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A Process for the Creation of T-MATS Propulsion System Models from NPSS Data

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Acknowledgments

Outline

- Background

- Process

- Example

- Conclusion

- References and Download information

Background, T-MATS

- **Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS**
  - Modular thermodynamic modeling framework
  - High fidelity dynamic gas turbine modeling capability based around component maps
  - Built in MATLAB/Simulink utilizing S-functions written in C
  - Open source and completely modifiable

- **Case study: Selecting T-MATS for generation of a dynamic model from an NPSS performance model.**

NPSS
Steady State
Performance
Model

Maps
Architecture
Data

T-MATS
Dynamic Model
(Simulink)
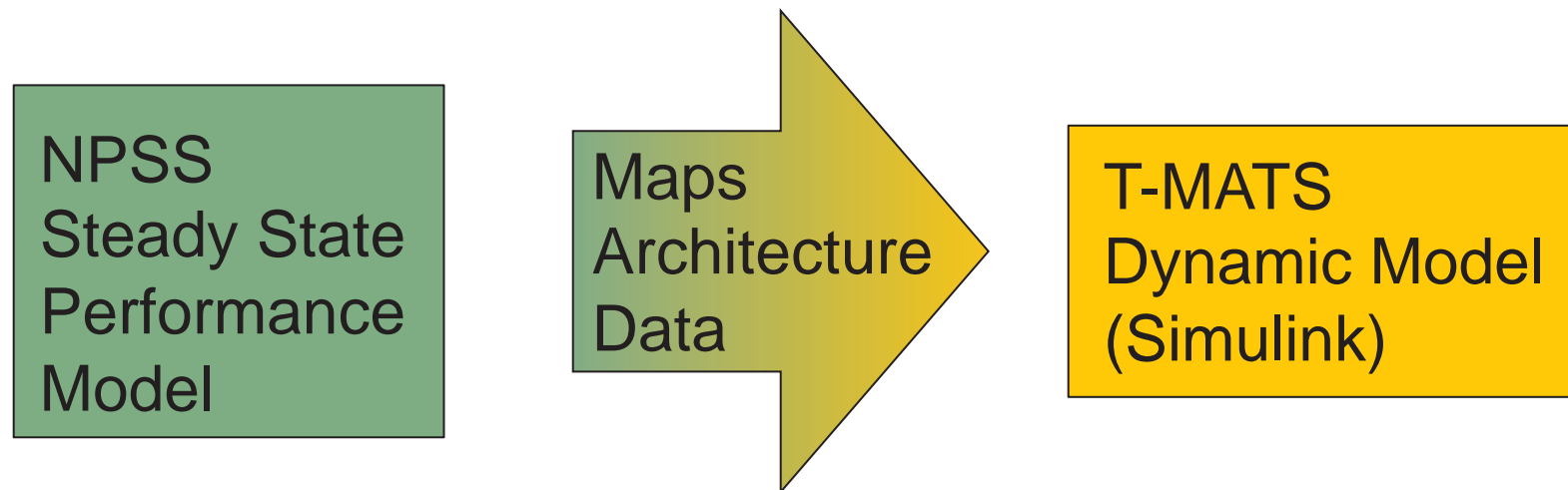
Background, Modeling example

- When developing a new engine, control design is typically performed after engine cycle design and performance analysis, and requires a dynamic engine model.

- Example situation:
  - Numerical Propulsion System Simulation (NPSS) used for cycle design and performance analysis
  - MATLAB®/Simulink® used for gas turbine control system development

- How are plant models for gas turbine control system development obtained?
  - Develop a new model from engine performance specifications.
  - Leverage pre-existing plant model directly by integrating it with the control system development tool (e.g., wrap NPSS into a Simulink S-function).
  - Develop a new model based on the pre-existing model.

Model creation

- **Process Overview**

    1. Gathering inputs and making modifications, verify the models have the same modeling strategy and inputs

        a) Convert maps and constants from NPSS into a usable format for T-MATS

        b) Modify T-MATS components to be compatible with the new maps and constants

    2. Component level testing, verify component models are operating similarly

    3. System level testing without a solver, verify simulation connections

    4. Steady state system level testing, verify the system converges to the correct operating points

    5. Converting the steady state simulation to a dynamic simulation

JT9D engine, model

- ## Engine Example:
  - Publicly available dual spool high-bypass turbofan engine model
    - Implemented in NPSS then converted to T-MATS
      - Plant components and architecture representative of both models and utilized in steps 1-3.
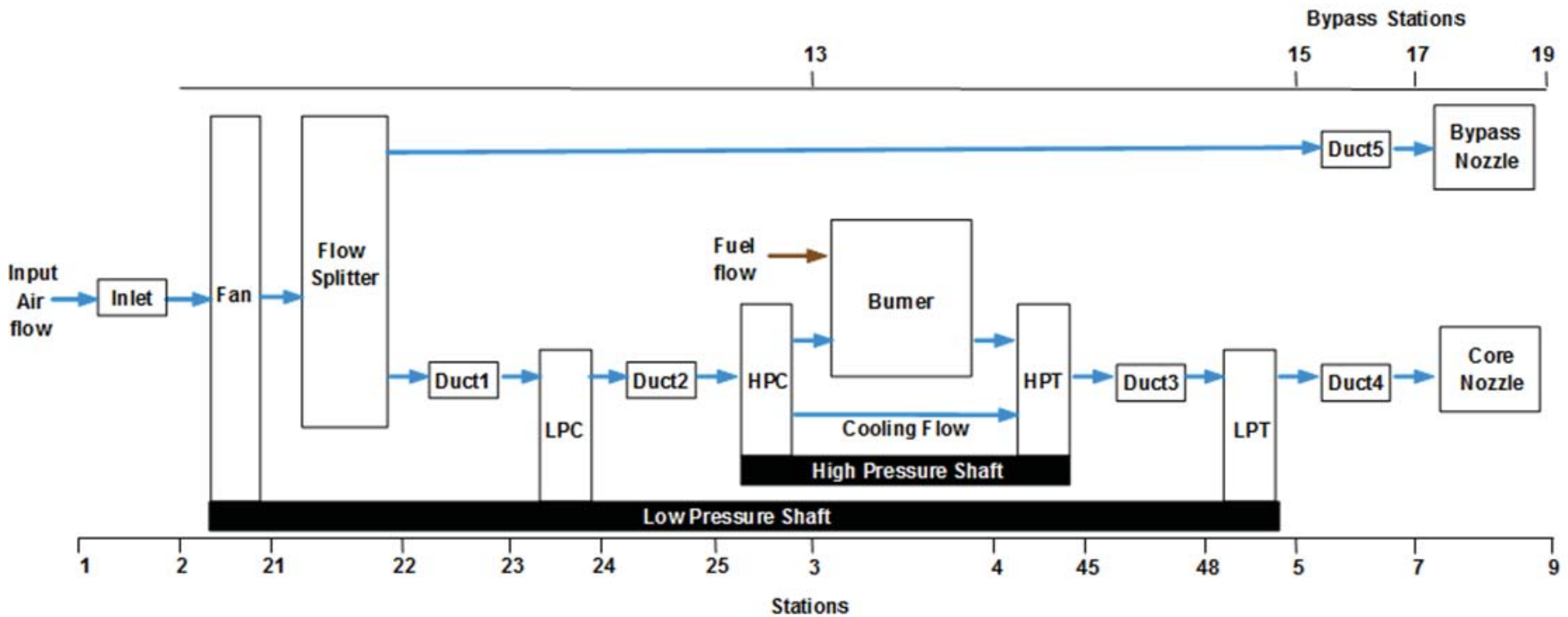
JT9D Engine: Model Matching Files

- **NPSS files required for model matching:**
  - Compressor and turbine map files (*.map)
  - NPSS output data file (*.viewOut) should contain
    - Operating point dependent variables
    - Thermodynamic properties (e.g. Pt, Tt, W, etc.) at each engine stage
    - Environmental variables as well as performance variables such as thrust
  - NPSS model definition (*.mdl)
    - Additional component variables not detailed in the data file, e.g. LHV
    - Static values consistent across the envelope

FAN.map   HPC.map   HPT.map   JT9D.mdl   JT9D.viewOut   LPC.map   LPT.map

JT9D Engine, Operating Points

- ## NPSS data utilized:

  - Two distinct operating points were run in NPSS to generate data for the model matching

    - Model inputs and modification requirements (step 1) were determined based on the takeoff operating point.

    - Component and system level testing (step 2 and 3) were completed using the takeoff operating point.

    - Steady state and dynamic model testing (step 4 and 5) was completed with both operating points. Additionally, an alternative method of automatically generating model matching scale factors (T-MATS iDesign tool) was implemented to demonstrate tool feasibility.

operating point	altitude, ft	Mach Number	Ambient Temperature, degR	fuel flow, pps
design point or cruise	34000.0	0.8	448.43	1.91
off-design point or takeoff	0.0	0.0	545.67	5.0

T-MATS Maps and Constants

- Baseline NPSS uses almost all maps and constants in the same way as T-MATS.

  - Turbine maps based on PR lookup
  - Compressor maps based on R-line
  - Key components input similarity:
    - Nozzle throat area used for thrust calculation
    - duct pressure drop
    - burner LHV and efficiency
    - Turbine cooling flow before or after 0D turbine component
    - Fractional calculated compressor bleed flow

Turbine
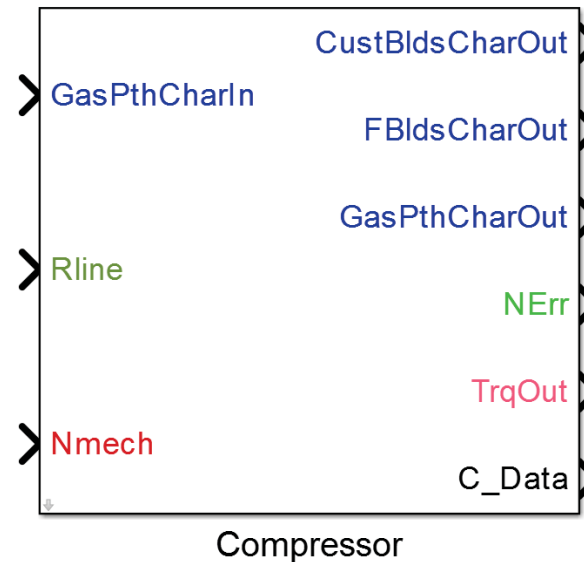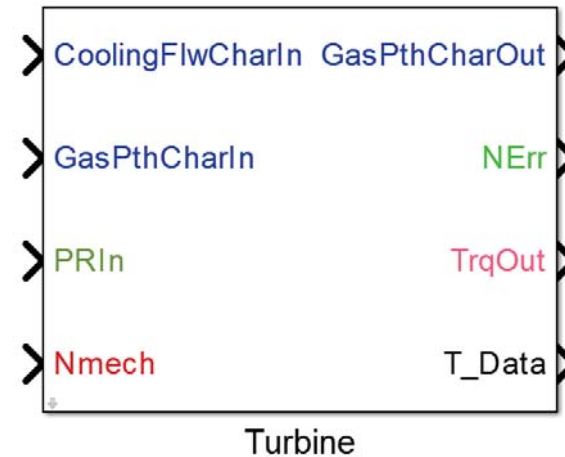
Compressor

Key Modifications: Scale Factors

- **NPSS and T-MATS both scale inputs and outputs to compressor and turbine maps**
  - Typically used to shrink or stretch a generic model or convert inputs or outputs to ratio values
  - Here, scale factors were used to ensure a model match
  - T-MATS scale factors are generated from NPSS output data by dividing a performance value by a map value. Alternatively the T-MATS tool iDesign was utilized to automatically generate scale factors from operating point performance data.

- **Corrected turbine speed**
  - T-MATS scales corrected shaft speed in the turbine by a constant (standard day temperature), while NPSS does not. This difference can be taken into account with the map scale factors.

Component	map scale factor	equation
Compressor	s_Nc	s_Nc = NcPerf / NcMap
Turbine	s_Nc	s_Nc = NcPerf × SQRT(T_std)/ NcMap
Compressor or Turbine	s_Wc	s_Wc = WcPerf / WcMap
	s_PR	s_PR = (PRPerf-1) / (PRMap-1)
	s_Eff	s_Eff = EffPerf / EffMap

Key Modifications: Turbine flow definition

- ## Flow Definition for turbine maps

  - Baseline NPSS defines turbine map Wc as simply the turbine input flow
 - T-MATS defines the turbine map Wc as the turbine input flow and a portion of the cooling flow
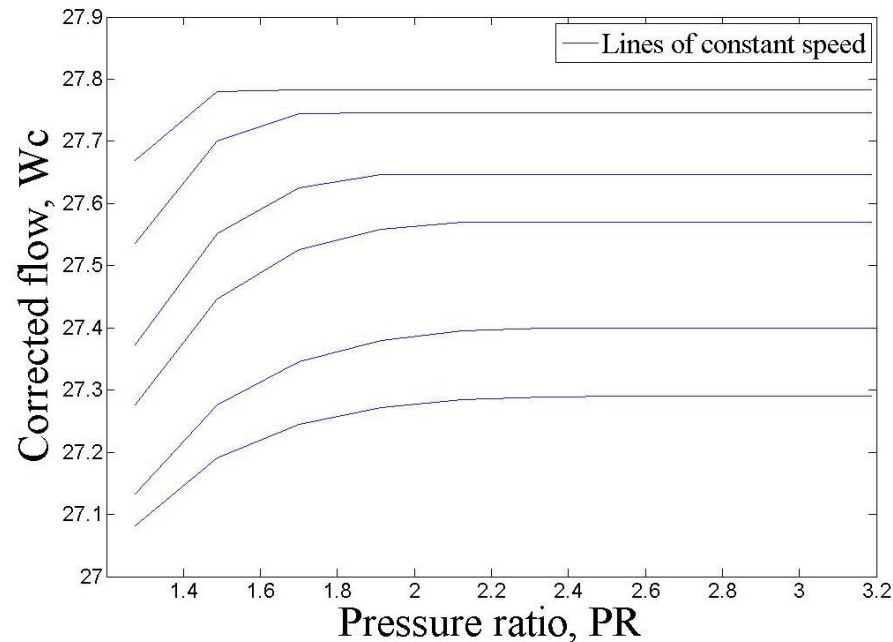
For T-MATS to use NPSS turbine maps, cooling flow must be removed from the T-MATS turbine map definition.
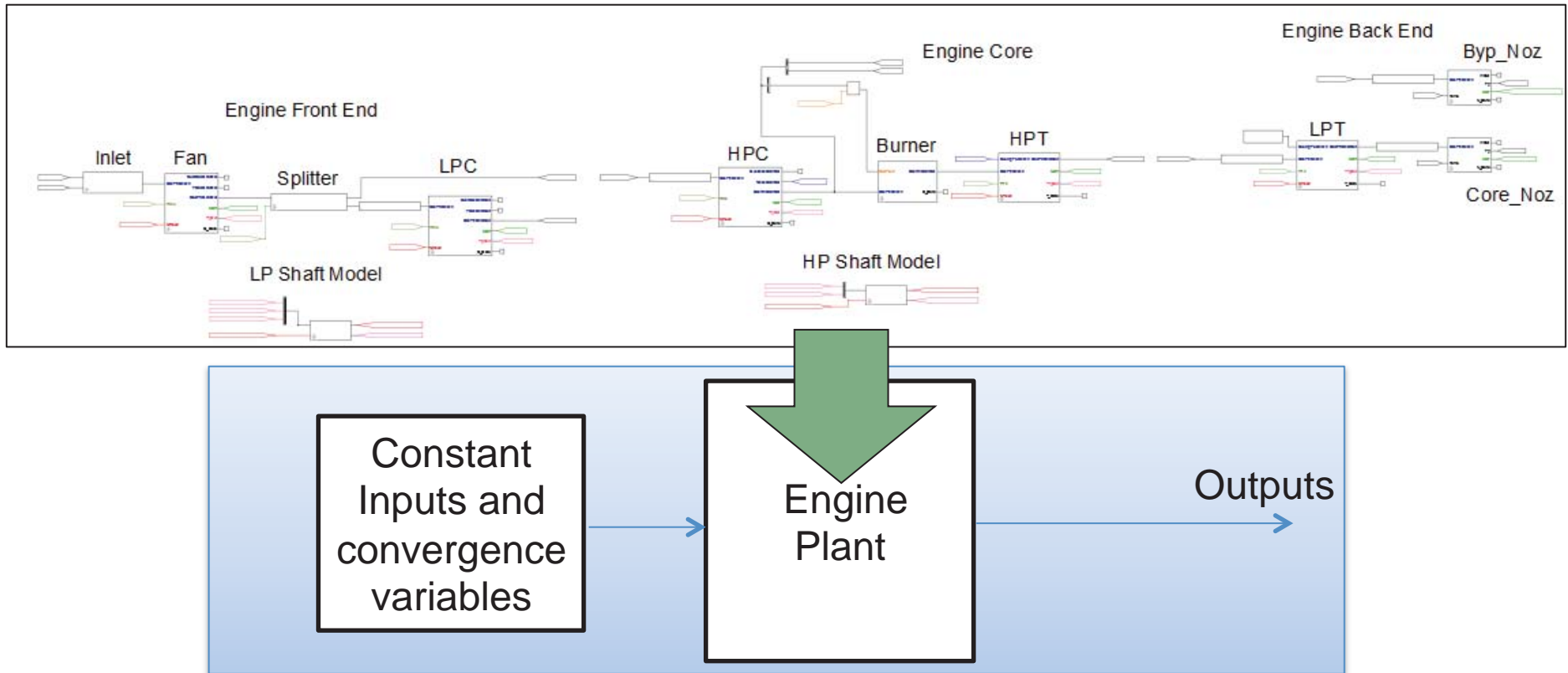
Component Level Matching

- ## Component models built for each major model section

  - NPSS station data at takeoff are used as inputs

  - Constant inputs without solver do not guarantee conservation of mass

 - Verifies component matching within acceptable limits
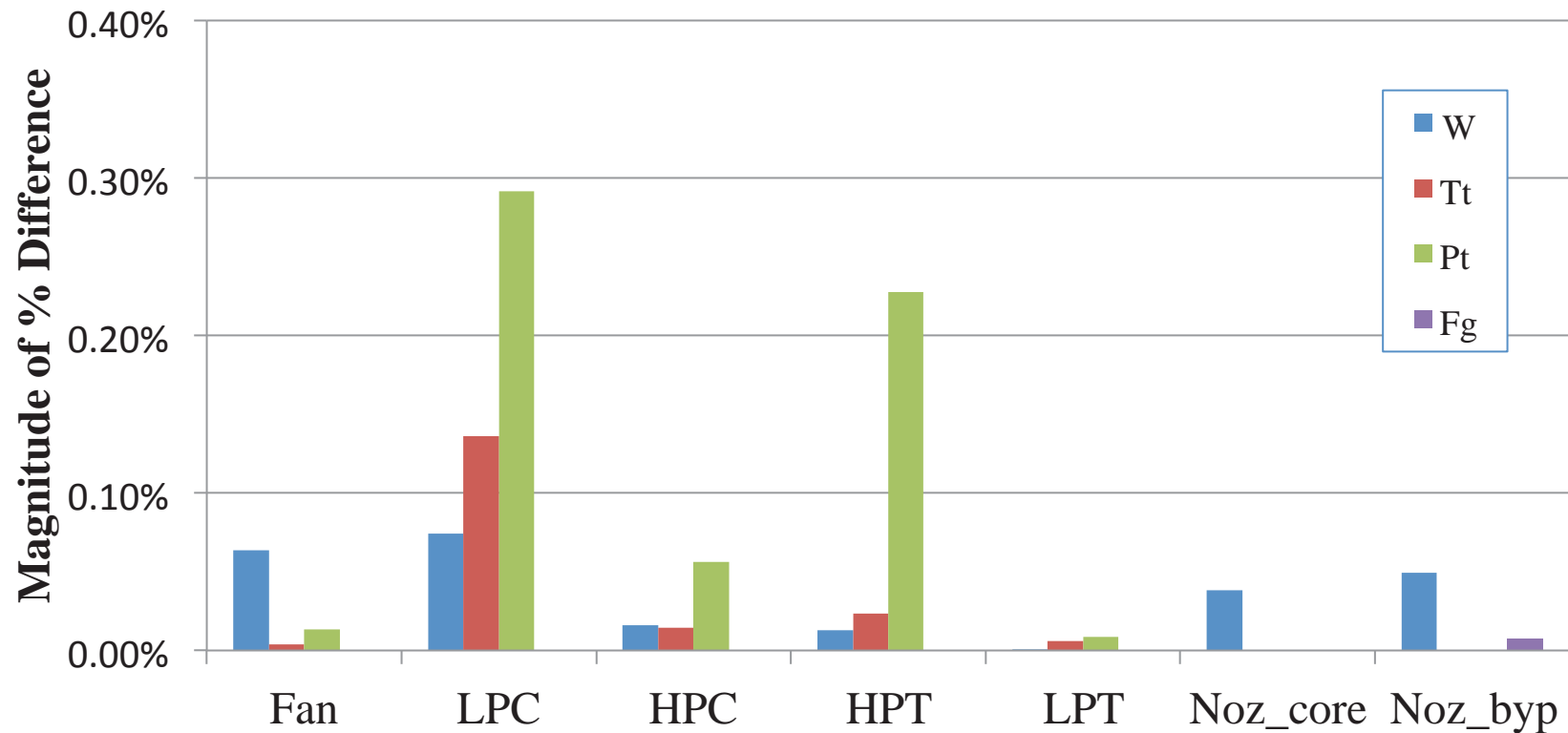
System Level Model

- ## Components combined to create a system plant model
  - Constant inputs without a solver do not guarantee conservation of mass
  - Inputs include control system inputs as well as convergence variables such as R-line.
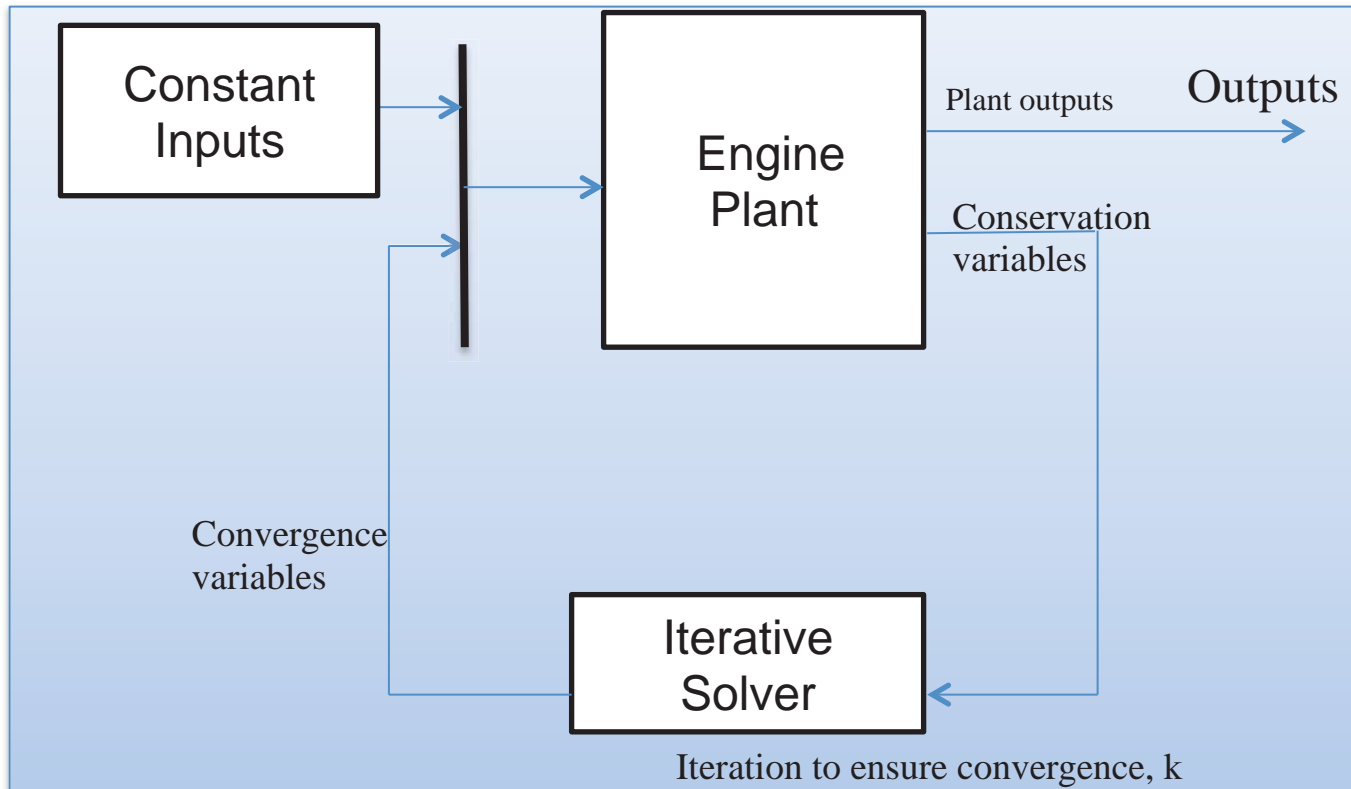
System Level Matching

- ## System model matching
  - Difference values generally higher than component matching due to error compounding, but still within acceptable levels.
 - Verifies component connections are accurate
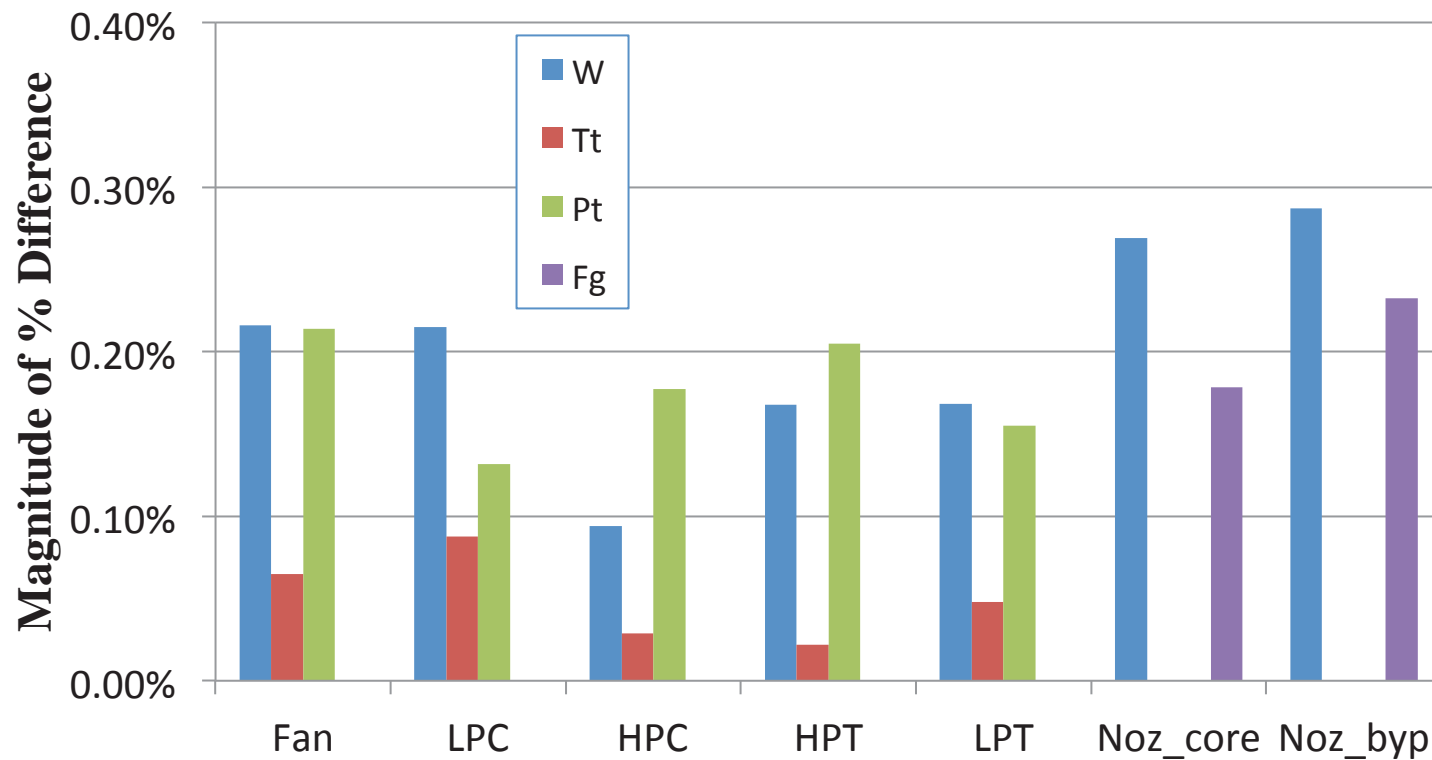
Steady State Model

- ## Solver added to system to ensure conservation

  - Convergence variables used to drive conservation variables to zero

  - Constant inputs include envelope point and control inputs

Steady State Model Matching

- ## Solver added to system model to ensure conservation of mass and negligible shaft acceleration

    - Fuel flow and environmental variables set to constants

    - Difference values higher than component matching, but still within acceptable levels.

   - Verifies system converges to correct operating point (in this case takeoff)
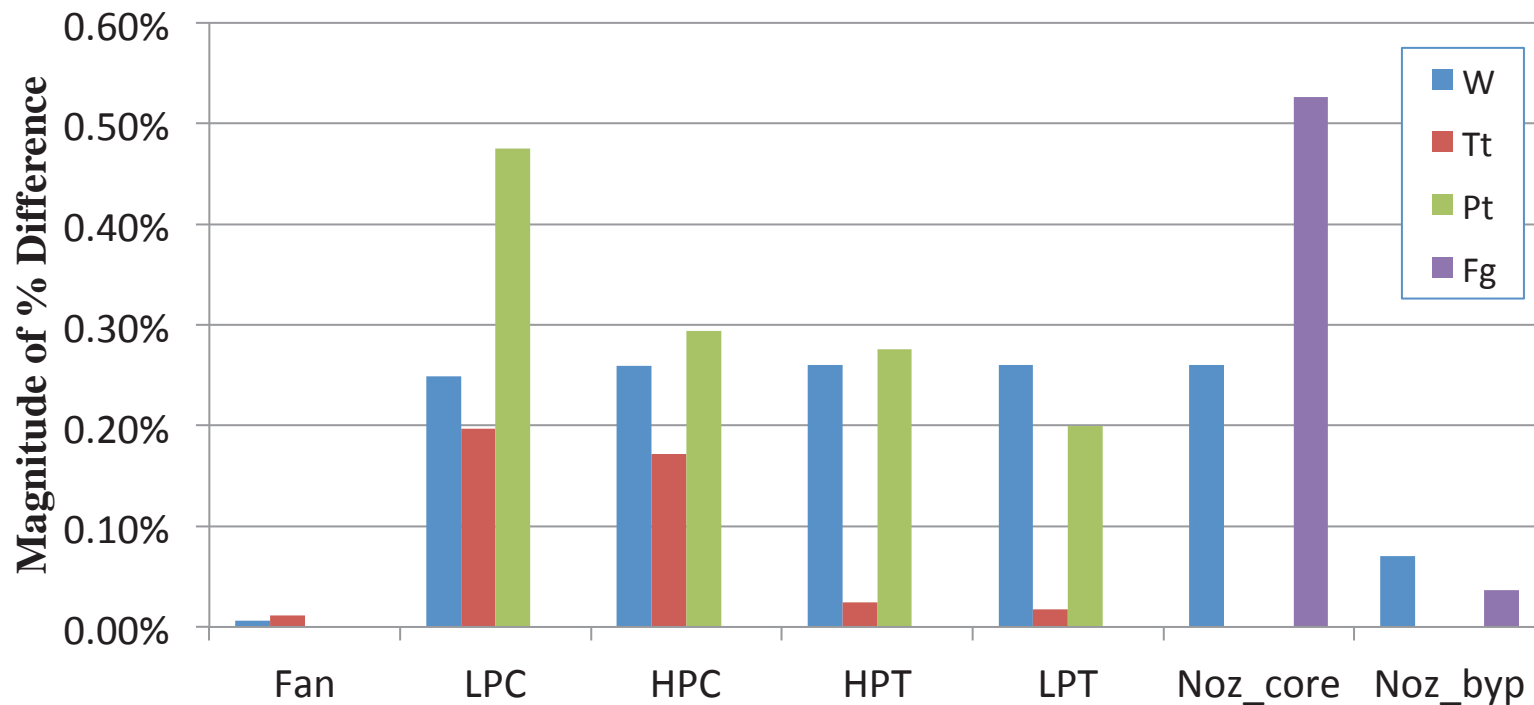
iDesign Tool

- ## iDesign tool develops map scale factors.

  – Uses scale factors to shift compressor maps, turbine maps, and nozzle throat areas effectively re-sizing components to fit a chosen operating point (design point)

- ## Compressor Map example:

  – PR at a given point modified by augmenting:

    - PR scale factor

    - Wc scale factor

    - Speed scale factor
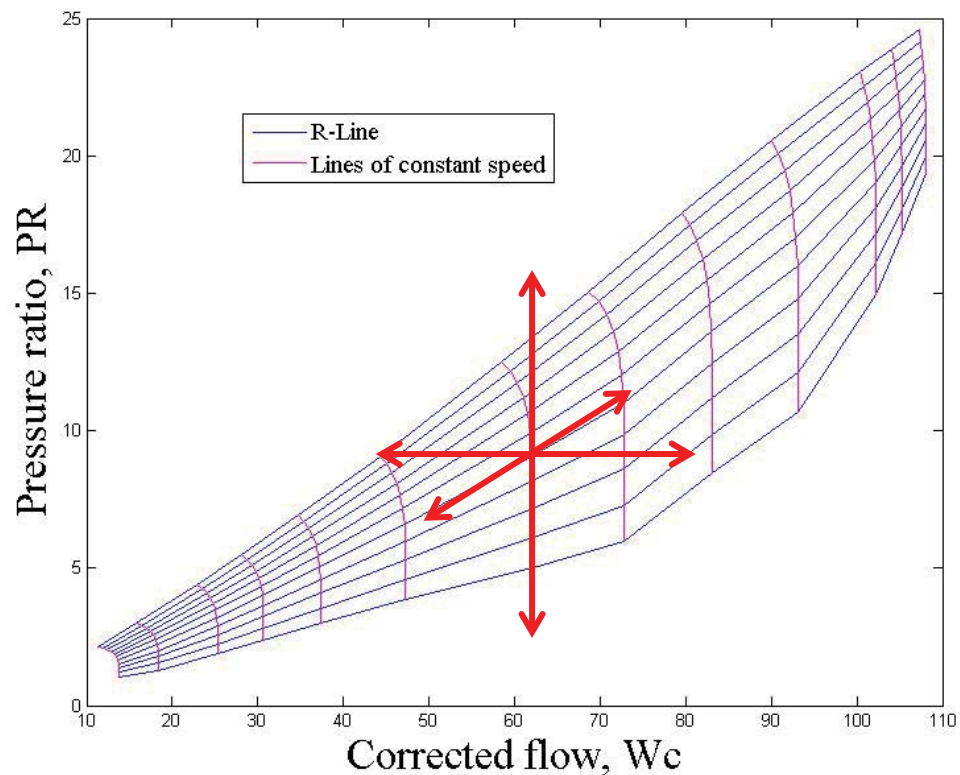
*It should be noted that the iDesign tool will fit the model to whatever operating point is specified, which may mask modeling discrepancies. This issue may be mitigated by testing many operating points across the entire flight envelope.

Alternate Operating Points and Constant Generation

- iDesign tool was run with the steady state model to automatically generate map scale factors to match the cruise operating point.

    - Steady state matching of two operating points (cruise and takeoff) were compared.

    - Average difference magnitudes comparable between scale factor generation methods

    - Additional operating point simulation verifies the match in alternate envelope conditions

| Simulation Level	Solver	Operating Point	Scale Factor Derivation Method	Average Difference
Component	No	takeoff	NPSS derived	0.0550%
System	No	takeoff	NPSS derived	0.1558%
System	Yes	takeoff	NPSS derived	0.1891%
System	Yes	cruise	NPSS derived	0.1233%
System	Yes	takeoff	iDesign	0.2490%
System	Yes	cruise	iDesign	0.0910%

Dynamic Model

- ## System updated to dynamic simulation architecture

  - integrators used to determine shaft speed
  - convergence errors solved for at every time step
  - Shaft dynamic properties assumed based on engine class
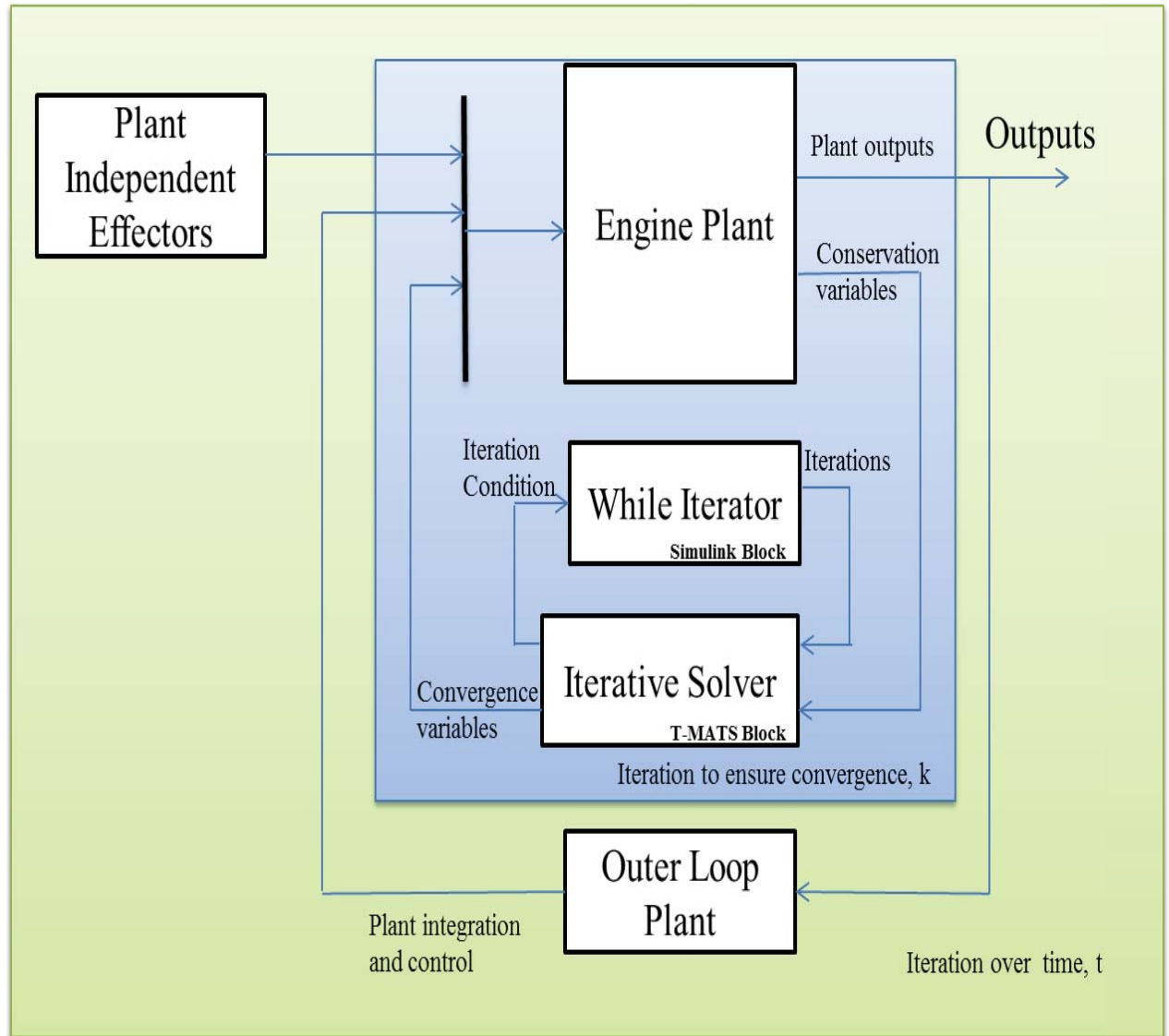
Dynamic operation

- Simulation of "chop" (sudden drop in fan speed demand) maneuver
  - PI Fan speed controller designed for demonstration purposes
  - Fan Speed Demand drops at 15 seconds with fall time roughly 2 seconds
  - Results typical for a dual spool high bypass turbofan
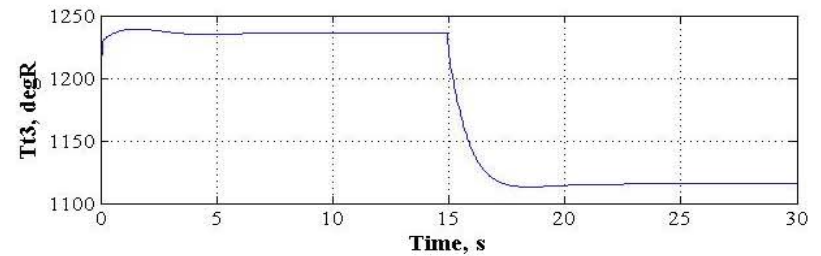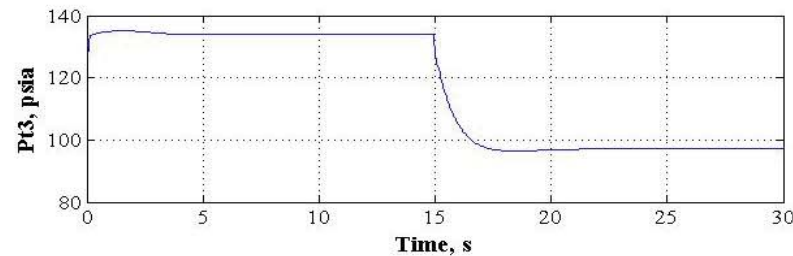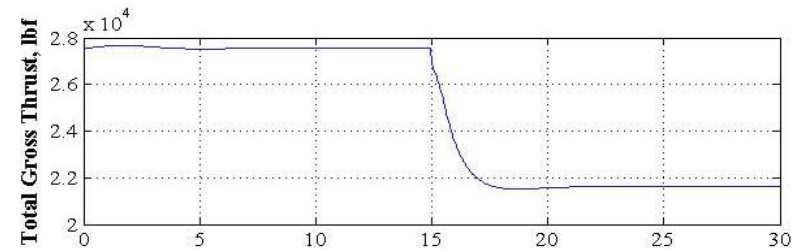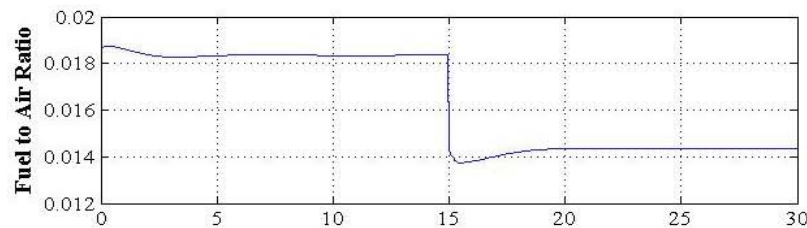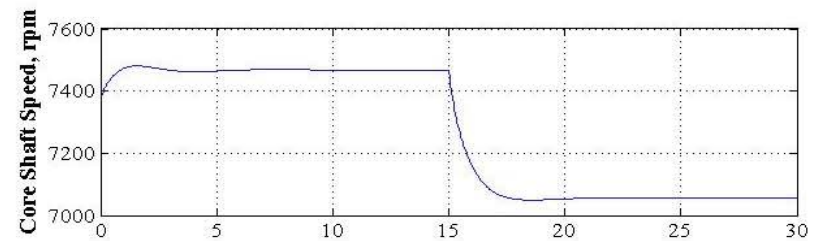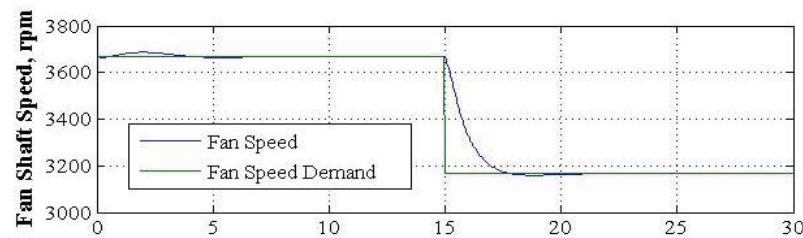
Conclusions

- A simple process may be followed to derive a T-MATS model from a baseline NPSS model.

  - Minimal Modifications to the T-MATS block set must be performed to achieve a "good" matching.
  - Scale factors may be generated manually from NPSS data or automatically with the T-MATS tool iDesign and operating point data.
  - Model may be updated to run dynamically by performing a quick adjustment to the model architecture.

- T-MATS enables rapid dynamic model creation and eliminates cross-platform model integration when system components are built in Simulink

References and Download Information

- Download information may be found at:
  https://github.com/nasa/T-MATS/releases/

- References:

1. Chapman, J.W., Lavelle, T.M., May, R.D., Litt, J.S., and Guo, T.M., "Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide," NASA/TM-2014-216638, January 2014.

2. Chapman, J.W., Lavelle, T.M., May, R.D., Litt, J.S., Guo, T-H., "Propulsion System Simulation Using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)," 2014 AIAA Joint Propulsion Conference, Cleveland, OH, Jul 28-30, 2014.

3. Lavelle, T.M., Chapman, J.W., May, R.D., Litt, J.S., and Guo, T.H., "Cantera Integration with the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)," 2014 AIAA Joint Propulsion Conference, Cleveland, OH, Jul 28-30, 2014.

4. Chapman, J.W., Lavelle, T.M., Litt, J.S., Guo, T-H., "A Process for the Creation of T-MATS Propulsion System Models from NPSS Data," 2014 AIAA Joint Propulsion Conference, Cleveland, OH, Jul 28-30, 2014.

5. Zinnecker, A.M., Chapman, J.W., Lavelle , T.M., and Litt, J.S., "Development of a twin-spool turbofan engine simulation using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)," 2014 AIAA Joint Propulsion Conference, Cleveland, OH, Jul 28-30, 2014.