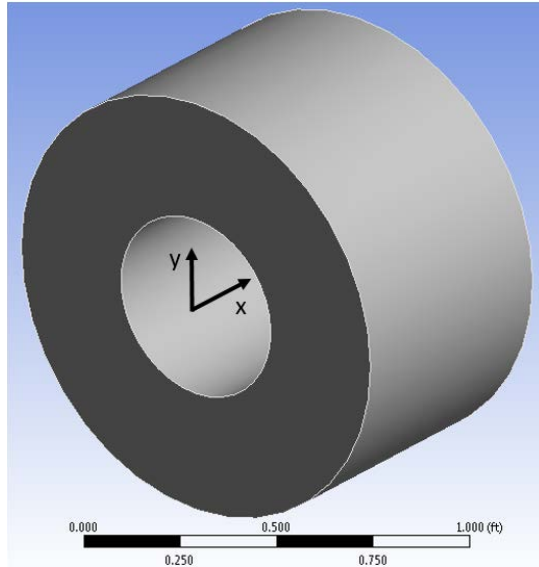
Active Bottom Boundary Conditions

convB_M - Convection
 radB_M - Radiation
 condB_M - Conduction

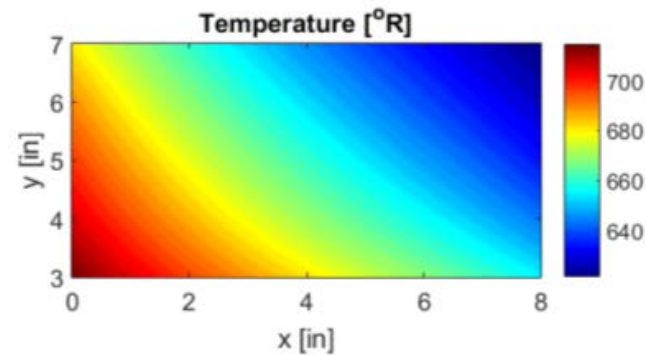
Active Top Boundary Conditions

convT_M - Convection
 radT_M - Radiation
 condT_M - Conduction

Application: Cylinder with Convection



TSA
T

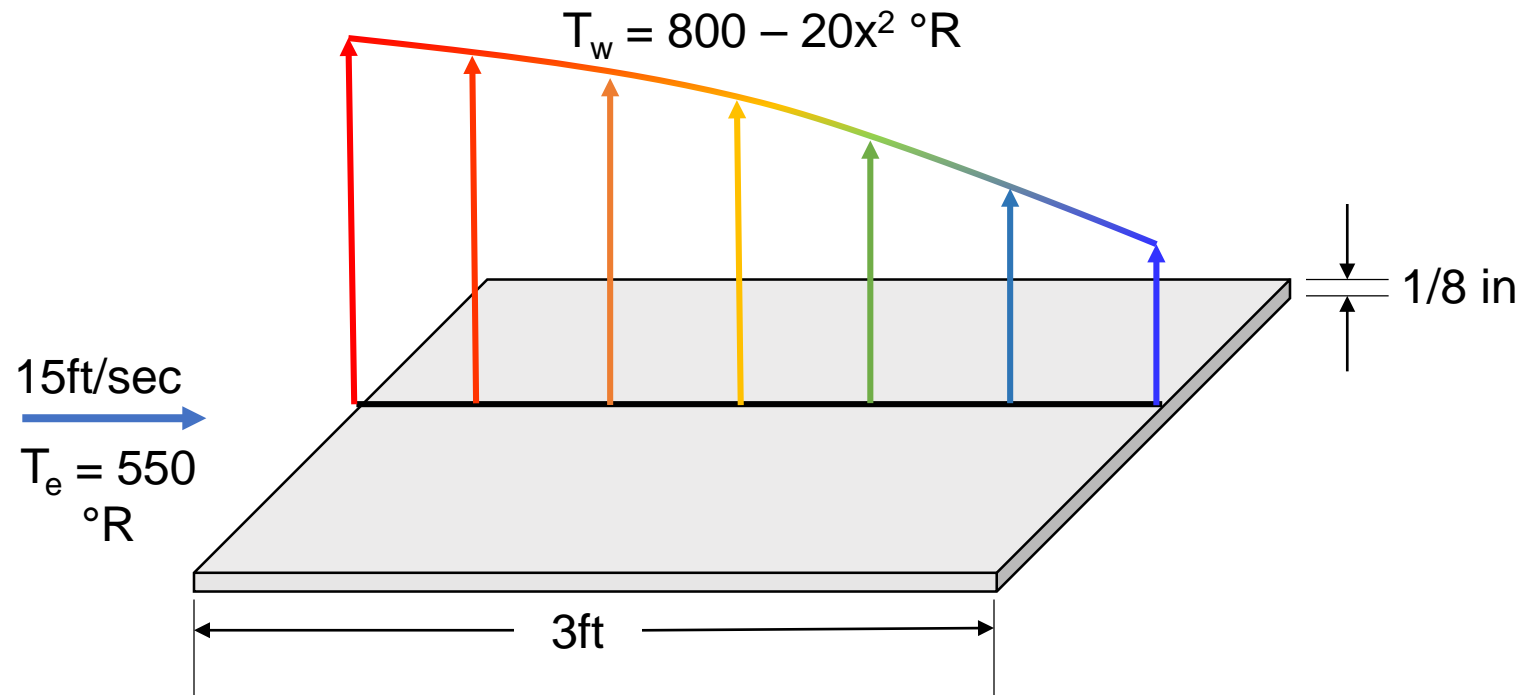


ANSYS
Workbench



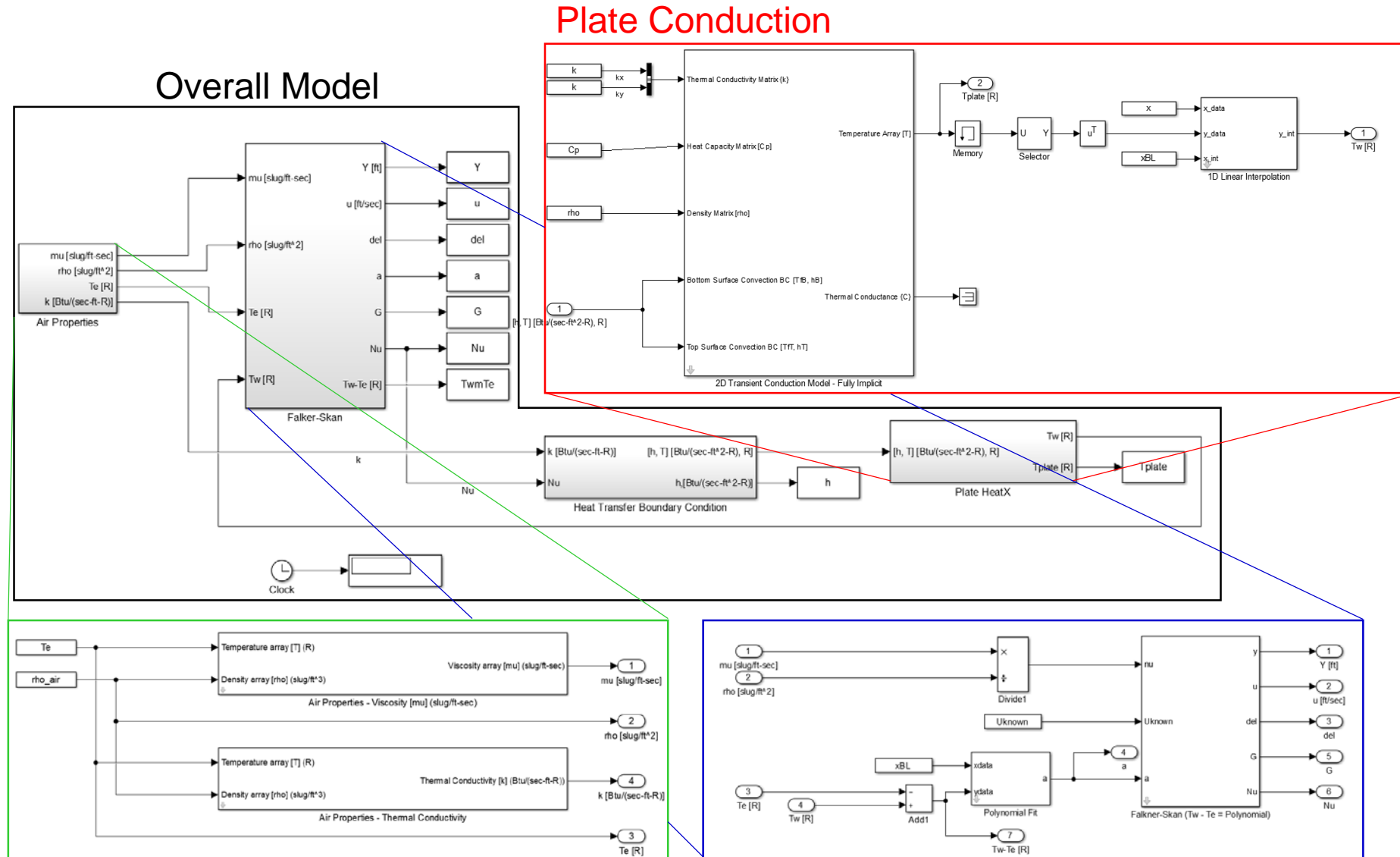
Application: Laminar Flow Flat Plate HeatX

- Flat plate
- Air is flowing over both sides at a slow rate
- The free stream air is at a constant temperature
- The surface of the plate is initially at an elevated temperature and varies along its length
- The plate has a thermal conductivity of 0.0328 Btu/(sec-ft-°R), heat capacity of 6.92 Btu/(slug-°R), and density of 5.24 slug/ft³.



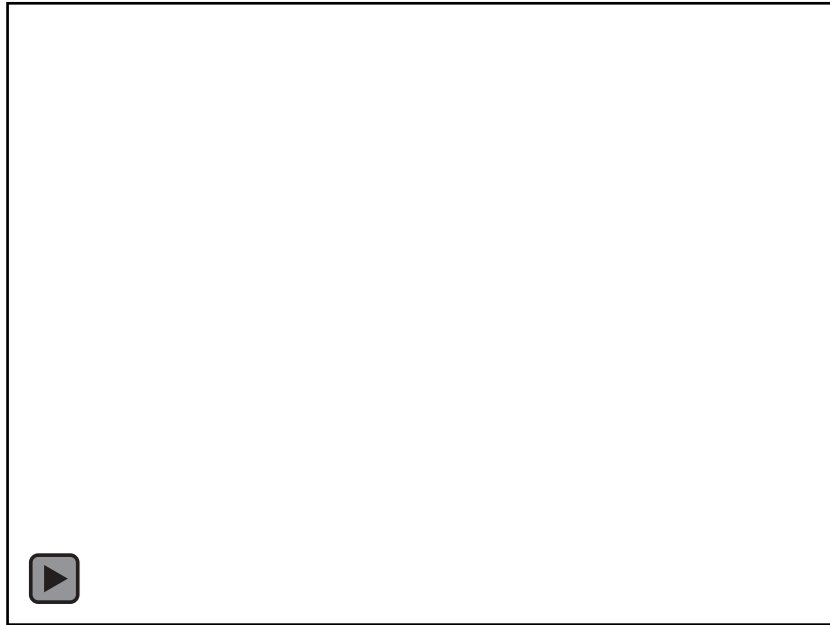


Application: Laminar Flow Flat Plate HeatX





Application: Laminar Flow Flat Plate HeatX



Captures dynamic and spatial variation of the air properties, heat transfer coefficient, and temperatures



On-the-fly polynomial fitting of the temperature differential is used in prediction of the Nusselt number via the Falkner-Skan block for computing the laminar boundary layer parameters

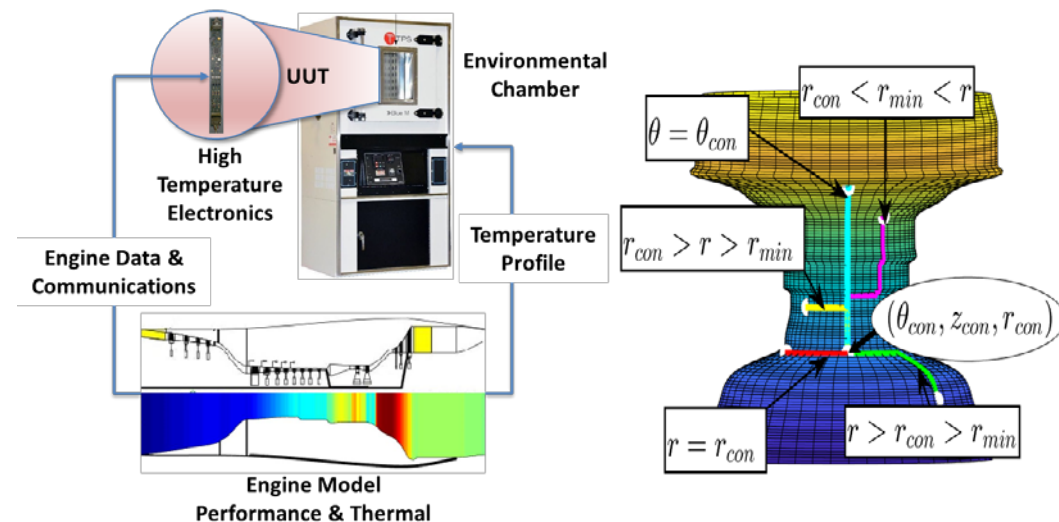
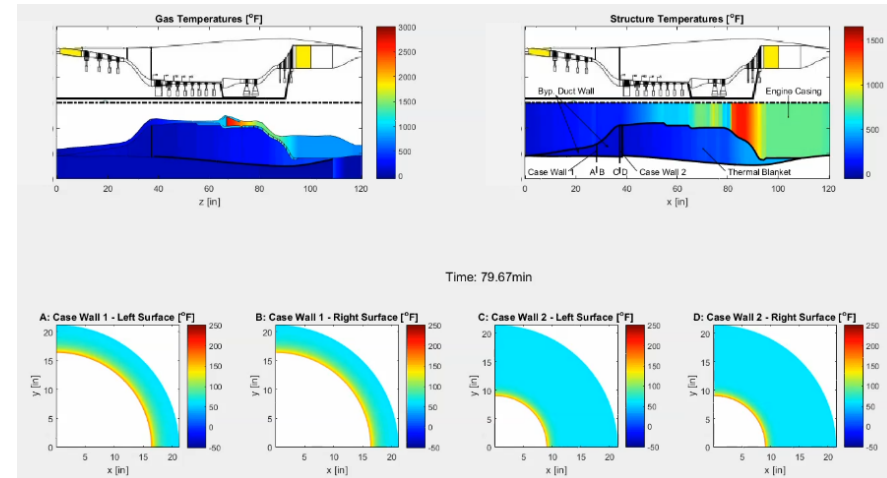
Other applications

Engine structure applications for distributed engine control

- Modern commercial turbofan using the Commercial Modular Aero-Propulsion System Simulation 40,000 lb model (C-MAPSS40k)
- Low Bypass Augmented Turbofan
- Advanced commercial turbofan using the Advanced Geared Turbofan 30,000 lb model (AGTF30)

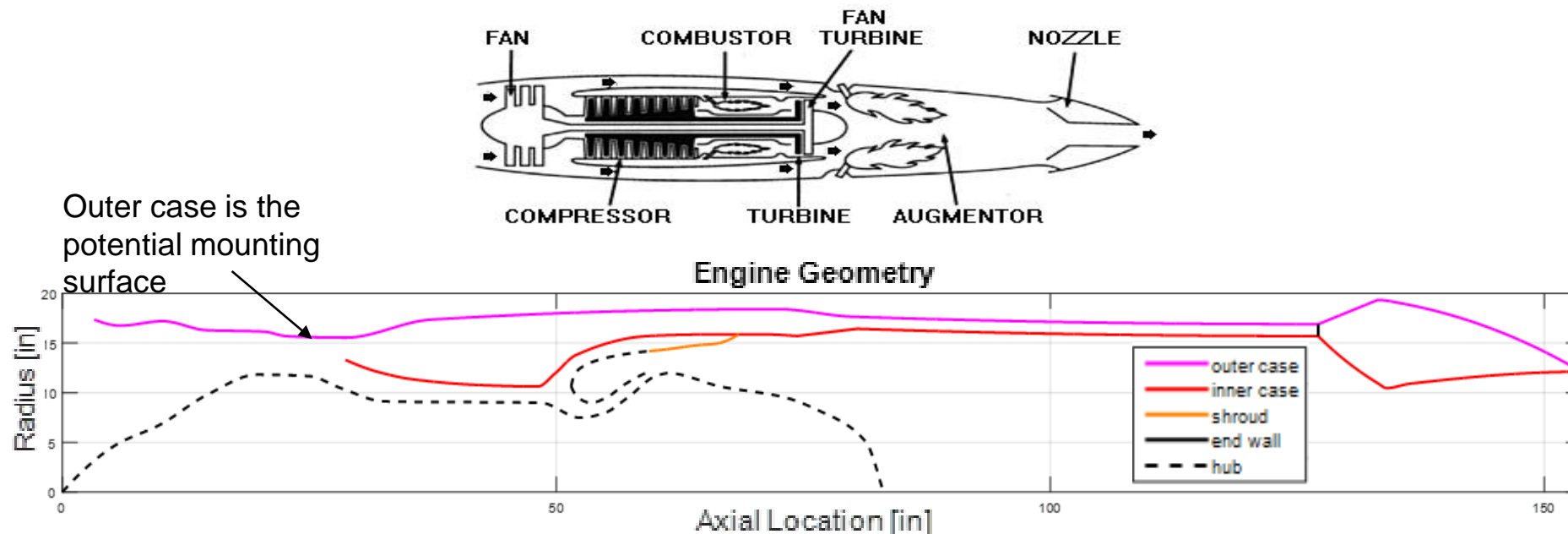
Turbine tip clearance applications

- Tip clearance modeling applied to C-MAPSS40k
- Tip clearance modeling applied to AGTF30



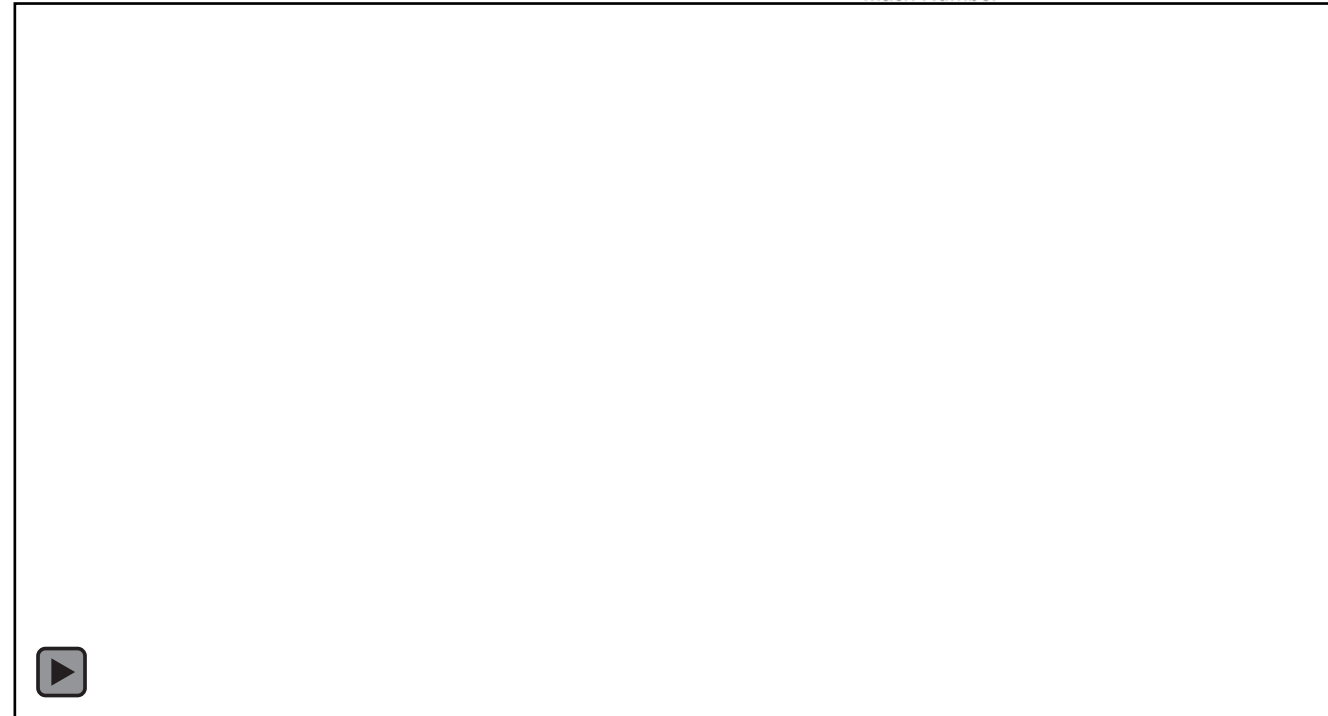
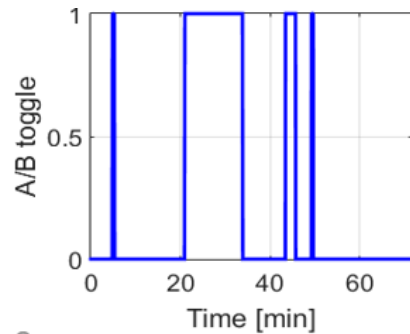
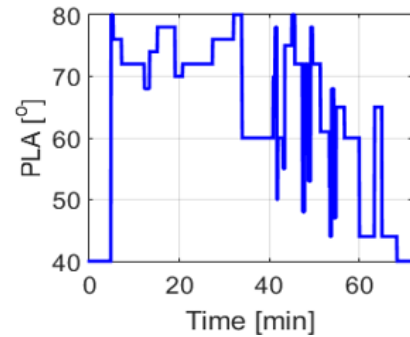
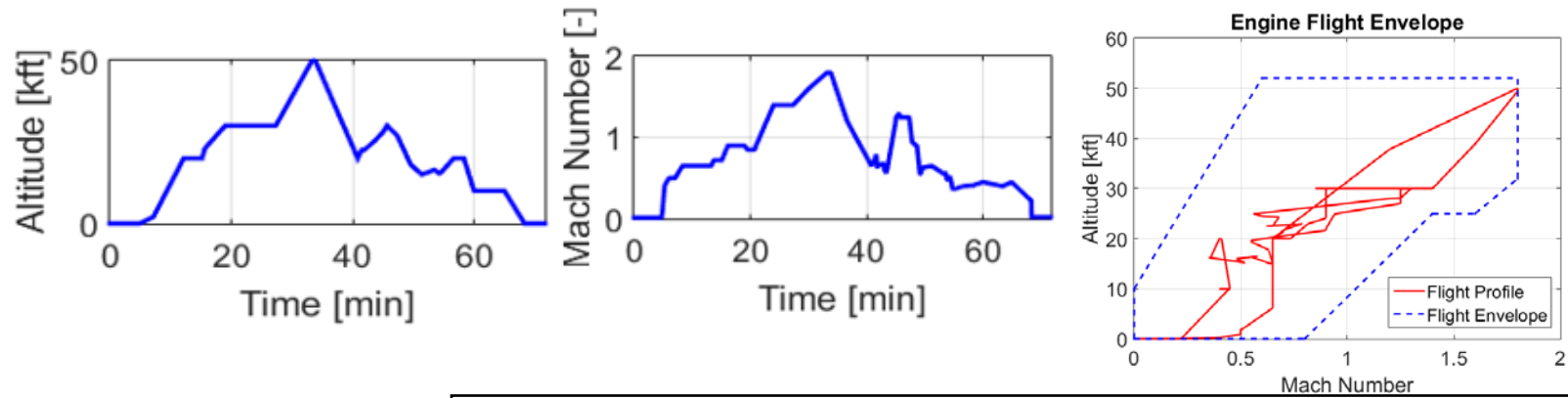
Application: Augmented Low Bypass Turbofan

- Developed a dynamic engine model and full envelop controller using the Toolbox for Modeling & Analysis of Thermodynamic Systems (T-MATS)
 - Model was based on NPSS outputs
 - Similar to a 4th – 5th generation military engine
 - Afterburner augmentation
- Developed thermal model of the engine structure using TSAT (2-D conduction, convective and radiative boundary conditions) and integrated it with the engine simulation



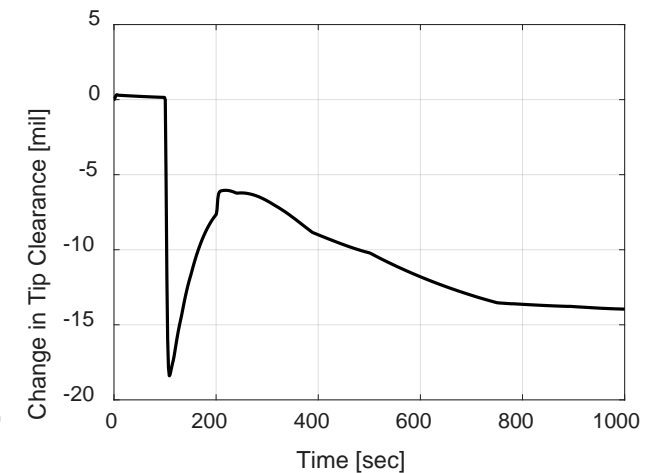
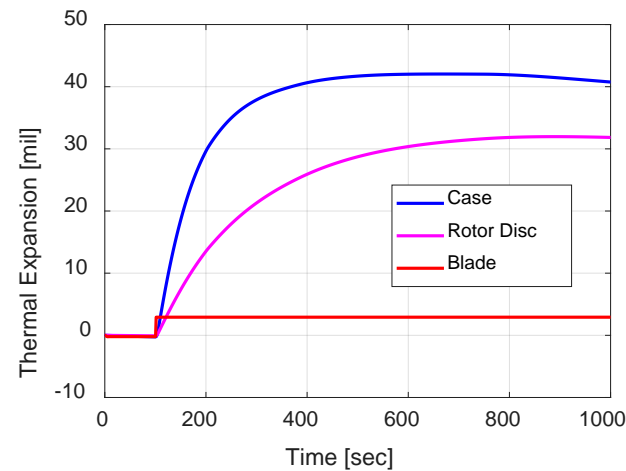
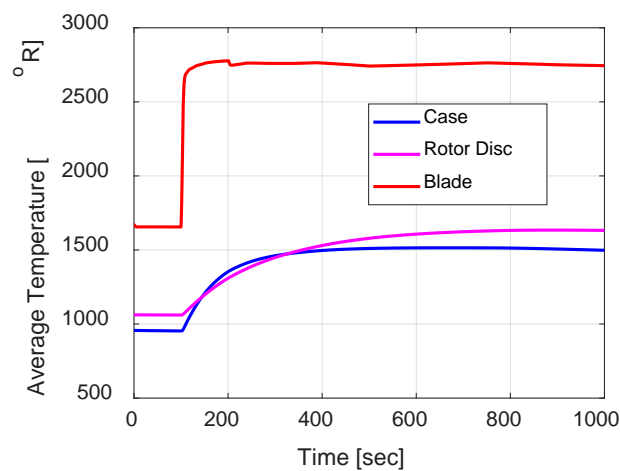
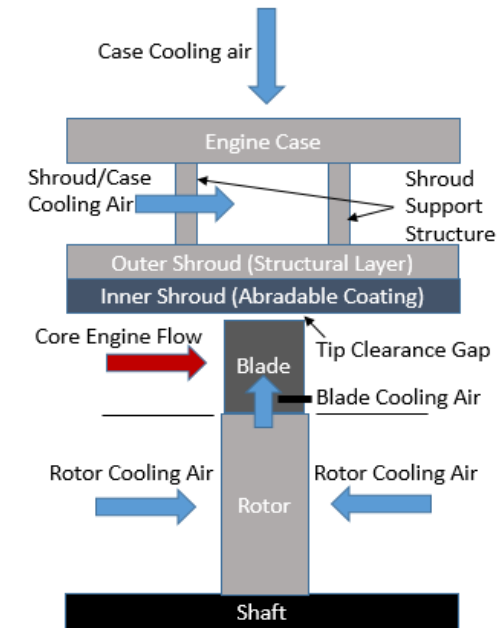


Application: Augmented Low Bypass Turbofan



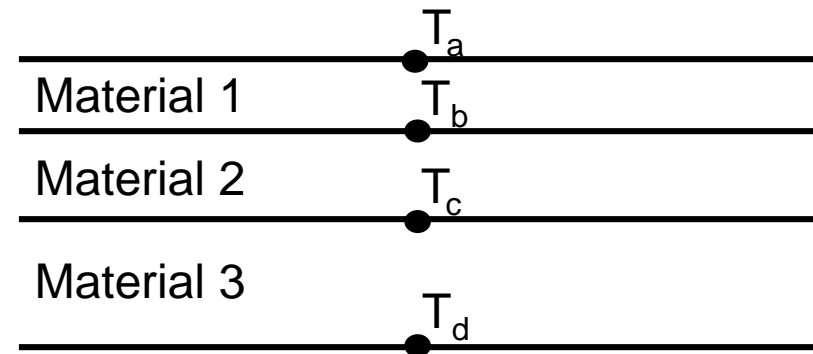
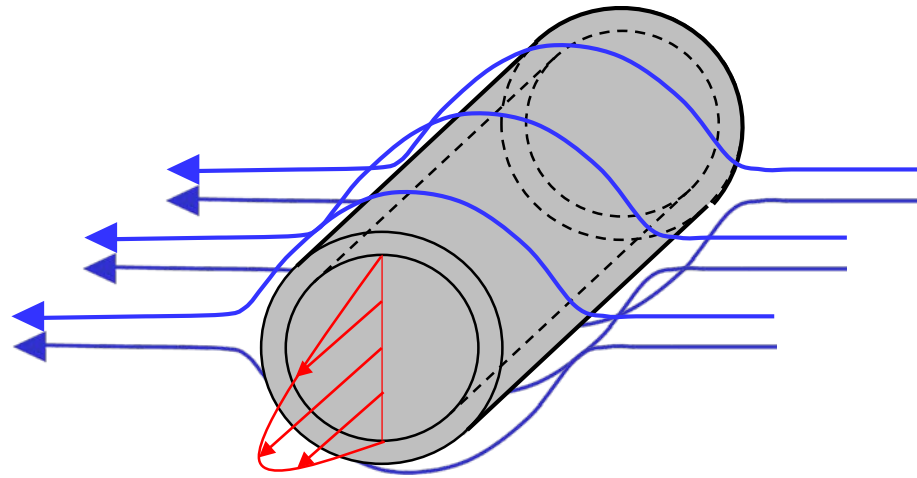
Application: Turbine Tip Clearance

- Application: high pressure turbine of the AGTF30 engine
- Need to know the temperature of the components
- Approximate the thermal expansion of the components
- Used TSAT to ...
 - model the blade as a lumped mass
 - model the engine case & rotor disc with 1-D conduction models
 - approximate the heat transfer coefficients
 - determine the average temperatures of the components
 - approximate the thermal expansion of each component using a linear elastic 1-D model



Applications: Other Applications

- Pipes and hoses
- Tube Banks
- Coils
- Plates & Bars
- Multi-layer structures (electronics junction temperature)
- Structures with directional properties or variable spatial properties
- Use your imagination



Remember, this is open source software so feel free to make your own additions to enhance the software capabilities



Acknowledgments

- Funded by the Transformational Tools and Technology (TTT) project under the Aerospace Research Mission Directorate (ARMD)
- Special thanks to: Dennis Culley, George Thomas, and Jeffryes Chapman from NASA GRC
- NASA civil servants & contractors who contributed in some way to this effort: Sanjay Garg, Scott Jones, Jonathan Litt, Vikram Shyam, Paht Juangphanich, Ram Bhatt, Jerry Lang, James DiCarlo, Joe Grady, Dan Paxson, and Shane Sowers
- The Distributed Engine Control Working Group (DECWG®) for providing input and guidance related to this work



Questions?

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- Jonathan Kratz – jonathan.kratz@nasa.gov

TSAT Link:

- <https://github.com/nasa/TSAT/releases>

Publications that employ TSAT or predecessor tools:

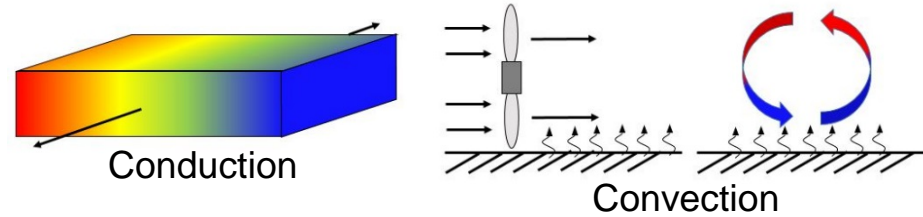
- Kratz, J., Culley, D., Thomas, G., “Thermal Modeling of an Advanced Geared Turbofan for Distributed Engine Control Application,” AIAA 2018-4659, *Proceedings of the 54th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Cincinnati, OH, 2018.
- Kratz, J., Chapman, J., “Active Turbine Tip Clearance Control Trade Space Analysis of an Advanced Geared Turbofan Engine,” AIAA 2018-4822, *Proceedings of the 54th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Cincinnati, OH, 2018.
- Kratz, J., Chapman, J., and Guo, T.H., “A Parametric Study of Actuator Requirements for Active Turbine Tip Clearance Control of a Modern High Bypass Turbofan Engine,” *Proceedings of the 2017 ASME Turbo Expo*, Charlotte, NC, 2017.
- Kratz, J., Culley, D., Chapman, J., “Approximation of Engine Casing Temperature Constraints of Casing Mounted Electronics,” AIAA 2016-4858, *Proceedings of the 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

Extra Slides





Scope of TSAT

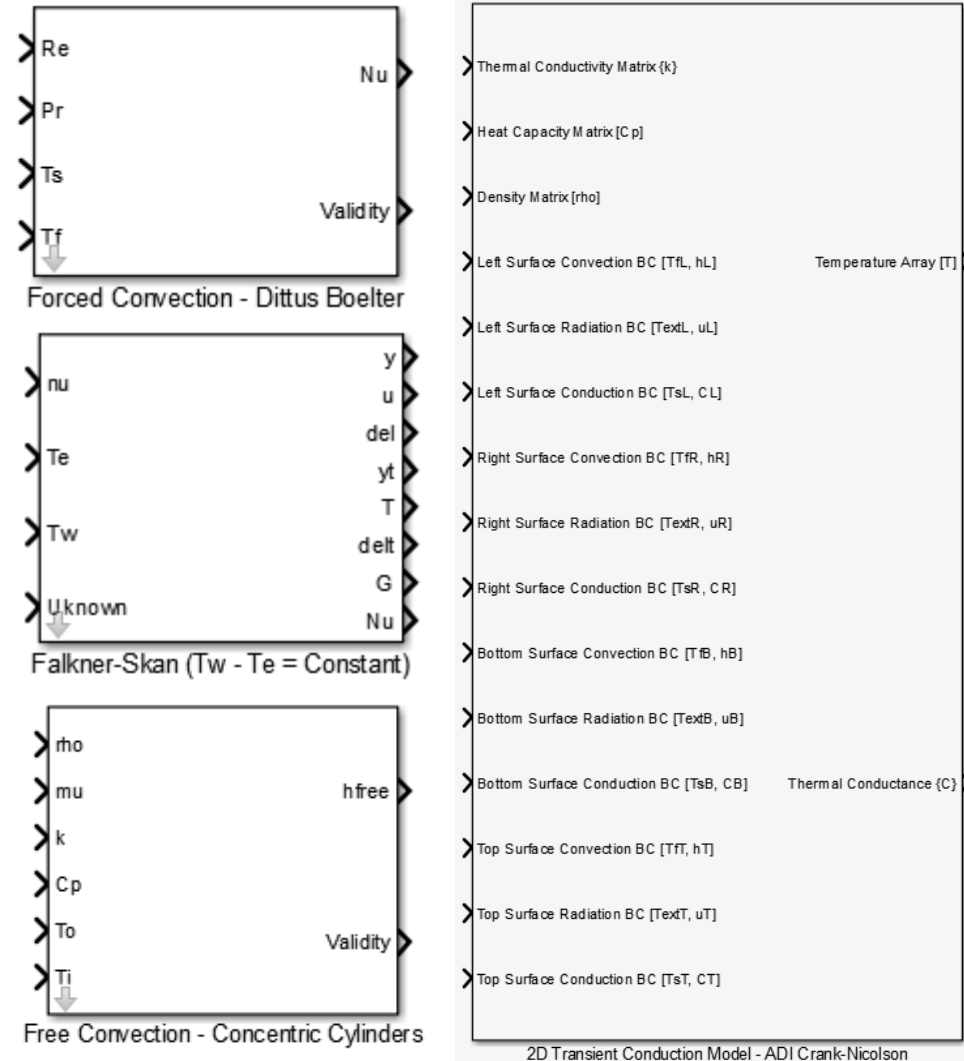


Conduction

- 1-D planar & axisymmetric heat conduction
- 2-D planar & axisymmetric heat conduction (ADI & implicit 2-D schemes)

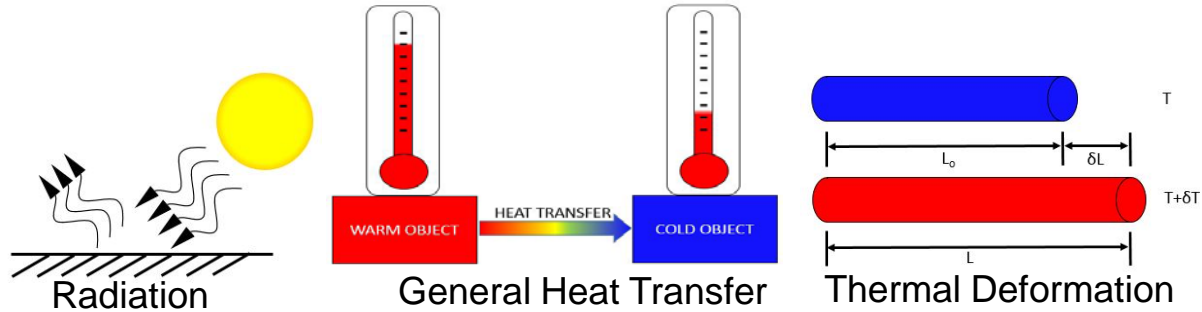
Convection

- Forced convection (internal & external flows + laminar & turbulent flows)
- Free (natural) convection
- Boundary layers
- Non-dimensional parameters (Re, Nu, Bi, Ra, etc.)
- Viscosity models





Scope of TSAT



Radiation

- Relations for ...
 - radiation to a black body
 - radiation between reflective parallel and concentric surfaces

General Heat Transfer

- Lumped capacitance thermal modeling

Thermal Deformation

- Linear elastic 1-D thermal expansion

> Surface Temperature [Tsurf] (R)
 > External Surface Temperature [Text] (R)
 > Surface Emissivity [eps_surf] (-)
 > External Surface Emissivity [eps_ext] (-)

Radiation HeatX Coefficient [u] (Btu/(sec-ft^2-R)) >

Radiation HeatX Coefficient - Reflective Planar Surfaces

> Heat capacity[Cp]
 > Temperature of fluid [T fluid]
 > Convective heat transfer coefficient [h]
 > Radiation heat transfer coefficient btwn fluid and surface [u]
 > Temperature of radiating surface [Trad]
 > Radiation heat transfer coefficient btwn surfaces [u]

Lumped mass temperature [Tmass] >

Lumped Mass Heat Transfer

> Previous/Reference Length [Lo]
 > Previous/Reference Temperature [To]
 > Current Temperature [Tf]

Current Length [L] >

Thermal Expansion 1D Elastic

Scope of TSAT



Air Properties



General Tools

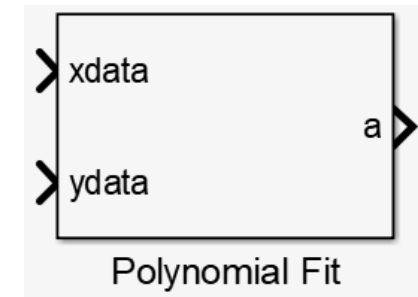
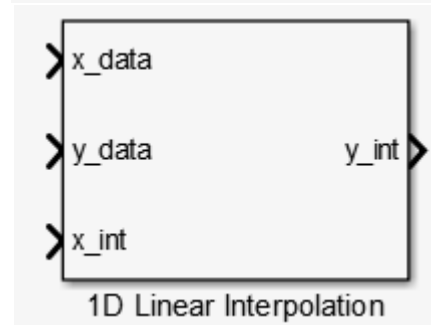


Air Properties

- Thermal properties (heat capacity, thermal conductivity, viscosity, constant volume specific heat)

General Tools

- Interpolation (1-D, 2-D, 3-D)
- Averaging
- Statistics
- Polynomial Fit

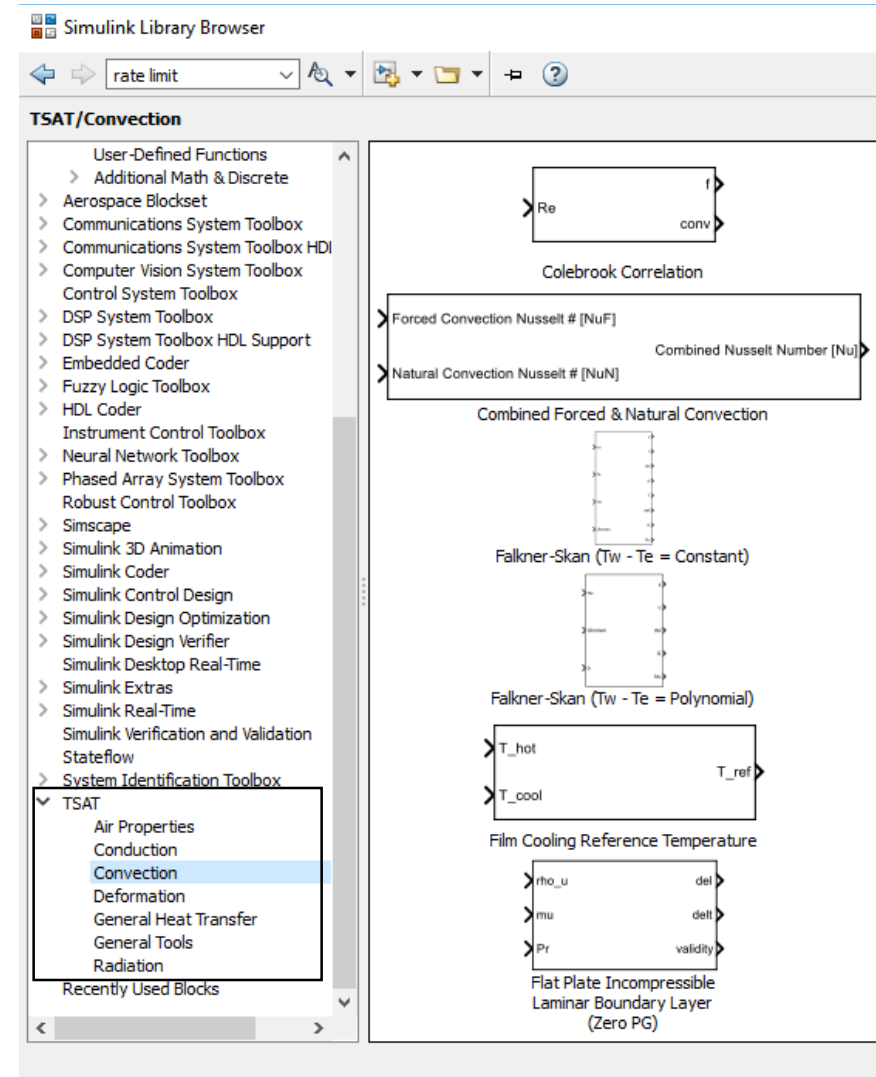
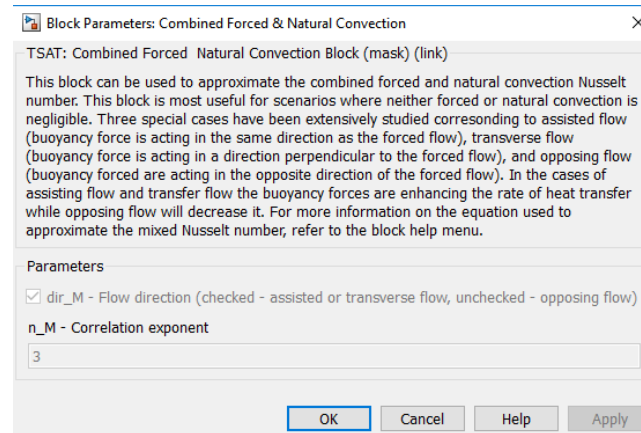




Scope of TSAT

Procedure for modeling (after TSAT has been installed)

- Open a new Simulink block diagram
- Navigate to the TSAT library within the Simulink library browser
- Drag and drop the blocks you desire into the new diagram (may be combined with other Simulink blocks)
- Appropriately connect the blocks
- Define block parameters through explicit definition in the block parameters dialog box or assigning variables and defining those variables in a pre-simulation script
- May be necessary to edit the simulation parameters (simulation step size & solver)
- Run the simulation and evaluate the results





Scope of TSAT

- Each block comes with a help file that
 - Describes the function of the block and provides equations where applicable
 - Provides sources where applicable
 - Defines inputs, outputs, and parameters
 - In some cases examples are provided as well as conditions for validity
- Each function has a description within it that defines its intended usage, inputs, and outputs
- Also provided:
 - A quick start guide
 - Several Examples

Snippets from the 1-D Conduction Block Help File

TSAT: 1-D Trans Conduction Model - Variable Props + Generic BCs Library Block

This function models the transient conduction of a 1-D structure which can either be of a planar or cylindrical geometry. This block solves the general 1-D heat equation shown below using a finite difference method.

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_p} \left[\left(\frac{\partial k}{\partial x} + \frac{ak}{x} \right) \frac{\partial T}{\partial x} + k \frac{\partial^2 T}{\partial x^2} \right]$$

It is able to handle variable thermal properties such as density, heat capacity, and thermal conductivity. It has the capability to address dynamic convection, conduction, and radiation boundary conditions. A generic non-uniform spatial discretization may be used with some restrictions but a constant time-step is encouraged for accuracy in time. Integration is done through the Crank-Nicolson Method and the system of discrete equations is solved with Thomas's Algorithm. The boundary nodes are assumed to be half the size of its interior neighbor in the formulation of boundary node equations. To assure this is the case, consider checking that the following conditions are met.

$$x(2) - x(1) = x(3) - x(2) \ \& \ x(n) - x(n-1) = x(n-1) - x(n-2)$$

1-D Trans Conduction Model - Variable Props + Generic BCs Inputs:

1-D Trans Conduction Model - variable Props + Generic BCs Inputs	Description
k	Thermal conductivity array for the structure (nx1)
Cp	Heat capacity array for the structure (nx1)
rho	Density array for the structure (nx1)
Tfin	Temperature of the fluid on the inner surface (convection boundary condition)
hfin	Convective heat transfer coefficient of the fluid on the inner surface (convection boundary condition)
Tsin	Temperature at the surface or interface of with a contacting solid on the inner side (conduction boundary condition)
Textin	Temperature of the external source/sink radiating heat to from the inner surface (radiation boundary condition)
uin	Radiative heat transfer coefficient between the external source/sink and the inner surface (radiation boundary condition)
Tfout	Temperature of the fluid on the outer surface (convection boundary condition)
hout	Convective heat transfer coefficient of the fluid on the outer surface (convection boundary condition)
Tsout	Temperature at the surface or interface of with a contacting solid on the outer side (conduction boundary condition)
Textout	Temperature of the external source/sink radiating heat to from the outer surface (radiation boundary condition)
uout	Radiative heat transfer coefficient between the external source/sink and the outer surface (radiation boundary condition)

1-D Trans Conduction Model - Variable Props + Generic BCs Outputs:

1-D Trans Conduction Model - Variable Props + Generic BCs Outputs	Description
T	The current temperature of each node in the structure (nx1)

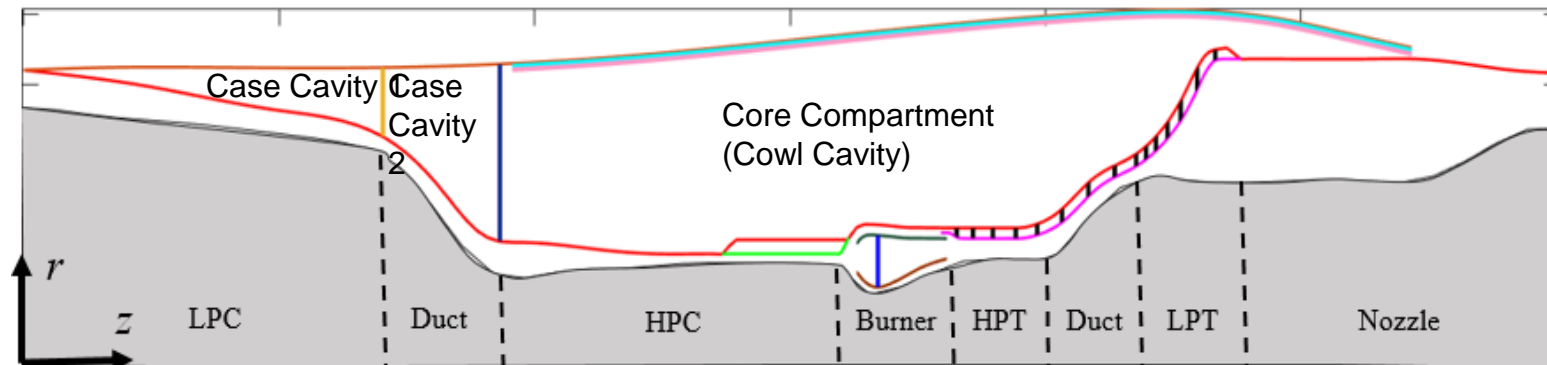
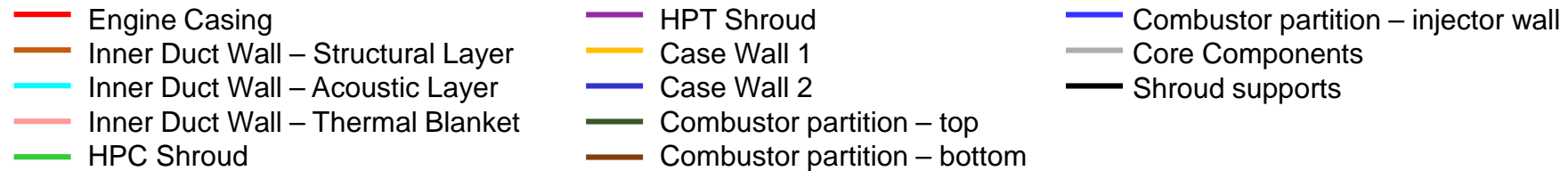
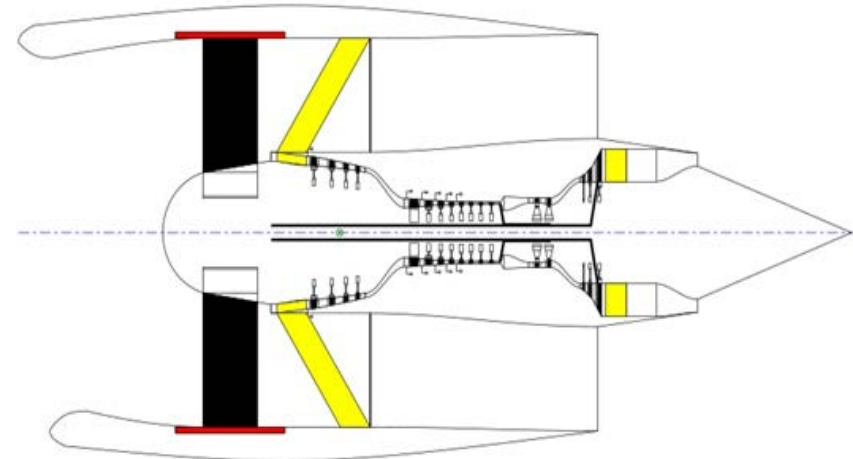
1-D Trans Conduction Model - Variable Props + Generic BCs Mask Variables:

1-D Trans Conduction Model - Variable Props + Generic BCs Mask Variables	Description
x_M	Spatial discretization (node locations) (nx1)
T0_M	Initial temperature of the structure at each node (nx1)
dt_M	Time Step
a_M	Shape (unchecked - planar (a_M=0), checked - cylindrical (a_M=1))
convin_M	Checked if there is a convection boundary condition on the inner surface
radin_M	Checked if there is a radiation boundary condition on the inner surface
condin_M	Checked if there is a conduction boundary condition on the inner surface
convout_M	Checked if there is a convection boundary condition on the outer surface
radout_M	Checked if there is a radiation boundary condition on the outer surface
condout_M	Checked if there is a conduction boundary condition on the outer surface

Application: NASA N+3 Geared Turbofan

Advanced Geared Turbofan 30,000lb_f (AGTF30)

- Based on the NASA N+3 NPSS reference engine
- NASA N+3 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



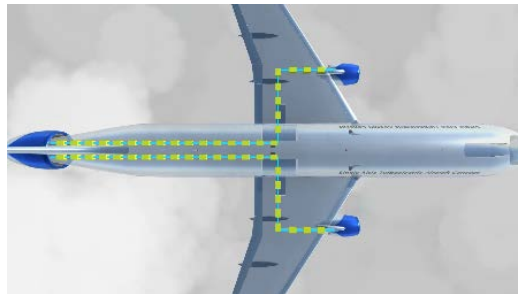
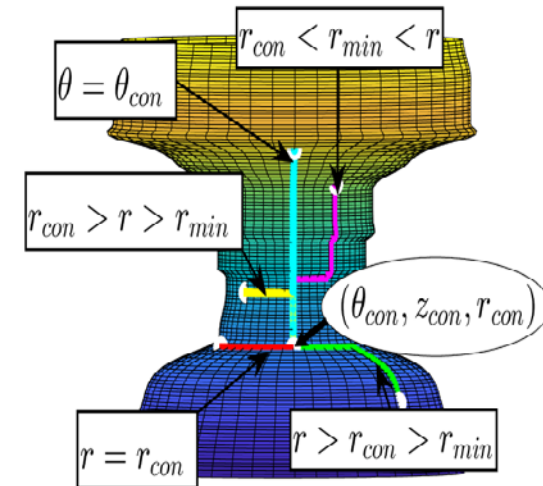
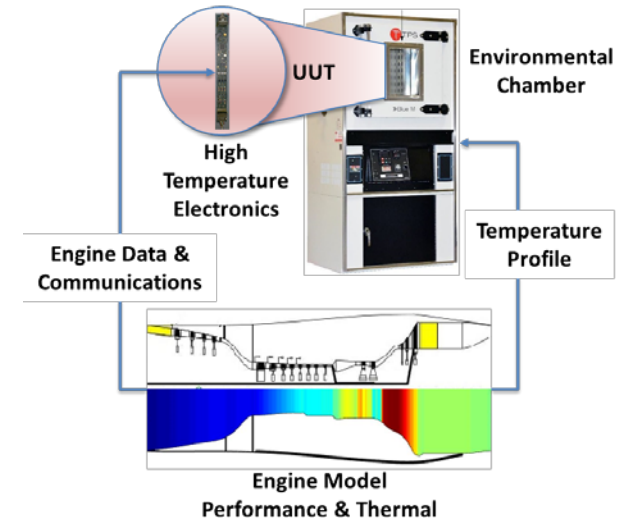


Application: NASA N+3 Geared Turbofan



Potential Work & Vision for Future Uses

- Using thermal gas turbine engine models to ...
 - drive test hardware to create the testing environment for embedded hardware
 - develop requirements/constraints on the control system
 - Investigate and quantify appropriateness and benefits of different control system architectures
- Using tip clearance models to ...
 - More thoroughly investigate the impact of material properties and other turbine design parameters
- Expanding TSAT to include tools more readily applied for modeling and evaluation of thermal cycles (heat engines, refrigerators, various heat exchangers, etc.)
- Applying, adapting, and expanding the TSAT tools to
 - model the thermal aspects of hybrid electric propulsion systems
 - investigate the challenges and benefits of integrated thermal, propulsion, power, and control



Extra: GTE Thermal Modeling Approach

