



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

*Jeffryes W. Chapman*  
*Vantage Partners, LLC, Brook Park, Ohio*

*Thomas M. Lavelle, Jonathan S. Litt, and Ten-Huei Guo*  
*Glenn Research Center, Cleveland, Ohio*

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:  
STI Information Desk  
NASA Center for AeroSpace Information  
7115 Standard Drive  
Hanover, MD 21076-1320



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

*Jeffryes W. Chapman*  
*Vantage Partners, LLC, Brook Park, Ohio*

*Thomas M. Lavelle, Jonathan S. Litt, and Ten-Huei Guo*  
*Glenn Research Center, Cleveland, Ohio*

Prepared for the  
50th Joint Propulsion Conference  
cosponsored by AIAA, ASME, SAE, and ASEE  
Cleveland, Ohio, July 28–30, 2014

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

## Acknowledgments

The authors would like to thank the NASA Aviation Safety Program's Vehicle Systems Safety Technologies Project for funding this work. Additionally the assistance of the NPSS team was critical in gaining a deeper understanding of the NPSS modeling process.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

*Level of Review:* This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information  
7115 Standard Drive  
Hanover, MD 21076-1320

National Technical Information Service  
5301 Shawnee Road  
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

# **A Process for the Creation of T-MATS Propulsion System Models From NPSS Data**

Jeffryes W. Chapman  
Vantage Partners, LLC  
Brook Park, Ohio 44142

Thomas M. Lavelle, Jonathan S. Litt, and Ten-Huei Guo  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

## **Abstract**

A modular thermodynamic simulation package called the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) has been developed for the creation of dynamic simulations. The T-MATS software is designed as a plug-in for Simulink (Math Works, Inc.) and allows a developer to create system simulations of thermodynamic plants (such as gas turbines) and controllers in a single tool. Creation of such simulations can be accomplished by matching data from actual systems, or by matching data from steady state models and inserting appropriate dynamics, such as the rotor and actuator dynamics for an aircraft engine. This paper summarizes the process for creating T-MATS turbo-machinery simulations using data and input files obtained from a steady state model created in the Numerical Propulsion System Simulation (NPSS). The NPSS is a thermodynamic simulation environment that is commonly used for steady state gas turbine performance analysis. Completion of all the steps involved in the process results in a good match between T-MATS and NPSS at several steady state operating points. Additionally, the T-MATS model extended to run dynamically provides the possibility of simulating and evaluating closed loop responses.

## **Nomenclature**

Ath	throat area (in. <sup>2</sup> )
Byp_NoZ	bypass nozzle
BPR	Branch Pressure Ratio
C-MAPSS40k	Commercial Modular Aero-Propulsion System Simulation 40,000 lbf thrust
C-MAPSS	Commercial Modular Aero-Propulsion System Simulation
Core_NoZ	core nozzle
dP	change in pressure or delta pressure (psia)
Eff	efficiency
FAR	fuel to air ratio
Fg	gross thrust
HPC	high pressure compressor
HPT	high pressure turbine
ht	enthalpy
LHV	lower heating value
LPC	low pressure compressor
LPT	low pressure turbine
N	shaft speed (rpm)

N1	low pressure shaft speed (rpm)
N2	high pressure shaft speed (rpm)
Nc	corrected shaft speed (rpm)
NPSS	Numerical Propulsion System Simulation
Pa	ambient pressure (psia)
PI	proportional-integral
PR	pressure ratio
Pt	total pressure (psia)
R-line	uniquely defined line on the compressor map
s_Eff	map scale factor for efficiency coming from a map
s_Nc	map scale factor for corrected shaft speed going to a map
s_PR	map scale factor for pressure ratio coming from a map
s_Wc	map scale factor for corrected flow coming from a map
T-MATS	Toolbox for the Modeling and Analysis of Thermodynamic Systems
T_std	standard day temperature (518.67 °R)
Tt	total temperature (°R)
W	mass flow (pps)
Wb	bleed mass flow (pps)
Wc	corrected mass flow (pps)
Win	component input mass flow (pps)
Subscripts:	
Des	variable at the design point
Map	map variables are inputs or outputs of an empirical map model
Perf	performance variables are final modeled parameter

## I. Introduction

In gas turbine control system design, a model is often used in place of hardware to simulate the system and verify controls requirements are met. This model can be obtained in many different ways. One such way is by developing the simulation utilizing the Numerical Propulsion System Simulation (NPSS), a widely used engineering modeling environment for the design and analysis of aircraft engines (Ref. 1). Using NPSS models can be a convenient approach because they are often created in the early stages of gas turbine development and they can be quite accurate, and are easily modifiable to incorporate additional turbine design information (Ref. 2). NPSS is a powerful gas turbine cycle modeling and analysis package; however, integrating NPSS models with control system models can be difficult because of the complexity of NPSS, which may not be compatible with the legacy codes and the simulation platform used in the development of the control (Ref. 3). Another approach is to use a model like C-MAPSS or C-MAPSS40k. Built in Simulink, C-MAPSS and C-MAPSS40k are generic commercial engine simulations with industry standard control architecture (Refs. 4 and 5). Controls design using a pre-existing generic engine with a basic controller that requires no cross platform integration can drastically reduce simulation setup time and allow a controls designer to test many different ideas quickly. However, customization of the engine model from such a tool can be difficult.

To eliminate cross platform integration and allow for maximum flexibility, the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) can be used for gas turbine simulation development (Refs. 6 and 7). Written as a plug-in for MATLAB/Simulink, T-MATS contains a library of generic engine component models, a numerical solver, and controller blocks designed to aid in the creation of thermodynamic models and control systems. While T-MATS can be used to create custom models from engine data, legacy model data may also be leveraged for simulation generation. For example, the C-MAPSS simulation was re-created in T-MATS and results compared favorably within an acceptable error tolerance (Ref. 8).

This paper describes a process for developing nonlinear dynamic aircraft engine simulations with T-MATS using information from NPSS models. Specifically, a process for leveraging maps, constants, and steady state data from NPSS-developed models for the creation of MATLAB/Simulink simulations with T-MATS. This process is demonstrated on the JT9D, a publicly available NPSS model of a dual spool high-bypass turbofan engine (Ref. 9).

This process can be summarized by describing how engine component models are generated in T-MATS from NPSS. For components like the fan, compressors, and turbines, performance maps are directly utilized from NPSS. For components that are not explicitly defined, like the inlet, NPSS is run at a steady state point and then the inputs are perturbed to form a partial relation between the input and output flow variables. Nozzle performance is based on thermodynamic equations that determine static and total conditions at the throat and exit utilizing input parameters taken from NPSS data. For the burner, the fuel thermodynamic properties are included in the model, as in NPSS. The rotor dynamics are added to the T-MATS model using a representative rotational moment of inertia and the associated equations of motion, as the change in rotor speed is a function of torque differential between the turbine and compressor on a given rotor. Conservation of energy is ensured internally for each component, however mass is ensured by adding a solver that reconciles inter-component imbalances at every computation step. This paper will focus on the specifics of the process involved with NPSS, including extracting pertinent information necessary to develop the T-MATS model for the JT9D, and the model matching, which will be performed at takeoff and cruise to show match variation due to changes in operating point (certain fixed boundary conditions). Scale factors that adjust the performance of the compressor and turbine are determined by two methods: a data derived method that back calculates the scale factors from NPSS, and the T-MATS iDesign tool, which generates the scale factors based on an operating point, cruise in this paper.

The paper is organized as follows. Section II offers a background on creating turbo-machinery simulations in T-MATS. Section III gives an overview of the procedure steps involved in this model development process. Section IV presents how the T-MATS simulation components and system architecture were selected and modified to match the NPSS model data. All model testing and results are detailed in Section V. Section VI describes how the simulation was converted from steady state to dynamic. Conclusions are discussed in Section VII.

## **II. T-MATS Background**

The T-MATS software is a MATLAB plug-in that introduces additional blocks and tools to the Simulink environment. The turbo-machinery block set, located within T-MATS, provides access to parameterized gas turbine modeling components such as turbines, burners, compressors, and nozzles that may be used to create simulations. Turbo-machinery components are assumed to be 0-D, where the component-level dynamics are not modeled. Internal component calculations contain a combination of physics based and empirical models. Algebraic relations and component maps are used to generate component or system steady state solutions at specific operating points. For example, compressor efficiency ( $\text{Eff}$ ), corrected mass flow ( $\text{Wc}$ ), and pressure ratio ( $\text{PR}$ ) are determined from the compressor map as functions of corrected shaft speed ( $\text{Nc}$ ) and R-line, where R-line is a uniquely defined line on the compressor map. Turbine  $\text{Eff}$  and  $\text{Wc}$  are determined from the turbine map as functions of  $\text{Nc}$  and  $\text{PR}$ , with input cooling flow being added either at the input or output of the component. Empirical calculations

for enthalpy and entropy are functions of temperature and pressure and are based on the assumption that all component mass flows consist of two compounds, air and Jet-A aircraft fuel. Physics based equations for turbo-machinery components in T-MATS are predominately used to calculate component energy and mass requirements, such as nozzle flow error.

As stated above, a T-MATS model ensures the conservation of energy and mass. Conservation of energy is ensured internally to each component with energy balance equations. Although T-MATS ensures conservation of mass internally for some components, conservation across the system must also be upheld by using one of the T-MATS numerical solvers. Generally, this is done by monitoring conservation errors, or dependents, then using a T-MATS solver to adjust floating model variables, or independents, to eliminate the errors. For example, the dependent variable for a T-MATS compressor component is mass flow error (the difference between input mass flow and an internally calculated mass flow), and the independent variable is R-line. A model will be considered converged once the solver has updated the independents so that all dependents are at or near zero.

While the T-MATS and NPSS environments are different, they operate in a very similar manner, in terms of simulating a given turbo-machinery design. Both are modular, use component maps and thermodynamic properties for calculations, and both require solving for system dependents by adjusting independents as discussed above. However, NPSS contains more flexibility in its temperature and pressure to enthalpy and entropy calculations, and allows for many different compound options. It should be noted that in this paper the JT9D engine was simulated in NPSS using air and Jet-A fuel, which are the same compounds as those used in T-MATS. Currently, work is being done to add alternate compound capability to T-MATS with the integration of the Cantera thermodynamic modeling package; however this is beyond the scope of this paper (Ref. 10).

### **III. Process Overview**

This process assumes that a particular engine architecture has already been simulated in NPSS and that the cycle analysis for this design has been completed. Once the T-MATS user decides on the NPSS engine architecture to simulate and the respective simulation components, the following process may be used to create a dynamic T-MATS model from steady state NPSS data and constants.

1. Converting maps and constants from NPSS into a useable format, while also modifying T-MATS components to be compatible with these maps and constants. In some cases it is necessary to perturb certain inputs to gain an understanding of how a component should be modeled.
2. Completing a component level model match by taking each portion of the NPSS model and recreating it in T-MATS.
3. Combining the model components into a system model with constant independent variables at the operating point.
4. Creating a steady state model by integrating a solver into the system model.
5. Converting the steady state T-MATS model to a dynamic T-MATS model.

In the final two steps of the process, several operating points at different power levels and flight conditions are selected for comparison purposes. These additional tests are used to ascertain the operating point dependence of the model match. It should be noted that for this paper a “good” matching was arbitrarily chosen to be anything under a 1 percent deviation between models. In the following section, this procedure is demonstrated using the JT9D NPSS model.



## IV. T-MATS Simulation Creation

Because NPSS and T-MATS are both modular it was determined that the T-MATS model would use the same components as the NPSS model. Figure 1 shows a block diagram detailing placement of components and subsequent connections, which is derived directly from NPSS module station numbers, shown in Appendix A.

As mentioned above, T-MATS and NPSS are both simulations that are developed around component maps. For example, both simulations define compressor maps that use R-lines and Nc to generate Eff, PR, and Wc. For this reason, component maps were copied as they were defined in NPSS and formatted to insure consistency in the variable names and table structures for use in T-MATS. These reformatted maps can be found in Appendix B.

Once the NPSS maps have been reformatted, it is necessary to integrate them with the T-MATS modeling structure using map scale factors. Map scale factors are multipliers that convert turbo-machinery map data to turbo-machinery performance data or vice versa and are typically used for shrinking or stretching a more generic model and/or converting Nc to a ratio value for map lookup. For this paper, map data are considered inputs or outputs of the component maps whereas performance (Perf) data are considered the actual values. For the creation of this T-MATS model, map scale factors were used to ensure a model match between NPSS and T-MATS. Shown in Table 1, for the arbitrarily chosen sea level static condition, are the map scale factors generated for the JT9D and the equations used to calculate them. Generating scale factors by deriving them from NPSS data essentially reformats the NPSS scale factors to be useable in T-MATS. It should be noted that there are differences between the data derived map scale factors in Table 1 and the map scale factors located within the NPSS data, as shown in Appendix A. These differences reflect variations in implementation between how T-MATS and NPSS use maps and scale factors.

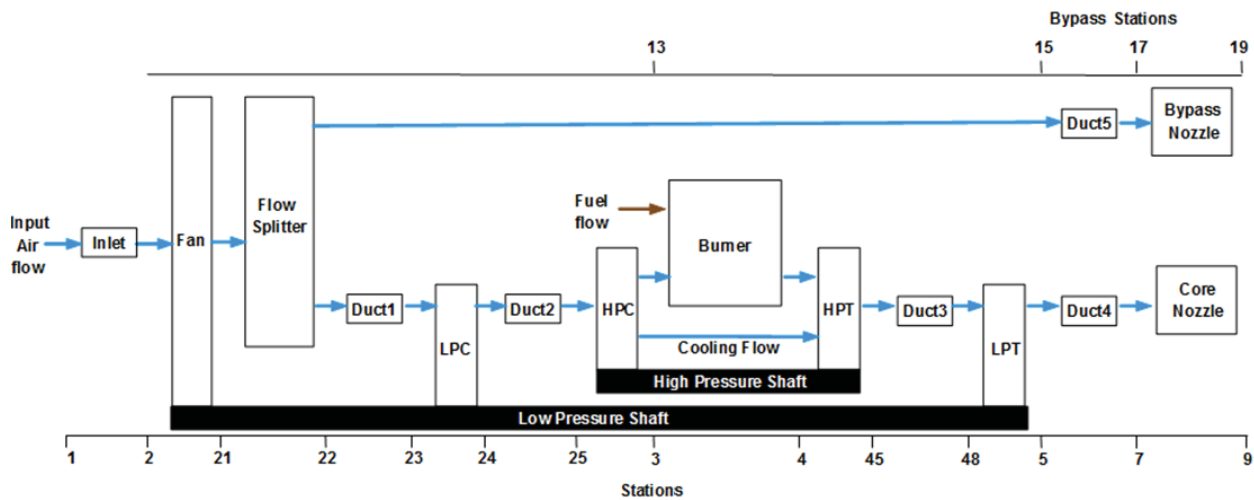


Figure 1.—JT9D engine component setup.

TABLE 1.—T-MATS DATA DERIVED MAP SCALE FACTORS, CALCULATED FROM NPSS DATA

Component	Map scale factor	Equation	Fan	LPC	HPC	HPT	LPT
Compressor	s_Nc	$s_{Nc} = Nc_{Perf} / Nc_{Map}$	3943.96	3662.66	6357.16	-----	-----
Turbine	s_Nc	$s_{Nc} = Nc_{Perf} \times \sqrt{T_{std}} / Nc_{Map}$	-----	-----	-----	34.87	18.47
Compressor or Turbine	s_Wc	$s_{Wc} = Wc_{Perf} / Wc_{Map}$	0.52	0.93	0.42	0.91	0.48
	s_PR	$s_{PR} = (PR_{Perf} - 1) / (PR_{Map} - 1)$	1.13	3.26	0.22	0.43	0.72
	s_Eff	$s_{Eff} = Eff_{Perf} / Eff_{Map}$	0.97	0.96	1.01	0.98	1.00

One such variation is in the turbine component equations, where NPSS and T-MATS calculate  $N_c$  differently. In T-MATS,  $N_c$  is referenced to a standard day temperature ( $T_{std}$ ), while in NPSS this is not the case. This variation is taken into account in T-MATS by adjusting the turbine map scale factor for  $N_c$  ( $s_{Nc}$ ) to include a  $T_{std}$  value, as shown in Table 1. It should be noted that the NPSS and T-MATS compressor components calculate  $N_c$  identically; therefore no additional multiplier was required for the compressor  $s_{Nc}$  definition.

Another implementation variation between the NPSS model and T-MATS has to do with the inclusion of bleed flow in the  $W_c$  component of a turbine map. For instance, in T-MATS there are three types of corrected flows used as input to the HPT turbine component: the HPT input mass flow, cooling flow to the input of the HPT, and cooling flow to the output of the HPT. In T-MATS, the summation of the HPT input mass flow and the cooling flow to the input of the HPT is compared to the internally calculated  $W_c$  to generate a mass flow error, which the solver utilizes to adjust the independent variables accordingly. In the NPSS data, this normalized flow error is based on component input  $W_c$  only. To resolve this variation, the T-MATS turbine block was modified to remove the HPT input cooling flow from the normalized flow error calculation. This adjustment moves the bookkeeping of the cooling flow from the turbine component to a component downstream, and must be done only because the T-MATS turbine map has cooling flow included in it and the NPSS turbine map does not.

As an alternative to using data to manually derive map scale factors for component maps, scale factors were also determined with the T-MATS tool iDesign. This tool is a time-saving feature that uses map scale factors and other key parameters to fit component maps to a design point automatically, effectively creating a model at a specific operating point. Map scale factors for the compressor and turbine may be generated by comparing the map values with performance values at a specified design point. Additionally, nozzle throat areas are generated by comparing nozzle mass flow at the design point with an internally calculated mass flow. The steady state design point selected for this study is detailed in Table 2, which in this case was chosen to be the cruise condition because a gas turbine is typically designed for this condition. Each step of the model creation process details the T-MATS model generated using data derived map scale factors as described earlier in this section. However, iDesign is also utilized during the final steps of the matching process as described in Section V.

Additional constants required for T-MATS simulation creation are detailed in Appendix C and were determined from the NPSS data output located in Appendix A. The T-MATS components used for modeling were selected based on NPSS engine architecture, as described above, with modeling accuracy similar to that of the NPSS model. For example, the inlet total temperature does not change appreciably in the NPSS model, therefore the T-MATS model does not consider it.

TABLE 2.—IDESIGN INPUTS FOR MAP SCALE FACTOR CALCULATION

Component	NcDesMap	EffDes	PRDes	R-lineMap
Fan	1.0	0.8674	1.644	2.37
LPC	0.993	0.8685	2.485	1.7716
HPC	0.996	0.8649	5.625	2.04
	NcDesMap	EffDes	PRMap	Ndes, rpm
HPT	99.0	0.9132	4.934	7392
LPT	105	0.9324	6.399	3667
	Wdes, pps	-----	-----	-----
Core_NoZ	113.61	-----	-----	-----
Byp_NoZ	562.59	-----	-----	-----
	Altitude, ft	Mach Number	Temperature, °R	-----
Flight conditions	34000	0.8	448.43	-----

## V. Model Matching

Once the NPSS engine simulation is converted to T-MATS, model matching tests were performed that compared NPSS data with T-MATS generated outputs. This testing was broken down into several groups consisting of component level testing, system level testing without a solver, and system level testing with a solver. Component level tests used NPSS station data to determine how each NPSS module compares with its equivalent T-MATS component. The system level test without a solver brings the model together and validates the T-MATS component connections. For the final matching, the solver is enabled to verify the model will converge at the correct operating points.

### A. Component Level Testing

A component level matching test was designed for each major part of the T-MATS JT9D high-bypass turbofan engine model, as detailed in Figure 1. Results from the component level testing using a takeoff operating point can be seen in Table 3. Stations immediately after each major engine component were selected for comparison purposes. Component data were gathered for the following parameters; flow (W), total temperature (Tt), total pressure (Pt), and gross thrust (Fg). If a parameter was not calculated at a particular station, either by T-MATS or NPSS, it was neglected, e.g., total pressure by the nozzle. In each component, the matching difference between the NPSS model and the T-MATS model was below 0.3 percent. The largest absolute difference was in the pressure output of the low pressure compressor (LPC). Thrust difference was negligible for both the core bypass and core nozzles. Engine flow difference was below 0.1 percent in all cases. These low error values are considered to demonstrate a sufficient component level match.

TABLE 3.—COMPONENT LEVEL MODEL MATCH RESULTS

Output	Parameter	NPSS	T-MATS	%Difference
Fan	W(pps)	1539.2	1539.21	0.0636%
	Tt(°R)	632.71	632.736	-0.0041%
	Pt(psia)	23.37	23.3669	0.0133%
Low Pressure Compressor (LPC)	W(pps)	245.29	245.2918	0.0743%
	Tt(°R)	821.38	822.4966	-0.1359%
	Pt(psia)	52.451	52.604	-0.2917%
High Pressure Compressor (HPC)	W(pps)	245.29	245.2904	0.0161%
	Tt(°R)	1398.6	1398.8	-0.0143%
	Pt(psia)	297.127	296.96	0.0562%
High Pressure Turbine (HPT)	W(pps)	228.18	228.1803	0.0127%
	Tt(°R)	2137.47	2136.97	0.0234%
	Pt(psia)	104.013	104.25	-0.2279%
Low Pressure Turbine (LPT)	W(pps)	250.25	250.25	-0.0009%
	Tt(°R)	1522.73	1522.82	-0.0059%
	Pt(psia)	22.575	22.577	-0.0089%
Nozzle core	W(pps)	250.25	250.251	0.0384%
	Fg(lbf)	11210	11210	0.0000%
Nozzle bypass	W(pps)	1293.91	1293.916	0.0495%
	Fg(lbf)	38674.8	38677.76	-0.0077%

## B. System Level Matching (Without Solver)

Once component models are developed, they are assembled appropriately based on the engine architecture, shown in Figure 1, to build the engine plant model. Input flow characteristics and independents (e.g., R-line) are set to constants, taken from NPSS data and consistent with the takeoff operating point, for model match testing. These inputs consist of the values shown in Table 4.

Table 5 shows the results from the system level test with constant inputs. It can be seen that the average matching differences increased significantly from those of the component level test. However, all differences in this test still remain well under 1 percent, with the highest difference being in nozzle W. Matching differences of such a low magnitude constitute a good match and it also shows that the model components have been connected correctly. Note in this matching step, that independents are held constant and the solver that insures satisfaction of conservation properties is not activated. Flow difference values shown in the model matching results are internal component differences and should be considered on a component by component basis.

TABLE 4.—T-MATS JT9D SIMULATION INPUTS FOR SYSTEM LEVEL TESTING WITHOUT A SOLVER

Plant inputs	W	Pt	Tt	Fan R-line	LPC R-line	HPC R-line	BPR	HPT PR	LPT PR	N1	N2
Value	1539.2	14.69	545.67	2.0	1.769	2.081	5.275	2.694	4.558	3750	8000

TABLE 5.—MODEL MATCHING RESULTS SYSTEM LEVEL TESTING WITHOUT A SOLVER

Output	Parameter	NPSS	T-MATS	%Difference
Fan	W(pps)	1539.20	1542.52	0.2158%
	Tt(°R)	632.71	632.30	-0.0648%
	Pt(psia)	23.37	23.32	-0.2139%
LPC	W(pps)	245.29	245.82	0.2150%
	Tt(°R)	821.38	822.10	0.0877%
	Pt(psia)	52.45	52.52	0.1316%
HPC	W(pps)	245.29	245.52	0.0938%
	Tt(°R)	1398.60	1399.00	0.0286%
	Pt(psia)	297.13	296.60	-0.1774%
HPT	W(pps)	250.25	250.67	0.1680%
	Tt(°R)	2137.47	2137.00	-0.0220%
	Pt(psia)	104.01	103.80	-0.2048%
LPT	W(pps)	250.25	250.67	0.1682%
	Tt(°R)	1522.73	1522.00	-0.0479%
	Pt(psia)	22.58	22.54	-0.1550%
Noz_core	W(pps)	250.25	250.92	0.2689%
	Fg(lbf)	11210.00	11190.00	-0.1784%
Noz_byp	W(pps)	1293.91	1297.62	0.2869%

### C. System Level Matching (With Solver)

Once the plant model is verified to have a good match, a steady state simulation is created by adding the T-MATS solver and connecting the system independents and dependents (Ref. 6). In this example, the steady state independents are system input flow (W), Fan R-line, splitter bypass ratio, LPC R-line, HPC R-line, HPT PR, LPT PR, N1, and N2. The steady state dependents are normalized flow differences for the Fan, LPC, HPC, HPT, LPT, core nozzle, and bypass nozzle, along with high and low pressure shaft acceleration. During simulation, the solver will drive the dependents to zero by adjusting the independents, effectively moving the simulation towards a new operating point. This simulation was performed at takeoff conditions with altitude, Mach number, and temperature, set to 0 ft, 0, and 545.67 °R, respectively.

Table 6 shows the results from the system level test after allowing the solver to converge with the scale factors developed from NPSS data as well as with scale factors created with iDesign. It can be seen that the matching differences from the model using NPSS-derived scale factors increase slightly from that of the system level test that contained constant independent variables. These differences occur due to the operating point moving on the map, caused by the manipulation of independents by the solver, to meet conservation of mass. Flow differences listed in this section take into account that each component input flow is matched with its component calculated flow with a difference less than 0.0001 percent. Although there was an increase in the difference between the models, all errors remain less than 1 percent, with the highest difference being the LPC pressure (Pt). The matching differences from the T-MATS model that utilized scale factors from the iDesign tool are generally greater in magnitude. This increase can be attributed to the iDesign scale factors being generated for a cruise operating point rather than the takeoff condition being shown below.

TABLE 6.—MODEL MATCHING RESULTS FOR SYSTEM LEVEL TESTING WITH SOLVER

Output	Parameter	NPSS	T-MATS, NPSS scale factors	%Difference	T-MATS, iDesign	%Difference
Fan	W(pps)	1539.20	1539.11	−0.0058%	1540.00	0.0520%
	Tt(°R)	632.71	632.78	0.0111%	632.90	0.0300%
	Pt(psia)	23.37	23.37	0.0000%	23.39	0.0685%
LPC	W(pps)	245.29	245.90	0.2487%	246.10	0.3302%
	Tt(°R)	821.38	823.00	0.1972%	823.30	0.2338%
	Pt(psia)	52.45	52.70	0.4747%	52.80	0.6654%
HPC	W(pps)	245.29	245.93	0.2593%	246.04	0.3066%
	Tt(°R)	1398.60	1401.00	0.1716%	1400.00	0.1001%
	Pt(psia)	297.13	298.00	0.2938%	298.20	0.3611%
HPT	W(pps)	250.25	250.90	0.2597%	251.00	0.2997%
	Tt(°R)	2137.47	2138.00	0.0248%	2139.00	0.0716%
	Pt(psia)	104.01	104.30	0.2759%	104.60	0.5644%
LPT	W(pps)	250.25	250.90	0.2597%	251.00	0.2997%
	Tt(°R)	1522.73	1523.00	0.0177%	1522.00	−0.0479%
	Pt(psia)	22.58	22.62	0.1993%	22.63	0.2436%
Noz_core	W(pps)	250.25	250.90	0.2597%	251.00	0.2997%
	Fg(lbf)	11210.00	11269.00	0.5263%	11280.00	0.6244%
Noz_byp	W(pps)	1293.91	1293.00	−0.0703%	1294.00	0.0070%
	Fg(lbf)	38674.80	38660.50	−0.0370%	38723.00	0.1246%

TABLE 7.—T-MATS JT9D SIMULATION INPUTS FOR SYSTEM LEVEL TESTING

Operating point	Altitude, ft	Mach Number	Temperature, °R	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

TABLE 8.—T-MATS JT9D SIMULATION MATCHING RESULTS

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 at cruise	0.2490%
System	Yes	cruise	iDesign at cruise	0.0910%

## D. Model Match Testing Summary

Up to this point, the majority of testing has been completed at the takeoff operating point with an engine model created by utilizing component maps and relationships developed from NPSS data or from the T-MATS iDesign tool. For comparison purposes, additional testing at a cruise operating point was also conducted. Flight conditions and fuel inputs for the takeoff and cruise operating points are listed in Table 7.

To gain a general understanding of the differences generated by these methods, the magnitudes of the difference values for all components were averaged and then tabulated. A comparison of average differences is shown in Table 8. The lowest differences generated in this study were from the component level simulations. System level simulations completed with and without a solver and NPSS derived scale factors generated comparable average difference values. Running at cruise with iDesign-generated map scale factors, the average difference is roughly half the amount generated by the simulation using map scale factors derived from NPSS data. However, when scale factors generated by iDesign at cruise are used at the takeoff operating point the average difference roughly doubles. Although there is a large rise, the values are still quite low, with an average difference of less than 0.25 percent, which shows that calculating map scale factors by data derivation or by the T-MATS iDesign tool can lead to difference values of less than 1 percent at the operating points tested.

## VI. Dynamic Conversion

Once the matching was satisfactory, the model was converted from steady state to dynamic for transient testing. This was accomplished by introducing integrators to calculate the shaft speeds from the shaft accelerations and setting up the solver discussed earlier to converge the system during each time step (Ref. 6). Spool moments of inertia were unavailable from the steady state NPSS model, so values were assumed based on engine class as detailed in Appendix C. T-MATS contains a library of control component blocks that can be combined to build a controller for the open-loop system (Ref. 6). In this example, the input fuel flow was connected to a simple proportional-integral (PI) controller based on fan speed. A sample run of the T-MATS dynamic simulation is shown in Figure 2. At time 15s, the fan speed demand is reduced by 500 rpm. It can be observed that N1, N2, gross thrust, HPC exit temperature, and HPC exit pressure reduce as the fuel flow is reduced. Startup transients before 5 sec are due to the system converging and then reaching a steady state value, and are typical with this type of simulation. Transient data for matching were unavailable and therefore, a direct dynamic model matching was not possible. It should be noted that the control system being utilized here is for demonstration purposes only; it was designed to adjust the fuel flow based on the fan speed error and does not take into account all of the operability and safety limits required in a realistic engine control design.



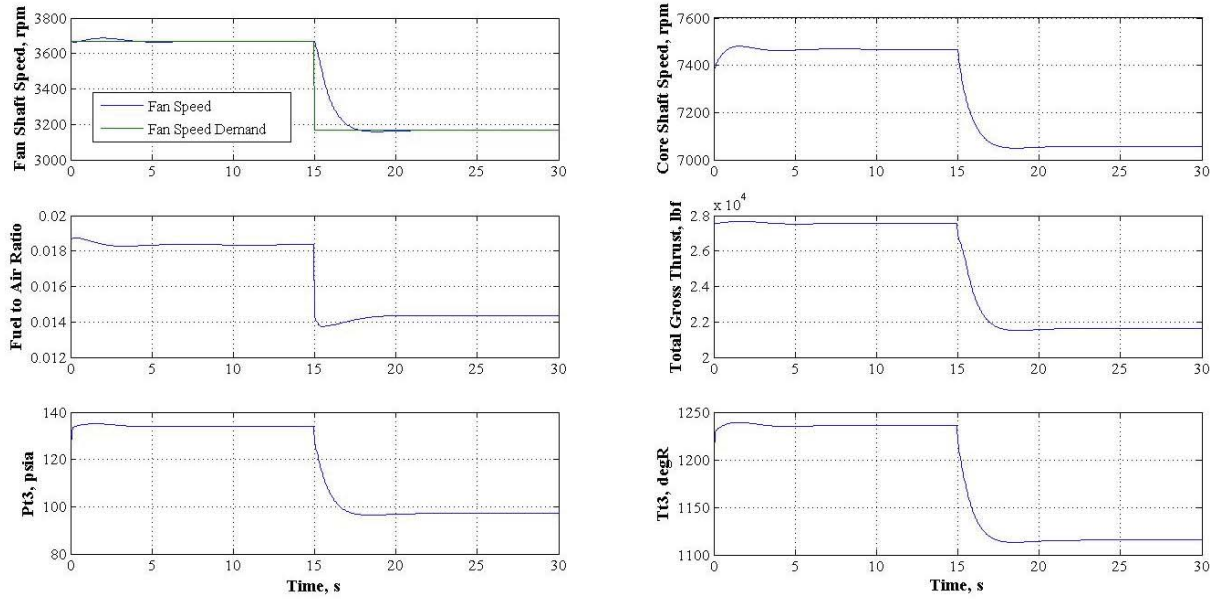


Figure 2.—JT9D dynamic simulation.

## VII. Conclusion

The T-MATS is a thermodynamic simulation system that allows developers to build custom thermodynamic system models within MATLAB/Simulink. The T-MATS Turbo-machinery modeling capability enables a user to create nonlinear steady state or dynamic gas turbine models. In creating a T-MATS simulation, the process described in this paper can be used to expedite the simulation development by leveraging NPSS data. As an example, a JT9D engine model, a publicly available dual-spool high bypass gas turbine, was created from a pre-existing steady state NPSS model. The process consisted of selecting components, determining maps and constants, and then performing component level testing. This was followed by system level testing without a solver, and finally performing system level testing with a solver. Demonstration of this process resulted in an acceptable level of matching error for all operating points tested. Once a reasonable match had been achieved, the steady state simulation was updated in a straightforward manner by inserting appropriate dynamics, as well as a simple PI fan speed controller. This approach demonstrates the capability of simulating and evaluating closed loop responses when starting with a steady state NPSS model and that the T-MATS package provides the ability to convert an industry standard NPSS simulation into the user-friendly Simulink environment for controls development.





# Appendix

## A. NPSS Data Output

\*\*\*\*\*

Date:08/27/13 Time:10:15:44 Model: Rough JT9D Turbofan Performance Model converge = 1 CASE: 0  
Version: NPSS\_2.4 Gas Package: Janaf iter/pass/JacB/Broy= 3/ 6/ 1/ 1 Run by: tlavelle

### SUMMARY OUTPUT DATA

MN alt	dTamb	W	Fn	TSFC	Wfuel	BPR	VTAS	OPR	T4	T41	T49
0.000 0.0	27.00	1539.20	50012.9	0.3597	17987.64	5.2751	0.00	20.218	2730.0	2662.0	2142.4
		core size:19.92		Q:sdfsffafd	0.00	Maximum Thrust: 0.0		% Thrust: 0.0	Power code: 0.0		

### FLOW STATION DATA

	W	Pt	Tt	ht	FAR	Wc	Ps	Ts	Aphy	MN	gamt
FS_1 Start.Fl_O	1539.20	14.696	545.67	0.30	0.0000	1578.75	14.696	545.67	-----	0.0000	1.39984
FS_2 Inlet.Fl_O	1539.20	14.578	545.67	0.30	0.0000	1591.49	12.015	516.34	5944.3	0.5329	1.39984
FS_21 Fan.Fl_O	1539.20	23.370	632.66	21.21	0.0000	1068.99	20.341	608.13	4515.2	0.4500	1.39800
FS_13 Splitter.Fl_O2	1293.91	23.370	632.66	21.21	0.0000	898.63	20.341	608.13	3795.7	0.4500	1.39800
FS_22 Splitter.Fl_O1	245.29	23.370	632.66	21.21	0.0000	170.35	20.341	608.13	719.5	0.4500	1.39800
FS_23 Duct1.Fl_O	245.29	23.312	632.66	21.21	0.0000	170.78	20.290	608.13	721.4	0.4500	1.39800
FS_24 LPC.Fl_O	245.29	52.451	821.24	66.89	0.0000	86.48	45.679	789.91	366.0	0.4500	1.39077
FS_25 Duct2.Fl_O	245.29	52.320	821.24	66.89	0.0000	86.69	45.565	789.91	366.9	0.4500	1.39077
FS_3 HPC.Fl_O	245.29	297.128	1398.32	212.41	0.0000	19.92	279.658	1376.22	119.9	0.3000	1.35605
FS_36 Bld3.Fl_O	223.21	297.128	1398.32	212.41	0.0000	18.13	279.658	1376.22	109.1	0.3000	1.35605
FS_4 Burner.Fl_O	228.21	280.786	2730.00	181.05	0.0224	27.40	279.007	2726.07	484.5	0.1000	1.28838
FS_45 HPT.Fl_O	250.28	104.217	2142.30	41.20	0.0204	71.73	98.312	2112.97	439.0	0.3000	1.30810
FS_48 Duct3.Fl_O	250.28	103.696	2142.35	41.20	0.0204	72.09	97.820	2113.02	441.2	0.3000	1.30810
FS_5 LPT.Fl_O	250.28	22.748	1529.55	-132.17	0.0204	277.66	20.978	1498.73	1470.0	0.3500	1.33466
FS_7 Duct4.Fl_O	250.28	22.521	1529.61	-132.17	0.0204	280.48	21.605	1513.77	2008.9	0.2500	1.33466
FS_9 Core_Nozz.Fl_O	250.28	22.521	1529.67	-132.17	0.0204	280.48	14.696	1372.96	855.7	0.8193	1.33465
FS_15 BypBld.Fl_O	1293.91	23.370	632.66	21.21	0.0000	898.63	20.341	608.13	3795.7	0.4500	1.39800
FS_17 Duct5.Fl_O	1293.91	23.195	632.66	21.21	0.0000	905.42	20.188	608.13	3824.4	0.4500	1.39800
FS_19 Byp_Nozz.Fl_O	1293.91	23.195	632.66	21.21	0.0000	905.42	14.696	555.46	2706.4	0.8345	1.39800

### TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Nc	TR	efPoly	pwr	SMN	SMW
Fan	1591.49	1.603	0.9038	3656.047	1.1594	0.9100	-45538.1	27.92	16.18
LPC	170.78	2.250	0.8658	3395.415	1.2981	0.8799	-15854.5	30.00	22.36
HPC	86.69	5.679	0.8625	6357.714	1.7027	0.8900	-50501.1	20.00	19.97
HPT	27.40	2.694	0.9144	153.112	1.2274	0.8987	50501.1		
LPT	72.09	4.558	0.9288	81.019	1.4009	0.9135	61391.9		

### TURBOMACHINERY MAP DATA

	WcMap	PRmap	effMap	NcMap	R/Parm	s_WcDes	s_PRdes	s_effDes	s_NcDes
Fan	3051.46	1.420	0.9337	0.927	2.0000	0.5215	1.4369	0.9679	3943.9560
LPC	183.19	1.383	0.9018	0.927	1.7688	0.9322	3.2631	0.9600	3662.7989
HPC	206.12	22.630	0.8508	1.000	2.0805	0.4206	0.2163	1.0137	6357.7140
HPT	30.15	5.000	0.9328	100.000	5.0000	1.4087	0.4236	0.9803	1.5311
LPT	149.90	6.000	0.9276	100.000	6.0000	0.7453	0.7117	1.0013	0.8102

===INLETS===	eRam	Afs	Fram										
Inlet	0.9920	-----	0.0	BLEEDS -	interstg	Wb/Win	BldWk	BldP	W	Tt	ht	Pt	
				CstmrBld	HPC.C>	0.0000	0.3500	0.1465	0.0000	1027.77	117.83	88.184	
====DUCTS====	dPnorm	MN	Aphy										
Duct1	0.0025	0.4500	719.55	C_LPTexit	HPC.C>	0.0000	0.3500	0.1465	0.0000	1027.77	117.83	88.184	
Duct2	0.0025	0.4500	366.01	C_LPTinlt	HPC.C>	0.0000	0.3500	0.1465	0.0000	1027.77	117.83	88.184	
Duct3	0.0050	0.3000	439.01	BLEEDS -	output	Wb/Win	hscale	Pscale	W	Tt	ht	Pt	
Duct4	0.0100	0.3500	1470.05	C_HPTexit	Bld3.>	0.0350	1.0000	1.0000	8.5850	1398.32	212.41	297.128	
Duct5	0.0075	0.4500	3795.70	C_HPTinlt	Bld3.>	0.0550	1.0000	1.0000	13.4908	1398.32	212.41	297.128	
				Duct5Lk	BypBl>	0.0000	1.0000	1.0000	0.0000	632.66	21.21	23.370	

==SPLITTERS==	BPR	dP/P 1	dP/P 2
Splitter	5.2751	0.0000	0.0000

===SHAFTS===	Nmech	trq in	pwr in
HP_Shaft	8000.0	33154.7	50501.1
LP_Shaft	3750.0	85983.3	61391.9



```

===BURNERS===  TtOut      eff  dPnorm  Wfuel    FAR
Burner         2729.98    0.9940  0.0550  4.99657  0.02238

```

```

===NOZZLES===   PR      Cfg    CdTh      Cv    Ath  MNth  Vact    Fg
Byp_Nozz        1.578    0.9975  1.0000  0.9975  2706.42  0.835  961.7  38674.0
Core_Nozz       1.532    0.9999  1.0000  0.9999  855.75  0.819  1457.6  11338.9

```

## B. T-MATS Formatted Maps

Fan map:

```

MWS.FAN.NcVec = [ 0.500 0.600 0.700 0.800 0.850 0.900 0.950...
                  1.000 1.050 1.100 1.150];

```

```

MWS.FAN.RlineVec = [ 1.000 1.200 1.400 1.600 1.800...
                     2.000 2.200 2.400 2.600 2.800...
                     3.000 3.200];

```

```

%===== Wc = f(NcMap, RlineMap) =====
MWS.FAN.WcArray = [ 1129.0825 1258.8474 1382.1909 1498.6384 1607.7749...
                    1709.2917 1802.8665 1888.3794 1965.6499 2034.6738...
                    2095.4690 2148.1226;
                    1396.9045 1546.6948 1685.6306 1813.0896 1928.5979...
                    2031.8818 2122.7800 2201.2161 2267.4148 2321.6023...
                    2364.1392 2395.5188;
                    1636.3572 1816.0977 1977.3179 2119.2051 2241.3333...
                    2343.6414 2426.3811 2490.0854 2535.5586 2563.8640...
                    2576.1626 2576.9243;
                    1884.0764 2099.0234 2284.7820 2440.4712 2565.9761...
                    2661.9326 2729.5161 2770.3828 2786.6572 2787.1653...
                    2787.1653 2787.1653;
                    2049.3005 2269.7354 2456.5759 2609.2085 2727.9202...
                    2813.8420 2868.7388 2894.8994 2898.0327 2898.0327...
                    2898.0327 2898.0327;
                    2288.3171 2492.5862 2662.3203 2797.5042 2898.9448...
                    2968.1807 3007.2944 3018.8535 3018.8535 3018.8535...
                    3018.8535 3018.8535;
                    2562.6401 2733.0469 2872.2166 2980.6609 3059.4998...
                    3110.3328 3135.1262 3138.4663 3138.4663 3138.4663...
                    3138.4663 3138.4663;
                    2769.6670 2909.9534 3022.0933 3106.9241 3165.6892...
                    3199.9995 3211.6814 3211.7039 3211.7039 3211.7039...
                    3211.7039 3211.7039;
                    2954.6721 3056.6882 3137.9358 3199.1514 3241.2805...
                    3265.4429 3272.8789 3272.8789 3272.8789 3272.8789...
                    3272.8789 3272.8789;
                    3130.1790 3195.2559 3246.9822 3285.8452 3312.4382...
                    3327.4097 3331.4949 3331.4949 3331.4949 3331.4949...
                    3331.4949 3331.4949;
                    3275.6797 3310.4507 3338.3101 3359.5127 3374.2856...
                    3382.9170 3385.6724 3385.6724 3385.6724 3385.6724...
                    3385.6724 3385.6724];

```

```
%===== eff = f(NcMap, RlineMap) =====
MWS.FAN.EffArray = [0.7900 0.8409 0.8835 0.9160 0.9360 0.9401...
    0.9257 0.8894 0.8233 0.7152 0.5453 0.2792
    0.7728 0.8298 0.8776 0.9141 0.9368 0.9421...
    0.9271 0.8885 0.8179 0.7026 0.5223 0.2425
    0.7237 0.7965 0.8579 0.9053 0.9352 0.9432...
    0.9256 0.8776 0.7882 0.6405 0.4067 0.0380
    0.6854 0.7705 0.8423 0.8978 0.9331 0.9431...
    0.9239 0.8702 0.7703 0.6058 0.3474 0.0000
    0.7003 0.7808 0.8483 0.9001 0.9327 0.9418...
    0.9243 0.8763 0.7882 0.6463 0.4299 0.1059
    0.7556 0.8178 0.8692 0.9080 0.9318 0.9379...
    0.9248 0.8907 0.8305 0.7378 0.6034 0.4147
    0.8143 0.8549 0.8878 0.9120 0.9262 0.9290...
    0.9201 0.8991 0.8639 0.8121 0.7405 0.6453
    0.8431 0.8697 0.8909 0.9059 0.9142 0.9150...
    0.9081 0.8936 0.8704 0.8373 0.7928 0.7353
    0.8613 0.8780 0.8909 0.8998 0.9042 0.9037...
    0.8984 0.8884 0.8731 0.8519 0.8243 0.7893
    0.8696 0.8785 0.8851 0.8892 0.8908 0.8896...
    0.8856 0.8791 0.8697 0.8573 0.8416 0.8222
    0.8644 0.8680 0.8704 0.8716 0.8714 0.8699...
    0.8670 0.8629 0.8575 0.8507 0.8424 0.8326];
```

```
%===== PR = f(NcMap, RlineMap) =====
MWS.FAN.PRArray = [ 1.1119 1.1119 1.1098 1.1058 1.0998 1.0919...
    1.0822 1.0711 1.0586 1.0446 1.0292 1.0125;
    1.1622 1.1638 1.1621 1.1570 1.1487 1.1372...
    1.1228 1.1060 1.0869 1.0655 1.0420 1.0164;
    1.2172 1.2249 1.2266 1.2221 1.2115 1.1950...
    1.1733 1.1471 1.1168 1.0825 1.0447 1.0035;
    1.2858 1.3036 1.3114 1.3090 1.2965 1.2742...
    1.2433 1.2052 1.1606 1.1099 1.0537 1.0000;
    1.3350 1.3543 1.3628 1.3603 1.3467 1.3224...
    1.2887 1.2474 1.1988 1.1438 1.0830 1.0174;
    1.4075 1.4214 1.4258 1.4204 1.4055 1.3813...
    1.3489 1.3098 1.2643 1.2131 1.1567 1.0957;
    1.4915 1.4971 1.4955 1.4869 1.4712 1.4487...
    1.4202 1.3867 1.3485 1.3058 1.2591 1.2086;
    1.5579 1.5567 1.5503 1.5386 1.5218 1.5000...
    1.4738 1.4439 1.4106 1.3739 1.3341 1.2914;
    1.6184 1.6123 1.6024 1.5888 1.5717 1.5510...
    1.5273 1.5010 1.4722 1.4410 1.4076 1.3720;
    1.6748 1.6655 1.6538 1.6399 1.6238 1.6054...
    1.5852 1.5633 1.5399 1.5150 1.4886 1.4608;
    1.7224 1.7122 1.7008 1.6882 1.6744 1.6595...
    1.6434 1.6266 1.6089 1.5904 1.5711 1.5510];
```

LPC map:

```
MWS.LPC.NcVec = [ 0.300 0.400 0.500 0.600 0.700 0.800 0.900...
    1.000 1.100 1.200 1.250];
```

```
MWS.LPC.RlineVec = [ 1.000 1.200 1.400 1.600 1.800 2.000...
    2.200 2.400 2.600 2.800 3.000 3.200];
```

```
%===== Wc = f(NcMap, RlineMap) =====
MWS.LPC.WcArray = [ 38.0744 42.9399 47.7510 52.5016 57.1863 61.7994...
66.3359 70.7905 75.1584 76.5663 76.5663 76.5663;
54.0383 60.0388 65.9233 71.6816 77.3038 82.7808...
88.1038 93.2648 98.2565 101.0545 101.0545 101.0545;
70.3200 77.5153 84.4949 91.2421 97.7419 103.9805...
109.9459 115.6273 121.0156 124.6409 124.6409 124.6409;
87.4860 95.6896 103.5393 111.0128 118.0907 124.7566...
130.9971 136.8019 142.1633 146.2312 146.2312 146.2312;
105.8588 114.8071 123.2285 131.0978 138.3948 145.1045...
151.2169 156.7268 161.6340 165.7319 165.7319 165.7319;
125.1164 134.6062 143.3572 151.3454 158.5548 164.9773...
170.6127 175.4677 179.5554 182.8951 183.0717 183.0717;
144.4910 154.5703 163.6243 171.6346 178.5959 184.5149...
189.4099 193.3090 196.2491 198.2745 198.4155 198.4155;
165.9141 176.2228 185.1849 192.7986 199.0806 204.0644...
207.7979 210.3410 211.7638 212.1506 212.1506 212.1506;
188.5677 198.3532 206.6834 213.5745 219.0613 223.1942...
226.0370 227.6647 228.1611 228.1611 228.1611 228.1611;
214.1402 222.1943 228.9021 234.2963 238.4220 241.3359...
243.1030 243.7959 243.8124 243.8124 243.8124 243.8124;
227.8569 234.5820 240.1193 244.5040 247.7802 250.0000...
251.2213 251.5216 251.5216 251.5216 251.5216 251.5216];
```

```
%===== eff = f(NcMap, RlineMap) =====
MWS.LPC.EffArray = [.7256 .7656 .7978 .8195 .8274 .8164 .7494...
.5651 .1931 .0000 .0000 .0000;
.7474 .7848 .8147 .8351 .8430 .8339 .7757...
.6161 .3003 .0000 .0000 .0000;
.7610 .7984 .8286 .8496 .8586 .8516 .7977...
.6479 .3526 .0000 .0000 .0000;
.7744 .8117 .8421 .8637 .8738 .8685 .8183...
.6765 .3970 .0000 .0000 .0000;
.7872 .8240 .8542 .8759 .8866 .8827 .8360...
.7028 .4407 .0000 .0000 .0000;
.7965 .8329 .8627 .8843 .8953 .8924 .8485...
.7222 .4748 .0391 .0000 .0000;
.7997 .8368 .8673 .8896 .9013 .8991 .8561...
.7310 .4858 .0551 .0000 .0000;
.8034 .8405 .8712 .8937 .9058 .9042 .8628...
.7420 .5068 .0979 .0000 .0000;
.8214 .8533 .8793 .8981 .9079 .9062 .8724...
.7766 .5961 .2955 .0000 .0000;
.8425 .8663 .8853 .8985 .9047 .9025 .8778...
.8117 .6929 .5052 .2255 .0000;
.8540 .8731 .8880 .8981 .9024 .9000 .8800...
.8286 .7386 .6003 .4004 .1206];
```

```
%===== PR = f(NcMap, RlineMap) =====
MWS.LPC.PRArray = [ 1.0423 1.0412 1.0393 1.0367 1.0333 1.0292 1.0234...
1.0151 1.0043 1.0000 1.0000 1.0000;
1.0760 1.0738 1.0704 1.0658 1.0600 1.0530 1.0434...
1.0297 1.0122 1.0000 1.0000 1.0000;
1.1215 1.1180 1.1127 1.1055 1.0965 1.0856 1.0707...
1.0497 1.0228 1.0000 1.0000 1.0000;
1.1789 1.1738 1.1660 1.1555 1.1423 1.1266 1.1052...
1.0753 1.0374 1.0000 1.0000 1.0000;
1.2494 1.2422 1.2312 1.2167 1.1986 1.1771 1.1481...
1.1078 1.0572 1.0000 1.0000 1.0000;
1.3353 1.3253 1.3105 1.2910 1.2669 1.2384 1.2002...
1.1476 1.0822 1.0056 1.0000 1.0000 ;
1.4411 1.4282 1.4088 1.3830 1.3512 1.3136 1.2632...
1.1942 1.1088 1.0101 1.0000 1.0000;
1.5724 1.5561 1.5313 1.4982 1.4572 1.4088 1.3440...
1.2556 1.1472 1.0233 1.0000 1.0000;
1.7323 1.7101 1.6785 1.6379 1.5888 1.5318 1.4572...
1.3572 1.2358 1.0982 1.0000 1.0000;
1.9360 1.9056 1.8662 1.8184 1.7625 1.6991 1.6190...
1.5142 1.3887 1.2471 1.0944 1.0000;
2.0507 2.0158 1.9729 1.9223 1.8645 1.8000 1.7201...
1.6176 1.4958 1.3584 1.2098 1.0546];
```

HPC map:

```
MWS.HPC.NcVec = [ 0.500 0.600 0.700 0.750 0.800 0.850 0.900 0.925 0.950 0.975...
1.000 1.025 1.050 ];
```

```
MWS.HPC.RlineVec = [ 1.000 1.200 1.400 1.600 1.800 2.000...
2.200 2.400 2.600 2.800 3.000];
```

```
%===== Wc = f(NcMap, RlineMap) =====
MWS.HPC.WcArray = [ 22.7411 24.0487 25.1548 26.0615 26.7738 27.2992...
27.6470 27.8286 27.8634 27.8634 27.8634;
31.7548 33.1181 34.2670 35.2054 35.9397 36.4783...
36.8308 37.0085 37.0362 37.0362 37.0362;
46.1066 47.4088 48.5066 49.4046 50.1096 50.6291...
50.9717 51.1469 51.1757 51.1757 51.1757;
56.7268 58.0480 59.1608 60.0704 60.7837 61.3084...
61.6527 61.8260 61.8517 61.8517 61.8517;
70.1448 71.5163 72.6688 73.6088 74.3429 74.8795...
75.2269 75.3943 75.4134 75.4134 75.4134;
89.3764 90.9746 92.3098 93.3900 94.2232 94.8199...
95.1897 95.3442 95.3504 95.3504 95.3504;
118.0620 120.1207 121.8253 123.1867 124.2166 124.9292...
125.3385 125.4609 125.4609 125.4609 125.4609;
138.5093 140.8966 142.8639 144.4238 145.5916 146.3836...
146.8174 146.9192 146.9192 146.9192 146.9192;
160.6243 162.5676 164.1805 165.4722 166.4536 167.1370...
167.5334 167.6563 167.6563 167.6563 167.6563;
181.7993 183.4993 184.9150 186.0545 186.9260 187.5389...
187.9029 188.0273 188.0271 188.0271 188.0271;
202.6315 203.5858 204.3958 205.0661 205.5998 206.0000...
206.2702 206.4145 206.4418 206.4418 206.4418;
209.9986 210.5917 211.1029 211.5321 211.8825 212.1554...
212.3516 212.4735 212.5220 212.5227 212.5227;
```

216.6847 217.0279 217.3287 217.5860 217.8015 217.9767...  
 218.1106 218.2041 218.2586 218.2739 218.2739];

```
%===== eff = f(NcMap, RlineMap) =====
MWS.HPC.EffArray = [ 0.6753 0.6913 0.7016 0.7050 0.7004 0.6864 0.6570...
  0.6044 0.5236 0.4075 0.2467;
  0.6953 0.7094 0.7184 0.7214 0.7176 0.7058 0.6812...
  0.6378 0.5717 0.4783 0.3512;
  0.7248 0.7359 0.7429 0.7452 0.7424 0.7335 0.7154...
  0.6838 0.6366 0.5713 0.4848;
  0.7427 0.7533 0.7600 0.7627 0.7606 0.7533 0.7379...
  0.7108 0.6703 0.6147 0.5414;
  0.7634 0.7736 0.7804 0.7834 0.7822 0.7762 0.7630...
  0.7394 0.7041 0.6556 0.5920;
  0.7891 0.8008 0.8090 0.8134 0.8136 0.8092 0.7974...
  0.7754 0.7417 0.6950 0.6335;
  0.8139 0.8280 0.8385 0.8449 0.8469 0.8439 0.8333...
  0.8117 0.7779 0.7303 0.6671;
  0.8206 0.8356 0.8469 0.8541 0.8567 0.8544 0.8442...
  0.8229 0.7892 0.7416 0.6783;
  0.8403 0.8512 0.8593 0.8643 0.8660 0.8641 0.8566...
  0.8415 0.8179 0.7852 0.7423;
  0.8408 0.8492 0.8552 0.8588 0.8597 0.8578 0.8516...
  0.8394 0.8209 0.7954 0.7624;
  0.8470 0.8505 0.8529 0.8539 0.8536 0.8520 0.8483...
  0.8418 0.8324 0.8200 0.8043;
  0.8350 0.8364 0.8371 0.8370 0.8362 0.8346 0.8318...
  0.8275 0.8217 0.8141 0.8049;
  0.8202 0.8203 0.8201 0.8195 0.8185 0.8171 0.8152...
  0.8124 0.8088 0.8045 0.7992];
```

```
%===== PR = f(NcMap, RlineMap) =====
MWS.HPC.PRArray = [ 2.4769 2.4288 2.3620 2.2778 2.1774 2.0627...
  1.9284 1.7711 1.5958 1.4083 1.2146;
  3.4633 3.3778 3.2643 3.1248 2.9619 2.7787...
  2.5679 2.3253 2.0595 1.7802 1.4973;
  5.0821 4.9375 4.7554 4.5391 4.2923 4.0194...
  3.7106 3.3602 2.9800 2.5826 2.1813;
  6.3490 6.1658 5.9371 5.6667 5.3594 5.0204...
  4.6377 4.2042 3.7342 3.2431 2.7467;
  8.0021 7.7686 7.4792 7.1388 6.7532 6.3287...
  5.8504 5.3097 4.7237 4.1114 3.4919;
  10.4899 10.1976 9.8249 9.3786 8.8669 8.2989...
  7.6539 6.9201 6.1229 5.2899 4.4495 ;
  14.4564 14.0970 13.6074 12.9977 12.2808 11.4715...
  10.5377 9.4621 8.2878 7.0614 5.8306;
  17.4426 17.0500 16.4870 15.7661 14.9034 13.9183...
  12.7692 11.4347 9.9718 8.4425 6.9104;
  20.7403 20.2486 19.6093 18.8329 17.9324 16.9227...
  15.7626 14.4263 12.9562 11.3983 9.8011;
  23.8298 23.2601 22.5536 21.7200 20.7705 19.7178...
  18.5212 17.1524 15.6466 14.0424 12.3810;
  26.6962 26.0933 25.4175 24.6733 23.8656 22.9999...
  22.0495 20.9930 19.8436 18.6163 17.3267;
```

```

27.6439 27.0687 26.4522 25.7969 25.1052 24.3798...
23.6033 22.7614 21.8600 20.9058 19.9057;
28.4663 27.9667 27.4460 26.9054 26.3460 25.7690...
25.1640 24.5225 23.8472 23.1399 22.4038];

```

HPT map:

```
MWS.HPT.NcVec = [ 60 70 80 90 100 110];
```

```

MWS.HPT.PRVec = [ 3.000 3.250 3.500 3.750 4.000 4.250 4.500...
4.750 5.000 5.250 5.500 5.750 6.000 6.250...
6.500 6.750 7.000 7.250 7.500 8.000];

```

%===== Wc = f(NcMap, PRMap) =====

```

MWS.HPT.WcArray = [...
30.446 30.533 30.568 30.572 30.572 30.572 30.572...
30.572 30.572 30.572 30.572 30.572 30.572 30.572...
30.572 30.572 30.572 30.572 30.572 30.572 ;
30.299 30.413 30.480 30.516 30.529 30.530 30.530...
30.530 30.530 30.530 30.530 30.530 30.530 30.530...
30.530 30.530 30.530 30.530 30.530 30.530 ;
30.120 30.239 30.317 30.368 30.398 30.415 30.421...
30.421 30.421 30.421 30.421 30.421 30.421 30.421...
30.421 30.421 30.421 30.421 30.421 30.421 ;
30.014 30.124 30.201 30.253 30.288 30.311 30.325...
30.333 30.337 30.337 30.337 30.337 30.337 30.337...
30.337 30.337 30.337 30.337 30.337 30.337 ;
29.856 29.948 30.013 30.059 30.091 30.113 30.128...
30.139 30.145 30.149 30.150 30.150 30.150 30.150...
30.150 30.150 30.150 30.150 30.150 30.150 ;
29.799 29.870 29.920 29.955 29.979 29.997 30.009...
30.017 30.023 30.026 30.028 30.029 30.029 30.029...
30.029 30.029 30.029 30.029 30.029 30.029];

```

%===== eff = f(NcMap, PRMap) =====

```

MWS.HPT.EffArray = [...
0.8460 0.8405 0.8349 0.8296 0.8249 0.8206 0.8165...
0.8127 0.8092 0.8060 0.8030 0.8002 0.7976 0.7953...
0.7931 0.7911 0.7892 0.7875 0.7858 0.7826 ;
0.8879 0.8842 0.8804 0.8769 0.8735 0.8701 0.8670...
0.8640 0.8614 0.8590 0.8568 0.8548 0.8529 0.8511...
0.8495 0.8479 0.8460 0.8436 0.8414 0.8373 ;
0.9125 0.9111 0.9096 0.9078 0.9055 0.9034 0.9014...
0.8995 0.8979 0.8964 0.8950 0.8936 0.8924 0.8903...
0.8877 0.8853 0.8830 0.8808 0.8787 0.8749 ;
0.9228 0.9242 0.9250 0.9247 0.9240 0.9232 0.9224...
0.9217 0.9210 0.9203 0.9197 0.9188 0.9162 0.9137...
0.9113 0.9091 0.9070 0.9050 0.9031 0.8980 ;
0.9215 0.9258 0.9289 0.9304 0.9313 0.9319 0.9323...
0.9326 0.9328 0.9329 0.9330 0.9311 0.9288 0.9266...
0.9245 0.9225 0.9206 0.9188 0.9161 0.9107 ;
0.9106 0.9176 0.9232 0.9267 0.9292 0.9312 0.9327...
0.9340 0.9351 0.9361 0.9369 0.9349 0.9329 0.9311...
0.9293 0.9276 0.9259 0.9239 0.9212 0.9161];

```



LPT map:

MWS.LPT.NcVec = [ 60 70 80 90 100 110 120];

MWS.LPT.PRVec = [ 3.000 3.250 3.500 3.750 4.000 4.250 4.500...  
4.750 5.000 5.250 5.500 5.750 6.000 6.250...  
6.500 6.750 7.000 7.250 7.500 8.000];

%===== Wc = f(NcMap, PRMap) =====

MWS.LPT.WcArray = [...  
153.812 153.812 153.812 153.812 153.812 153.812 153.812...  
153.812 153.812 153.812 153.812 153.812 153.812 153.812...  
153.812 153.812 153.812 153.812 153.812 153.812 ;  
153.511 153.511 153.511 153.511 153.511 153.511 153.511...  
153.511 153.511 153.511 153.511 153.511 153.511 153.511...  
153.511 153.511 153.511 153.511 153.511 153.511 ;  
152.799 152.982 153.052 153.061 153.061 153.061 153.061...  
153.061 153.061 153.061 153.061 153.061 153.061 153.061...  
153.061 153.061 153.061 153.061 153.061 153.061 ;  
150.995 151.316 151.518 151.647 151.729 151.781 151.814...  
151.834 151.846 151.852 151.856 151.858 151.859 151.859...  
151.859 151.859 151.859 151.859 151.859 151.859 ;  
148.751 149.107 149.349 149.517 149.635 149.719 149.779...  
149.822 149.852 149.872 149.885 149.894 149.898 149.899...  
149.899 149.899 149.899 149.899 149.899 149.899 ;  
145.352 145.680 145.905 146.061 146.169 146.244 146.293...  
146.324 146.339 146.344 146.344 146.344 146.344 146.344...  
146.344 146.344 146.344 146.344 146.344 146.344 ;  
140.863 141.131 141.310 141.428 141.503 141.547 141.567...  
141.569 141.569 141.569 141.569 141.569 141.569 141.569...  
141.569 141.569 141.569 141.569 141.569 141.569];

%===== eff = f(NcMap, PRMap) =====

MWS.LPT.EffArray = [...  
0.8388 0.8309 0.8234 0.8159 0.8091 0.8030 0.7975...  
0.7924 0.7876 0.7832 0.7791 0.7753 0.7717 0.7684...  
0.7652 0.7623 0.7595 0.7568 0.7542 0.7495;  
0.8878 0.8813 0.8745 0.8685 0.8629 0.8577 0.8528...  
0.8484 0.8443 0.8404 0.8368 0.8334 0.8302 0.8272...  
0.8242 0.8210 0.8179 0.8150 0.8122 0.8071;  
0.9201 0.9152 0.9105 0.9061 0.9018 0.8978 0.8940...  
0.8905 0.8872 0.8840 0.8810 0.8776 0.8741 0.8707...  
0.8676 0.8646 0.8618 0.8590 0.8565 0.8516;  
0.9381 0.9360 0.9336 0.9310 0.9283 0.9257 0.9231...  
0.9206 0.9182 0.9153 0.9119 0.9087 0.9056 0.9027...  
0.8999 0.8973 0.8948 0.8924 0.8901 0.8858;  
0.9447 0.9455 0.9456 0.9450 0.9440 0.9429 0.9417...  
0.9404 0.9383 0.9355 0.9327 0.9301 0.9276 0.9252...  
0.9229 0.9207 0.9186 0.9165 0.9146 0.9099;  
0.9415 0.9454 0.9479 0.9495 0.9504 0.9510 0.9512...  
0.9511 0.9492 0.9472 0.9452 0.9433 0.9414 0.9396...  
0.9378 0.9361 0.9344 0.9326 0.9304 0.9262;  
0.9295 0.9366 0.9419 0.9458 0.9487 0.9509 0.9526...  
0.9538 0.9528 0.9517 0.9505 0.9493 0.9481 0.9468...  
0.9456 0.9444 0.9432 0.9413 0.9395 0.9360];

## C. T-MATS Parameters

TABLE 9.—ADDITIONAL REQUIRED T-MATS CONSTANTS

T-MATS component	NPSS variable	T-MATS variable	Value	Description	Method
Inlet	eRam	eRambase_M	0.992	Base dP across inlet	Per Data
	eRam derived	X_eRamVec_M	[0.99 1 1.007 1.028 1.1 2]	Ram dP vector	Determined empirically by viewing change in pressure as Pt/Pa is changed
	eRam derived	T_eRamtbl_M	[1 1 1.001 1.002 1.003 1.003]	Ram dP pressure multiplier	Determined empirically by viewing change in pressure as Pt/Pa is changed
HPC	Bleeds - Wb/Win	C_FBD_M	[0.55 0.035]	Fractional bleed demand, for each bleed	Per Data, Bleed - output
	Bleeds - ht	C_BFht_M	[1 1]	Fractional bleed enthalpy	Calculated by assuming enthalpy rises linearly from component input to output.
	Bleeds - Pt	C_BFPt_M	[1 1]	Fraction bleed pressure	Calculated by assuming enthalpy rises linearly from component input to output.
Burner	LHV	LHV_M	18400	Lower Heating Value	Per Data, from model definition file
	dPnorm	dPnormBurner_M	0.055	dP across Burner	Per Data
	eff	Eff_M	0.944	Burner Efficiency	Per Data
HPT	C_HPT exit or inlt	CoolFlwPos_M	[0 1]	Location of input cooling flows	Per Data, HPT_in - 0 , HPT_exit - 1
Core nozzle	Ath	N_Tarea_M	862.88	Nozzle throat area	Per Data
	Cv	CvArray_M	[0.999 0.999]	Cv value	Per Data, in this instance the value is constant
Byp nozzle	Ath	N_Tarea_M	2706.4	Bypass nozzle throat area	Per Data
	Cv	CvArray_M	[0.9975 0.9975]	Cv value	Per Data, in this instance the value is constant
Duct1	dPnorm	dP_M	0.0025	dP loss across duct1	Per Data
Duct2	dPnorm	dP_M	0.0025	dP loss across duct2	Per Data
Duct3	dPnorm	dP_M	0.005	dP loss across duct3	Per Data
Duct4	dPnorm	dP_M	0.01	dP loss across duct4	Per Data
Duct5	dPnorm	dP_M	0.0075	dP loss across duct5	Per Data
HP shaft	None	Shaft_Inertia_M	20	High Pressure Shaft Inertia	Assumption based on engine class. This is a dynamic criteria and NPSS data is steady state.
LP shaft	None	Shaft_Inertia_M	100	Low Pressure Shaft Inertia	Assumption based on engine class. This is a dynamic criteria and NPSS data is steady state.

## References

1. Jones, S.M., “An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code,” NASA/TM—2007-214690, March 2007.
2. Jones, S.M., “Steady-State Modeling of Gas Turbine Engines Using The Numerical Propulsion System Simulation Code,” GT2010-22350, June 2010.
3. Nichols, L.D. and Chamis, C.C., “Numerical Propulsion System Simulation: An Interdisciplinary Approach,” AIAA-91-3554, September 1991.
4. May, R.D., Csank, J., Lavelle, T.M., Litt, J.S., and Guo T.H., “A High-Fidelity Simulation of a Generic Commercial Aircraft Engine and Controller,” NASA/TM—2010-216810, October 2010.
5. DeCastro, J.A., Litt, J.S., Frederick, D.K., “A Modular Aero-Propulsion System Simulation of a Large Commercial Aircraft Engine,” NASA/TM—2008-215303, January 2008.
6. 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.
7. 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.
8. 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.
9. Daly, M., *Jane’s Aero Engines*, Issue 28, Ed., Jane’s Information Group, London, England, September 2010.
10. 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.





