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Modeling and Simulation of a Dynamic Turbofan Engine Using MATLAB/Simulink

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MODELING AND SIMULATION OF A DYNAMIC TURBOFAN ENGINE USING MATLAB/SIMULINK

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

By

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B.S., The University of Akron, 2010

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ABSTRACT


A dynamic, high-bypass turbofan engine has been developed in the modeling and simulation environment of MATLAB/Simulink. Individual elements, including the fan, high pressure compressor, combustor, high pressure turbine, low pressure turbine, plenum volumes, and exit nozzle, have been combined to investigate the behavior of a typical turbofan engine throughout an aircraft mission. Special attention has been paid to the development of transient capabilities throughout the model, increasing model fidelity, eliminating algebraic constraints, and reducing simulation time through the use of advanced numerical solvers. This lessening of computation times is paramount for conducting future aircraft system-level design trade studies efficiently, as demonstrated in previous thermal “Tip-to-Tail” modeling of a long range strike platform. The new engine model is run for a specified mission while tracking critical parameters. These results, as well as the simulation times for both engine models, are compared to the previous “Tip-to-Tail” engine to verify accuracy and quantify computational time improvements.
The new engine model is then integrated with the full “Tip-to-Tail” aircraft model. This new model is compared to the previous “Tip-to-Tail” aircraft model to confirm accuracy and quantify computational time improvements. The new “Tip-to-Tail” aircraft model is then used for a simple design trade study of a critical component of the cooling system.
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Dedication

I owe a great deal of thanks to my family and friends for supporting me over the many years of my education. I would not have made it this far without their encouragement, guidance, and love. Special thanks to my parents for providing a solid foundation for my life as well as instilling in me the importance of hard work and education. I am particularly grateful to my fiancé for all of her love, support, and patience over the last eight years. I look forward to the next chapter of our lives together. I dedicate this to my future wife, Andrea.
CHAPTER 1 – INTRODUCTION

Project Background

Next-generation tactical aircraft are experiencing increasing amounts of thermal challenges. One major reason is that the utilization of more and more electric components on these modern aircraft results in escalated power generation demands. In fact, over the years the power system loads have grown by nearly an order of magnitude to support these new high-power components, increasing the internal heat generated by the aircraft that must be removed by the thermal management system (TMS) (1). At the same time, these thermal systems have been constrained considerably by a number of technical and operational constraints. For example, in order for the aircraft to maintain low radar observability, ram air inlet areas have been greatly reduced, limiting the effectiveness of a primary heat sink. In addition, modern aircraft are being constructed with new composite skins that reduce the amount of heat convected to the environment.

Collectively, these characteristics have augmented the challenges faced by modern TMSs. In order to assist in the mitigation of these thermal challenges, new modeling and simulation tools need to be developed. Modeling and simulation tools allow conceptual designers to conduct design trade studies, ultimately determining what system configurations yield optimized aircraft performance (2).
Traditionally, conceptual design groups have designed aircraft from a subsystem-level viewpoint. As a result, the propulsion, electrical, and thermal management subsystems are often optimized without considering the significant vehicle-level interactions between these subsystems. Consequently, final aircraft designs are not necessarily optimized at the aircraft system level. Vehicle-level analysis of subsystem interactions, however, may reveal major performance gain possibilities across the aircraft, improving the overall effectiveness of future platforms. One method for quantifying these performance gains is to develop a modeling and simulation tool that captures subsystem optimization across the entire vehicle. In addition, designing this modeling tool without aircraft-specific proprietary data will allow collaboration among design groups, improving the utility of the “Tip-to-Tail” (T2T) model.

One such T2T model was developed through the collaboration of Air Force Research Laboratory (AFRL), Wright State University, and Georgia Institute of Technology during the summer of 2010. Non-proprietary in nature, this T2T model was developed for distribution to various research facilities and conceptual design groups. It was anticipated that these groups would use the tool to optimize various subsystems of future aircraft through design trade studies. Trade studies can only be completed effectively and efficiently, however, with real time or faster computation times. While the new system-level model did provide insight into subsystem interactions, the computation times were found to be much too large. It was determined that these large computation times were the result of an overly-complex engine model. Initially developed as a steady state model, the previous engine model has gradually incorporated transient capabilities over time, leading to a complex subsystem model. Subsequently, a new engine model
with reduced complexity must be developed. This new engine model, developed exclusively in MATLAB/Simulink, will reduce complexity without sacrificing considerable accuracy. In addition, the engine will be fully dynamic from its conception, once again simplifying the model. This new engine model will then be integrated with the T2T vehicle-level model in order to complete design trade studies. From this point forward, the new engine model will be referred to as the “WSU engine model”.

Overview of Previous “Tip-to-Tail” Modeling

During the summer of 2010, a non-proprietary thermal T2T aircraft model was developed entirely in MATLAB/Simulink. The model was intended to stimulate the optimization of individual subsystems at the vehicle-level, improving overall performance and mitigating the thermal and power challenges of future aircraft platforms (2). In addition, the non-proprietary nature of the model allowed the tool to be distributed to various conceptual design groups and researchers. It was foreseen that conceptual designers would use the model to conduct design trade studies, allowing the analysis of multiple design configurations and the resulting subsystem interactions in short time periods. In order for effective trade studies to be conducted, the model needed to have relatively fast computation times. Previous work has demonstrated that while effective and accurate, the newly developed T2T model had extremely large simulation times. As a result, the tool failed to meet a major requirement for conducting valuable design trade studies.

One of the major modeling efforts within the T2T aircraft model was the development of the Integrated Power Package (IPP). The IPP is responsible for powering
a closed loop air cycle that absorbs heat from the cockpit and avionics systems. The IPP consists of a power turbine that is driven by high pressure bleed air from the engine compressor, a closed loop compressor, and a closed loop turbine. All three of these turbo-machines are located on a single shaft, resulting in a system architecture similar to that of a gas turbine engine.

In search of increased model fidelity and reduced algebraic constraints and simulation time, special attention was paid to capturing dynamic behaviors within the IPP. Two different methods were utilized to model these transients. First, conservation of mass was used in plenum volumes located before the different turbo-machinery models. The turbo-machine models contain generic performance maps that can be easily altered to match experimental data. These maps are a function of shaft speed, pressure ratio, and inlet conditions, such as temperature and molar composition of the incoming air, and output a corrected mass flow. With the incoming and outgoing mass flows of the plenum volume known, the dynamic pressure of the plenum volume can be calculated via integration of the ideal gas law, shown by Equation 1.

\[
P = \int \frac{(\dot{m}_{in} - \dot{m}_{out}) \cdot R \cdot T}{V} dt
\]

Equation 1. Dynamic Pressure

Secondly, the IPP model also considered shaft inertia since any changes in torque to the IPP shaft will vary the shaft speed. By considering the shaft inertia this variation does not occur instantaneously. This time delay was captured in the model, once again demonstrating dynamic capabilities.
The completed T2T model was run for a 7700 second mission profile of varying altitude and Mach number and is shown below in Figure 1. The profile consisted of climbs, level flight, and descents. These commanded altitudes and Mach numbers were sent to the Air Vehicle System (AVS) model which calculated the thrust necessary for matching the desired mission profile. These calculated thrusts were then sent to the engine controller which varied the fuel flow accordingly.

![Figure 1. Aircraft Mission Profile Used for T2T Simulation](image)

In an effort to locate computationally intensive subsystem models, several combinations of models were also run for this mission profile. The results of these simulation run times are shown in Figure 2. As Figure 2 illustrates, the full T2T model ran for approximately two times the length of the mission. The second trial consisted of the AVS model combined with the engine model. This arrangement ran significantly faster, near real time. The final trial used only the thermal management systems (TMSs), which included the complex IPP model. The TMS model completed the 7700 second in just 70 seconds, or approximately 110 times faster than real time.
As previously mentioned, the IPP model architecture is similar to that of a gas turbine engine. As a result, it has been determined that the development of a new engine model, using similar techniques to those used in the IPP, may be useful in reducing the simulation times of the T2T vehicle level model.
CHAPTER 2 – REVIEW OF RELATED LITERATURE

Although other engine simulation tools already exist, the goal of this project is to develop a specific engine model for integration with the AFRL T2T model. The WSU engine model is being developed to match the previous T2T engine model with reduced simulation times, but analytical techniques as well as key equations discussed in other literature are still applicable. The following section will examine the literature and discuss how the contents can be applied to the current research efforts.

At The University of Cincinnati, a thesis was submitted on modeling and simulation of a single spool jet engine describing the conversion of an existing engine model from GEXX to Simulink (3). The purpose of the conversion was to show the potential benefits of a graphical user interface (GUI) on simulation systems. The jet engine model consisted of a burner, compressor, turbine, and a plenum volume between the turbine and nozzle. The compressor had variable stators, the nozzle area was variable, and the compressor had bleed capabilities. There were four main uses for their engine model, including:

1. A nonreal-time engine model for testing engine control algorithms
2. An embedded model with a control algorithm or observer
3. A system model for evaluating engine sensor and actuator models
4. A subsystem powertrain or vehicle dynamics model
The model was developed for the high speed spool of the GE16 engine. The modeling techniques applied were chosen so that the model can be used for many different jet engines simulated through various altitudes and velocities. These characteristics will be included in the WSU engine model.

A NASA paper examined the conceptual cycle and mechanical designs of two different engine concepts (4). NASA’s Fundamental Aeronautics Research program was directed at the development of three different generations of aircraft with anticipated operation by 2015, 2020, and 2030. Each of these aircraft had specific goals in terms of fuel burn, NOx, noise, and field-length reductions. The paper of interest looked at the 2020 aircraft, which will be a hybrid wing body (HWB). For the HWB aircraft, two different types of engines were examined, including podded (N2A) and embedded (N2B), and applied to a HWB cargo freighter. The N2A engine is a typical pylon-mounted engine found on most of today’s aircraft. The N2B engine is a “futuristic” concept.

For the engine cycle design, aerodynamic design point and off-design parameters were simultaneously solved. Four N2A engines were modeled using NASA’s software tool NPSS (Numerical Propulsion System Simulation). The software was used to calculate engine thrust and specific fuel consumption. The engines were modeled with the same ADP (altitude, Mach number, and thrust). The inlet mass flow rate was found so that the desired thrust value was met at the given ADP. The extraction ratio (ratio of pressures of bypass nozzle to core nozzle) was set to 1.25 by varying the bypass ratio. Efficiencies for the fan and low pressure compressor were found by the Aerospace Systems Design Lab (ASDL) at Georgia Tech. Many key engine parameters, such as fan pressure ratios, bypass ratios, component inlet temperatures, specific fuel consumptions,
and thrust production were provided within the paper and will be used for reference during the development of the WSU engine model.

A second NASA paper has outlined the development of a turbofan engine simulation (5). A generic component level turbofan engine model was created in a graphical simulation environment. The primary goal was to develop a simulation platform to be used in the future research of propulsion system control and diagnostics. A FORTRAN based model of a military-type turbofan engine had previously been created, but because FORTRAN does not have control design analysis tools or a means of doing real-time control implementation, a new engine model was required. The new engine model was implemented using Simulink as a modular aero-propulsion system simulation (MAPSS) so that these capabilities could be leveraged.

The components modeled in MAPPS include a fan, booster, high pressure compressor, burner, high and low pressure turbines, mixer, afterburner, and nozzle. No inlet model was used since the inlet is not typically considered part of the engine. The MAPPS engine model used the bypass duct to determine the pressure, temperature, enthalpy, and flow rate up to the point where the core air and bypass air streams meet. The WSU engine model will use the same configuration and the block diagrams in Simulink were built using state space and nonlinear algebraic equations in the FORTRAN engine model.

A script was written in MATLAB to compare the MAPPS outputs with the FORTRAN model outputs. Through both open and closed loop analysis, it was shown that the new MAPPS engine model produced results within 1% of the FORTRAN engine
model (when looking at individual components). The authors did mention, however, that
the bypass model was modified in order to prevent the bypass ratio from becoming
negative. Anticipated future work will look at the development of a commercial, high
bypass turbofan engine in MAPPS.

Researchers at Cranfield University looked at a hybrid approach to simulating a
real-time transient three spool turbofan engine (6). The hybrid approach refers to the
combination of intercomponent volume and iterative techniques that were used within the
engine model. A primary benefit to using a hybrid approach is the combination of
simplicity (intercomponent volume method) with accuracy (iterative method). The model
was built in Simulink and ran in real time. The intercomponent volume method was used
to calculate pressure derivatives and pressures at engine stations. The iterative method
was used to solve algebraic thermodynamic equations for exit enthalpy, entropy, and
temperature. The WSU engine model will apply similar techniques to create dynamic
capabilities in the engine model.

The Cranfield engine model was applied to a Rolls Royce Trent 500 three-spool
turbofan engine and the results were compared to an engine model solely utilizing the
iterative method. For the hybrid approach, the intercomponent volume method was used
to calculate the mass flow rates in each volume. The iterative method was used to solve
the thermodynamic algebraic equations associated with each engine component. Using
the dynamic pressures as well as the instantaneous spool speeds, the compressor and
turbine mass flows and efficiencies are calculated using static component maps. This
technique will be applied within the WSU engine model as well.
Simulations were performed at design point for three approaches:

1. Purely iterative technique
2. Hybrid technique
3. Intercomponent volume technique (with assumption of fixed gas constants)

It was shown that the hybrid results closely follow the results of the purely iterative method. The hybrid method runs faster, has comparable accuracy, and is convenient to implement and integrate with other programs (including nonlinear aircraft simulations and real-time engine diagnostics). The purely intercomponent volume method resulted in increased errors across the high pressure stages. It was determined that the selection of component volumes and simulation step sizes requires care. Specifying larger component volumes than actual allows larger simulation step sizes but reduces the peak value of the pressure derivatives. These points will be considered in the WSU engine model.

Research conducted by the Royal Jordanian Air Force conducted modeling and simulation of a gas turbine for use in power generation (7). A primary driver behind the research was the ability to predict gas turbine engine performance at off design conditions where its performance is impacted by load and operating conditions. After discussing the modeling approach, the paper uses component matching between the compressor and turbine by superimposing the turbine’s power characteristics on the compressor’s power characteristics. The paper then discusses the gas turbine simulation program which was used to determine five main ideas:
1. Operating range and running line of the matched components
2. Proximity of the operating points to the compressor surge line
3. Proximity of the operating points at the allowable maximum turbine inlet temperature.
4. Is the gas turbine engine operating in a region of sufficient compressor and turbine efficiency?
5. How can an efficient control system for the gas turbine engine for a particular application be designed?

The components modeled within the paper included an intake, compressor, combustion chamber, turbine, and engine auxiliaries (fuel pump, lubrication pump, electrical power supply, starting gear, control system, etc.). For the compressor and turbine, several dimensionless parameters were used to determine the overall performance of each component. In addition, performance maps were utilized to determine efficiencies and mass flow rates. The maps were generally found experimentally, but they can also be found using geometric properties [(8),(9),(10)].

During the component matching of the compressor and turbine, several conditions and assumptions were made:

1. Compressor shaft speed equals the turbine shaft speed
2. The gas mass flow rate through the turbine consists of the compressor’s air mass flow rate and the fuel mass flow rate
3. Pressure loss in combustor is a small percentage of the combustion chamber inlet pressure

4. Pressure loss in compressor inlet is a small percentage of the atmospheric pressure

5. Power flows, also, in balance

In the Royal Jordanian Air Force research, bleed air was removed from the compressor in order to provide cooling for the turbine blades and bearings. It was assumed that the bleed air mass flow rate was equal to the fuel mass flow rate, resulting in a constant mass flow through the compressor and turbine. For the WSU engine model, bleed air will be removed from the compressor for turbine cooling, but the bleed air mass = fuel mass flow rate assumption will not be made because there are too many mass flow rate interactions to know with certainty that the bleed air will always match the fuel flow rate.

The computer program built by the Royal Jordanian Air Force for the simulation had several main features. Care was taken to ensure that the user was able to simulate components individually or as a complete plant. The outputs were also formatted so that the program could be linked with a steam power plant. The program was modular so that different gas turbine plant configurations could be modeled. Finally, the program was designed to be user friendly so data can be transferred easily between modules.

The WSU engine model will apply similar characteristics found in the Royal Jordanian Air Force engine model. The WSU engine model will be built so that it is easily adaptable to various aircraft or engine configurations. Test stands will also be built in order to easily create engine to engine comparisons.
CHAPTER 3 – METHODOLOGY

Turbofan Engine Overview

In order to improve the utility of the newly developed T2T model, overall computation times must be reduced. Previous research has shown that the TMSs, which include the complex Integrated Power Package (IPP), run many times faster than real time. As a result, a new engine model will be developed using similar techniques to those found within the IPP model. The development of this less complex WSU engine model is expected to reduce these large simulation times. Details outlining the development of each component within the WSU engine model are covered in the following sections.

Signal Descriptions

Several different signals are used as inputs and outputs throughout the WSU engine model. A brief description of these signals is outlined below.
Environment

The environment signal contains mission profile data. Specifically, this signal provides an altitude and Mach number at every time step through the 7700 second simulation. These values are specified using vectors and can be easily modified to create varying mission types. Both the altitude signal and Mach number signal are combined using a bus creator in Simulink to create the Environment signal, as shown in Figure 3. The altitude is specified using units of “feet” and Mach number is non-dimensional.

![Simulink Environment Signal Composition](image)

Figure 3. Simulink Environment Signal Composition.

NXT

The turbo-machine models used throughout the WSU engine are built to work with vectored flows. These vectors, referred to as NXT, contain a molar flow rate (N), a molar composition of the flow (X), and a flow temperature (T). Three different compositions are used in the WSU engine. First, an air stream is used through the fan, HP compressor, and bypass plenum volume. Table 1 illustrates the assumed air composition.
<table>
<thead>
<tr>
<th>Species Name</th>
<th>Symbol</th>
<th>Molar Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>0.00</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>0.00</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>H₂O</td>
<td>0.00</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>0.79</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 1. Molar Composition of Air Stream

In order to simplify calculations within the combustor model, an equivalent molar composition of JP-8 jet fuel, in terms of Carbon and Hydrogen, must be defined. The actual composition of JP-8 is shown in Table 2. The equivalent Carbon and Hydrogen contents are found using Equation 2 and Equation 3, respectively. With these equivalent values known, the second NXT vector molar composition can be defined, shown in Table 3 (11).

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Symbol</th>
<th>Molar Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isooctane</td>
<td>C₈H₁₈</td>
<td>0.10</td>
</tr>
<tr>
<td>Methylcyclohexane</td>
<td>C₇H₁₄</td>
<td>0.20</td>
</tr>
<tr>
<td>m-Xylene</td>
<td>C₈H₁₀</td>
<td>0.15</td>
</tr>
<tr>
<td>Tetralin</td>
<td>C₁₂H₂₆</td>
<td>0.30</td>
</tr>
<tr>
<td>Dodecane</td>
<td>C₁₀H₁₂</td>
<td>0.05</td>
</tr>
<tr>
<td>Tetradecane</td>
<td>C₁₄H₃₀</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 2. Actual Composition of JP-8 Jet Fuel
\[ Equivalent_C = .1(8) + .2(7) + .15(8) + .30(12) + .05(10) + .2(14) = 10.30 \]

**Equation 2. Equivalent Carbon Calculation for JP-8**

\[ Equivalent_H = .1(18) + .2(14) + .15(10) + .30(26) + .05(12) + .2(30) = 20.50 \]

**Equation 3. Equivalent Hydrogen Calculation for JP-8**

The third and final NXT vector used in the WSU engine model is a mixture of air and fuel. After the combustion process, the NXT vector must align with the products of combustion. As Table 4 shows, the molar fraction is unknown, since this will constantly change throughout the mission. The species that make up the mixture, however, are constant and the model can be built around them accordingly. The mixture NXT vector passes from the combustor outlet through the high pressure (HP) and low pressure (LP) turbines. Ultimately, the mixture will merge with the bypass air NXT vector in the nozzle before exiting the engine.

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Symbol</th>
<th>Molar Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP-8 Equivalent</td>
<td>C_{10.3}H_{20.5}</td>
<td>1.00</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO_{2}</td>
<td>0.00</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H_{2}</td>
<td>0.00</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>H_{2}O</td>
<td>0.00</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N_{2}</td>
<td>0.00</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O_{2}</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Table 3. Molar Composition of Fuel Stream**
## NXT_Mixture

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Symbol</th>
<th>Molar Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP-8 Equivalent</td>
<td>$C_{10.3}H_{20.5}$</td>
<td>Varies</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>Varies</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>$CO_2$</td>
<td>Varies</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>$H_2$</td>
<td>Varies</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>$H_2O$</td>
<td>Varies</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$N_2$</td>
<td>Varies</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$O_2$</td>
<td>Varies</td>
</tr>
</tbody>
</table>

Table 4. Molar Composition of Combustion Mixture

The molar flow rate can be calculated using the molar composition ($X$), the molar mass of each species, and the mass flow rate, as shown by an example in Figure 4. This $N$ signal is then combined with the $X$ and $T$ signals using the Mux block in Simulink. The resulting NXT vector creation can be seen by the Figure 5 example.
Figure 4. Simulink “N” Calculation

Figure 5. Simulink NXT Vector Mux
**RPM**

Two different shaft speeds are present in the WSU engine model. The high pressure (HP) shaft connects the HP compressor to the HP turbine. The low pressure (LP) shaft connects the fan to the LP turbine. The rotational speeds, measured as revolutions per minute (RPM), of these shafts are used in each turbo-machine model. The signal for these speeds is generically called RPM, but each input is specified as either LP or HP shaft speeds.

**Work\_kW**

This signal is used to specify work terms for the turbo-machine models.

**Load**

Input to HP and LP shaft models from work terms described above. Within the shaft model, these signals are used to calculate the shaft RPM.

**P**

This signal represents a pressure (kPa), typically from a plenum volume.

**mdot**

Mass flow rates throughout the engine are communicated using the “mdot” signals. These signals are specified in units of kg/sec. The mass flow rates entering and exiting the plenum volumes are required to calculate the dynamic pressures mentioned above. The “PV\_mdot\_in” term is a mass flow as well, but is sent directly to a plenum volume calculation.
Engine Component Model Overview

The WSU engine consists of several key component models. These models include:

1. Fan
2. High Pressure (HP) Compressor
3. Combustor
4. High Pressure (HP) Turbine
5. Low Pressure (LP) Turbine
6. Bypass Plenum Volume
7. Nozzle
8. High Pressure (HP) Shaft
9. Low Pressure (LP) Shaft

Detailed descriptions of each of these models as well as the equations used to model the appropriate physics are covered in the following sections. In addition, inputs and outputs for each model are also included.
Fan

Located at the front of the engine, the fan is responsible for drawing air into the engine. The fan is driven by the LP shaft and compresses the air entering the engine. Some of this compressed air then enters the HP compressor (core stream) where it will be compressed even further, but the majority of the fan air enters the bypass plenum volume (bypass stream). The Simulink model used to represent the fan is shown in Figure 6.

![Simulink Fan Model](image)

**Figures 6. Simulink Fan Model**

**Inputs:**
- Outlet Pressure …………………….. kPa
- LP Shaft Speed …………………….. RPM
- Environment ……………….. Altitude (feet)
  - Mach Number (non-dimensional)
- NXT_In ……………….. Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)

**Outputs:**
- NXT_Out ……………….. Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Outlet Mass Flow Rate ……………………. kg/sec
- Work ……………………………………. kW
Within the fan model, several key equations are modeled to describe the relevant physics. It is also worth mentioning that the outlet pressure term is represented by the bypass plenum volume pressure. The derivation of this value will be outlined in the bypass component section. Within the fan model, the following relationships are derived:

A. Inlet Pressure

A pressure ratio term is needed for the performance maps, but only the outlet pressure is specified as an input to the fan model. The inlet pressure is found by calculating the total pressure at the front of the aircraft. This relationship is shown by Equation 4.

\[ P_{inlet} = P_{ambient} + \frac{1}{2} \rho_{ambient} \left( Mach \sqrt{k_{ambient} R_{ambient} T_{ambient}} \right)^2 \]

Equation 4. Fan Inlet Pressure

The Environment signal, specifically the altitude term, is used to define the ambient conditions of Equation 4. The Mach number is also specified by the Environment signal. As a result, the inlet pressure is entirely dependent upon aircraft altitude and Mach number.

B. Outlet Mass Flow Rate

The fan model contains a performance map that determines a corrected mass flow for a given shaft speed and pressure ratio. The map is represented by a 2D lookup table that contains a predetermined matrix for the specific fan being used. Row and column vectors are also defined within the map, allowing interpolation within the matrix based on the input signals to the lookup table. These input signals
are normalized pressure ratio and speed, shown below by Equation 5 and Equation 6 respectively.

\[ P_{r_{\text{normalized}}} = \frac{P_{\text{out}}}{(P_{\text{in}})(P_{r_{\text{design}}})} \]

**Equation 5. Fan Normalized Pressure Ratio**

\[ N_{\text{normalized}} = \left( \frac{N}{\sqrt{T_{\text{in}}}} \right) \left( \frac{T_{\text{in}_{\text{design}}}}{N_{\text{design}}} \right) \]

**Equation 6. Fan Normalized Shaft Speed**

Using these two normalized signals, the performance map interpolates within the predefined matrix to output a normalized mass flow rate based on the corrected and design mass flow rates. This normalized mass flow rate is used to calculate an actual mass flow rate using Equation 7.

\[ \dot{m}_{\text{actual}} = \dot{m}_{\text{normalized}} \left( \frac{\dot{m}_{\text{design}} \sqrt{T_{\text{in}_{\text{design}}}}}{P_{\text{in}_{\text{design}}}} \right) \left( \frac{P_{\text{in}}}{T_{\text{in}}} \right) \]

**Equation 7. Fan Outlet Mass Flow Rate**

With the outlet mass flow rate known, the NXT_Out term can be created. The molar composition of the air remains the same as the inlet composition, but the temperature and molar flow rate terms are different. Using these signals, the NXT_Out term is created as shown by Figure 4 and Figure 5.
C. Outlet Temperature

The fan model contains a performance map that determines an efficiency for a given shaft speed and pressure ratio. Just as the mass flow rate performance map, the efficiency performance map contains a matrix defining efficiencies for predetermined shaft speeds and pressure ratios. The normalized signals for pressure ratio and shaft speed are shown by Equation 5 and Equation 6 respectively. The efficiency term yielded from the performance map is then used to calculate the outlet temperature for the fan, shown by Equation 8.

\[
T_{out} = T_{in} \left[ 1 + \frac{1}{\eta} \left( \frac{P_{in}}{P_{out}} \right)^{\frac{1}{k}} \right]
\]

Equation 8. Fan Outlet Temperature

D. Work

The work absorbed by the fan is based on the outlet mass flow rate as well as the inlet and outlet temperatures. The inlet and outlet temperatures of the model are used to calculate an enthalpy value. These inlet and outlet enthalpies are combined with the outlet mass flow rate to calculate the work for the fan model, as shown by Equation 9.

\[
Work = \dot{m}_{actual} (h_{in} - h_{out})
\]

Equation 9. Fan Work
High Pressure Compressor

Air from the fan that does not enter the bypass plenum volume is sent to the HP compressor. The HP compressor increases the core air pressure to its largest value before it enters the combustor. The HP compressor is driven by the HP shaft, which is powered by the HP turbine. The Simulink model used to represent the HP compressor is shown in Figure 7.

![Simulink High Pressure Compressor Model](image)

Figure 7. Simulink High Pressure Compressor Model

**Inputs:**
- NXT_In……………………………Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- High Pressure Shaft Speed……….RPM
- Inlet Mass Flow Rate..................kg/sec
- Outlet Pressure......................kPa
- Inlet Pressure......................kPa

**Outputs**
- NXT_Out……………………………Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Outlet Mass Flow Rate...............kg/sec
- Work....................................kW
- Bleed..................................Mass Flow Rate (kg/sec)
  - Temperature (K)
The outlet pressure is provided by the combustor and will be discussed in the combustor section. The inlet pressure is equivalent to the bypass plenum volume pressure and will be discussed in the bypass component section. Within the HP compressor model, several key equations are modeled to describe the relevant physics. The following relationships are modeled:

A. Outlet Mass Flow Rate

The HP compressor model contains a performance map that determines a corrected mass flow for a given shaft speed and pressure ratio. The map is represented by a 2D lookup table that contains a predetermined matrix for the specific HP compressor being used. Row and column vectors are also defined within the map, allowing interpolation within the matrix based on the input signals to the lookup table. These input signals are normalized pressure ratio and speed, shown below by Equation 10 and Equation 11 respectively.

\[ P_{r,\text{normalized}} = \frac{P_{\text{out}}}{(P_{\text{in}})(P_{r,\text{design}})} \]

Equation 10. High Pressure Compressor Normalized Pressure Ratio

\[ N_{\text{normalized}} = \left( \frac{N}{\sqrt{T_{\text{in}}}} \right) \left( \frac{T_{\text{in,design}}}{N_{\text{design}}} \right) \]

Equation 11. High Pressure Compressor Normalized Shaft Speed
Using these two normalized signals, the performance map interpolates within the predefined matrix to output a normalized mass flow rate based on the corrected and design mass flow rates. This normalized mass flow rate is used to calculate an actual mass flow rate using Equation 12.

$$m_{actual} = m_{normalized} \left( \frac{m_{design} T_{in\text{design}}}{P_{in\text{design}}} \right) \sqrt{\frac{P_{in}}{T_{in}}}$$

Equation 12. High Pressure Compressor Outlet Mass Flow Rate

**B. Bleed Flow**

As air exits the HP compressor, a bleed air stream is extracted to be used elsewhere in the engine and the aircraft’s TMSs. Some of the bleed air removed from the core air stream is a fixed ratio of the actual mass flow produced by the HP compressor, as shown by Equation 13. This air is used for blade cooling in the HP and LP turbines, which will be discussed in detail further in this chapter.

$$m_{bleed} = .2202(m_{actual})$$

Equation 13. High Pressure Compressor Bleed Air for Turbine Blade Cooling

In addition, bleed air is removed to power the IPP, a closed loop air cycle machine that provides cooling for the cockpit and avionics. This mass flow rate is determined by the Adaptive Power and Thermal Management System (APTMS)
controller and then relayed to the engine controller. Details of this process will be outlined later in the paper.

The engine also has the ability to monitor surging in the HP compressor. Within the HP compressor model, the surge margin is calculated at each point of the mission using Equation 14.

\[
Surge\ Margin\ (\%) = \left( \frac{\frac{P_{r\ normalized}}{m_{normalized\ Surge}} - 1}{\frac{P_{r\ normalized}}{m_{normalized\ Actual}}} \right) \times 100
\]

**Equation 14. High Pressure Compressor Surge Margin**

The engine controller contains a simple proportional-integral (PI) controller that maintains that surge margin to 12%. As the surge margin becomes smaller than 12%, the HP compressor is approaching a surge condition and the controller increases the bleed air removed from the HP compressor. By increasing the bleed air mass flow rate, the HP compressor moves away from the surge condition, thereby increasing the surge margin.

The remaining air that enters the combustor is the outlet mass flow rate signal shown in Figure 7 and is represented by Equation 15.

\[
\dot{m}_{HP\ compressor\ outlet} = (1 - .2202)(\dot{m}_{actual}) - \dot{m}_{IPP\ Bleed} - \dot{m}_{Surge\ Control}
\]

**Equation 15. High Pressure Compressor Outlet Net Mass Flow Rate**
With an outlet mass flow rate known, the NXT_Out term can be created. The molar composition of the air remains the same as the inlet air stream, but the temperature and molar flow rate terms are different. Using these signals, the NXT_Out term is created as shown by Figure 4 and Figure 5.

C. Outlet Temperature

The HP compressor model contains a performance map that determines an efficiency for a given shaft speed and pressure ratio. This efficiency performance map contains a matrix defining efficiencies for predetermined shaft speeds and pressure ratios. The normalized signals for pressure ratio and shaft speed are shown by Equation 10 and Equation 11 respectively. The efficiency term yielded from the performance map is then used to calculate the outlet temperature for the HP compressor, shown by Equation 16.

$$T_{out} = T_{in} \left[ 1 + \frac{1}{\eta} \left( \frac{P_{in}}{P_{out}} \right)^\frac{1}{k} \right]$$

Equation 16. High Pressure Compressor Outlet Temperature

D. Work

The work absorbed by the HP compressor is based on the outlet mass flow rate as well as the inlet and outlet temperatures, which are used to calculate an enthalpy value. These enthalpies are combined with the outlet mass flow rate to calculate the work for the HP compressor model, as shown by Equation 17.

$$Work = \dot{m}_{actual}(h_{in} - h_{out})$$

Equation 17. High Pressure Compressor Work
**Combustor**

The combustor model receives an air stream from the HP compressor as well as a fuel stream of JP-8. Energy balances are used to determine the temperature and composition of the outgoing air stream. This mixture is sent to the HP turbine. The Simulink model used to represent the combustor is shown in Figure 8.

![Simulink Combustor Model](image)

**Figure 8. Simulink Combustor Model**

**Inputs:**
- Outlet Pressure………………….....kPa
- NXT_In (Fuel)………………….Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- NXT_In (Air)…………………..Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)

**Outputs:**
- NXT_Out (Mixture)………………….Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Outlet Mass Flow Rate…………….kg/sec
- Inlet Pressure…………………..kPa
Within the combustor model, several key equations are modeled to describe the relevant physics. The following relationships are modeled:

A. Inlet Pressure

The previous T2T engine combustor utilized a constant pressure drop. In order to obtain similar results, the WSU engine combustor is also setup with a constant pressure drop. Using this fixed ratio, it is possible to express the inlet pressure of the combustor based on the outlet pressure, as shown by Equation 18.

\[ P_{\text{Inlet}} = \frac{258.31 \text{ kPa}}{233.4 \text{ kPa}} P_{\text{Outlet}} = 1.1067(P_{\text{Outlet}}) \]

Equation 18. Combustor Inlet Pressure

B. Outlet NXT

The major effort within the combustor model is determining the exiting molar flow rate, molar composition, and temperature. The combustor inlet has two different streams entering that must be accounted for. The first stream consists of core air that has just exited the HP compressor. The second stream is a flow of the fuel, JP-8, from the aircraft’s fuel tanks. The first computation of interest is determining the enthalpy flow of both the air and the fuel streams, as shown by Equation 19 and Equation 20 respectively. The specific heat of each species (kJ/kmole) as well as the molar flow rate of that species (kmole/s) is needed to complete the computation. The molar flow rates for the streams are known from the appropriate NXT signals, and the specific heat values are found using the respective stream temperatures.
With the inlet enthalpy flows known, the combustion process can be analyzed. A new molar composition exists after the combustion process has occurred, with the new composition being a combination of the air stream as well as the fuel stream. It is assumed that complete combustion of the JP-8 fuel occurs, yielding CO\(_2\) and H\(_2\)O as the sole products of the reaction. The general form of the JP-8 reaction can be written as Equation 21.

\[
C_{10.3}H_{20.5} + aO_2 \rightarrow b(CO_2) + c(H_2O)
\]


The coefficients “a”, “b”, and “c” must be solved for. Conservation of species dictates that the amount of a particular species on the left (reactants) must equal the amount of species on the right (products). Using this result, the coefficients can be solved for and the JP-8 combustion becomes Equation 22.
\[ C_{10.3}H_{20.5} + 15.425O_2 \rightarrow 10.3(CO_2) + 10.25(H_2O) \]

Equation 22. Solved JP-8 Combustion Equation

In conceptual terms, Equation 22 shows that for every kmole of JP-8 fuel entering the combustor, 15.425 kmoles of \( O_2 \) will be consumed, 10.3 kmoles of \( CO_2 \) will be produced, and 1.25 kmoles of \( H_2O \) will be produced.

In order to determine the products of the combustor, the results of the JP-8 combustion process must be combined with the incoming air stream. This yields the molar composition of the combusted mixture leaving the combustor and entering the HP turbine. In order to do so, a second application of the conservation of species principle is required.

Equation 22 shows that for every kmole of JP-8 burned, 10.3 kmoles of \( CO_2 \) will be produced. Combining this result with the \( CO \) and \( CO_2 \) molar flow rates entering the combustor in the air stream, the carbon conservation of species can be represented by Equation 23.

\[
10.3(kMoles \ of \ JP8)_CO_2 + a(CO_{Air\ Stream}) = b(CO_{2\ Air\ Stream})
\]

Equation 23. Combustor Product Calculation – Carbon Balance

Similarly, Equation 22 shows that for every kmole of JP-8 burned, 10.25 kmoles of \( H_2O \) will be produced. Combining this result with the \( H_2 \) and \( H_2O \) molar flow rates entering the combustor in the air stream, the hydrogen conservation of species can be represented by Equation 24.
The total number of kmoles of $O_2$ leaving the combustion chamber can be expressed by Equation 25.

$$O_{2product} = -15.425(k\text{Moles of JP8})_O_2 + a(O_2\text{Reactants})$$

Equation 25. Combustion Product Result – $O_2$

The species balance analysis also determines the molar flow rate of each of the products, which are combined to form a vector of the molar flow rates (the N portion of the NXT vector). The new molar composition of each species is calculated using Equation 26.

$$X_{\text{Species}} = \frac{N_{\text{Species}}}{\sum N_{\text{Species}}}$$

Equation 26. Molar Composition of Combustor Outlet

Expressions for the molar mass flow rate as well as the molar composition of the combusted stream are now known (the NX portion of the NXT signal). The next step is to calculate how much energy the combustion process produced. Using heat of combustion values for the relevant species, it is possible to determine the amount of energy being added to the combustion stream that enters the HP turbine (12). Heat of combustion will be generated by the JP-8, CO, CO$_2$, and H$_2$O portions of the reaction. The molar flow rates of these species are fed into a function block with the appropriate heat of
combustion values (kJ/kmole). The function block outputs an energy value (kW). The energy terms from each of the species is added together to obtain a total energy addition to the stream.

In order to calculate the temperature of the stream leaving the combustor, an energy balance is required. The inlet enthalpy flows for the air and fuel have been solved by Equation 19 and Equation 20, respectively. The outlet enthalpy flow is shown by Equation 27. The specific heat of each species (kJ/kmole) as well as the molar flow rate of that species (kmole/s) needed to complete the computation is known from the combustion analysis. The molar flow rates for the streams are known from the combustion NX signal and the specific heat values are found using the temperature of the outgoing stream. Because the temperature of the outgoing stream is not known, the analysis creates a loop between the temperature (which depends on the specific heats) and the specific heat (which depends on the temperature).

\[
h_{\text{Outlet}} = C_{p_{C_{10.3}H_{20.5}}} N_{C_{10.3}H_{20.5}} + C_{p_{CO}} N_{CO} + C_{p_{CO_2}} N_{CO_2} + C_{p_{H_2}} N_{H_2} + C_{p_{H_2O}} N_{H_2O} \\
+ C_{p_{N_2}} N_{N_2} + C_{p_{O_2}} N_{O_2}
\]

Equation 27. Combustor Outlet Enthalpy

The total specific heat of the outgoing stream is also required to determine the stream temperature. This value is based on the specific heat of the individual species as well as the molar composition of the stream, as shown by Equation 28.
\[ C_{p_{Outlet}} = C_{p_{C_{10.3}H_{20.5}}} X_{C_{10.3}H_{20.5}} + C_{p_{CO}} X_{CO} + C_{p_{CO_2}} X_{CO_2} + C_{p_{H_2}} X_{H_2} + C_{p_{H_2O}} X_{H_2O} + C_{p_{N_2}} X_{N_2} + C_{p_{O_2}} X_{O_2} \]

Equation 28. Combustor Outlet Specific Heat

The outlet temperature also depends on the molar concentration, shown by Equation 29:

\[ C = \frac{P_{Inlet}}{R T_{Outlet}} \]

Equation 29. Combustor Outlet Molar Concentration

The molar concentration is based on the pressure of the incoming stream (kPa), the temperature of the outgoing stream (K), and the gas constant (kJ/kmole*K), resulting in units of (kmole/m³).

Lastly, the temperature of the combustor outlet stream can be found using Equation 30.

\[ T_{Outlet} = \int \frac{Q_{Net}}{C_{p_{Outlet}} * V * C} dt \]

Equation 30. Combustor Outlet Temperature

where \( V \) is the combustor volume and \( Q_{net} \) is given by Equation 31.

\[ Q_{Net} = h_{Air\,Inlet} + h_{Fuel\,Inlet} - h_{Outlet} - Heat\,of\,Reaction \]

Equation 31. Combustor Energy Change

The heat of reaction is found using Equation 32.
Equation 32. Combustor Heat of Reaction

\begin{equation}
\text{Heat of Reaction} = -N_{C_{10.3}H_{20.5}} h_{fC_{10.3}H_{20.5}} - N_{CO} h_{fCO} + (10.3N_{C_{10.3}H_{20.5}} + N_{CO}) h_{fCO_2} \\
+ (10.25N_{C_{10.3}H_{20.5}} + N_{H_2}) h_{fH_2O}
\end{equation}

With the outlet temperature of the combustor now known, the final NXT vector signal leaving the combustor can be defined.

C. Outlet Mass Flow Rate

The outlet mass flow rate of the combustor is found using the NXT vector outlined above. The mass flow depends on the molar flow rate, the molar composition, and the molecular weights of the species leaving the combustor. The Simulink model used for this calculation is shown in Figure 9.

As Figure 9 shows, a dot product is used to determine the overall molecular weight of the outlet stream (kg/kmole). This molecular weight is then multiplied by the molar flow rate (kmole/s) to result in a total mass flow rate (kg/s) leaving the combustor.
Figure 9. Simulink Combustor Outlet Mass Flow Rate
High Pressure Turbine

The HP turbine receives the combustor outlet mixture. Power generated by the turbine is used to apply a torque to the HP shaft, which then drives the HP compressor. The Simulink model used to represent the HP turbine is shown in Figure 10.

![Figure 10. Simulink High Pressure Turbine Model](image)

**Inputs:**
- NXT_In……………………………Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Outlet Pressure………………………kPa
- Inlet Mass Flow Rate………………..kg/sec
- High Pressure Shaft Speed………..RPM
- Bleed………………………………Mass Flow Rate (kg/sec)
  - Temperature (K)

**Outputs:**
- NXT_Out……………………………Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Outlet Mass Flow Rate………………kg/sec
- Inlet Pressure………………………kPa
- Work………………………………kW
- Bleed………………………………Mass Flow Rate (kg/sec)
  - Temperature (K)
Within the HP turbine model, several key equations are required to describe the relevant physics. The following relationships are modeled:

**A. Outlet Mass Flow Rate**

The HP turbine model contains a performance map that determines a corrected mass flow for a given shaft speed and expansion ratio. The map is represented by a 2D lookup table that contains a predetermined matrix for the specific HP turbine being used. Row and column vectors are also defined within the map, allowing interpolation within the matrix based on the input signals to the lookup table. These input signals are the expansion ratio and a corrected speed, shown below by Equation 33 and Equation 34 respectively.

\[
Expansion\ Ratio = \frac{P_{out}}{P_{in}}
\]

*Equation 33. High Pressure Turbine Expansion Ratio*

\[
N_{corrected} = \left( \frac{N}{\sqrt{T_{in}}} \right) \left( \frac{\sqrt{T_{std}}}{N_{design}} \right) \times 100
\]

*Equation 34. High Pressure Turbine Corrected Shaft Speed*

Using these two signals, the performance map interpolates within the predefined matrix to output a corrected mass flow rate. This corrected mass flow rate is used to calculate an actual mass flow rate using Equation 35.
Equation 35. High Pressure Turbine Outlet Mass Flow Rate

\[ \dot{m}_{\text{actual}} = \dot{m}_{\text{corrected}} \frac{P_{\text{in}}}{P_{\text{std}}} \sqrt{\frac{T_{\text{std}}}{T_{\text{in}}}} \]

B. Inlet Pressure

A plenum volume located between the combustor outlet and the HP turbine inlet is modeled within the HP turbine to derive the inlet pressure. The mass flow rate entering this plenum volume is known from the combustor model. Conservation of mass dictates that the mass flow rate exiting the plenum volume must be equivalent to the outlet mass flow rate of the HP turbine, as specified by the performance map. With the incoming and outgoing mass flows of the plenum volume known, the dynamic pressure of the plenum volume can be calculated via integration of the ideal gas law, shown by Equation 36.

\[ P_{\text{inlet}} = \int \frac{(\dot{m}_{\text{in}} - \dot{m}_{\text{out}}) * R * T}{V} \, dt \]

Equation 36. High Pressure Turbine Inlet Pressure

C. Bleed Flow

As air enters the HP turbine, a bleed air stream is added to reduce the temperature of the core air. This bleed stream is fed by the bleed air removed at the HP compressor exit. Within the HP turbine model, a subsystem exists to calculate what flow rate of bleed air cools the HP turbine inlet as well as the flow rate of air that continues on to the LP turbine. The LP turbine bleed is one of the HP turbine model outputs, as shown in Figure 10. The percentage of bleed air fed
to the HP and LP turbines is a fixed value based on the original T2T engine bleed ratio. The bleed mass flow rate calculations are shown by Equation 37 and Equation 38 respectively.

\[
\dot{m}_{HPT\text{ Bleed}} = (1 - 0.1680)(\dot{m}_{HP \text{ Compressor Bleed}})
\]

Equation 37. High Pressure Turbine Bleed Mass Flow Rate

\[
\dot{m}_{LPT\text{ Bleed}} = 0.1680(\dot{m}_{HP \text{ Compressor Bleed}})
\]

Equation 38. Low Pressure Turbine Bleed Mass Flow Rate

As previously mentioned, the HP turbine bleed flow is mixed with core air from the combustor outlet before it enters the HP turbine in order to provide cooling. Two calculations are required to determine the resulting mass flow rate as well as the temperature of the newly formed mixture that enters the HP turbine. The required calculations for the mass flow rate and temperature signals entering the HP turbine are shown by Equation 39 and Equation 40 respectively.

\[
\dot{m}_{HPT\text{ Inlet}} = \dot{m}_{HPT\text{ Bleed}} + \dot{m}_{\text{Combustor Outlet}}
\]

Equation 39. High Pressure Turbine Inlet Mass Flow Rate

\[
T_{HPT\text{ Inlet}} = T_{HP \text{ Compressor Bleed}} \frac{\dot{m}_{HPT\text{ Bleed}}}{\dot{m}_{HPT\text{ Inlet}}} + T_{\text{Combustor Outlet}} \frac{\dot{m}_{\text{Combustor Outlet}}}{\dot{m}_{HPT\text{ Inlet}}}
\]

Equation 40. High Pressure Turbine Inlet Temperature
The NXT_In signal shown in Figure 10 is the NXT signal from the combustor outlet. A new NXT signal is formed within the HP turbine model using the HP turbine inlet temperature and mass flow signals calculated by Equation 39 and Equation 40. This new NXT signal is used within the HP turbine model as required.

D. Outlet Temperature

The HP turbine model contains a performance map that determine an efficiency for a given shaft speed and expansion ratio. The efficiency performance map contains a matrix defining efficiencies for predetermined shaft speeds and expansion ratios. The signals for expansion ratio and normalized shaft speed are shown by Equation 33 and Equation 34 respectively. The efficiency term is then used to calculate the outlet temperature, shown by Equation 41.

\[
T_{out} = T_{in} \left[ 1 + \eta \left( \frac{P_{in}}{P_{out}} \right)^{\frac{1}{c}} \right]
\]

Equation 41. High Pressure Turbine Outlet Temperature

E. Work

The work produced by the HP turbine is based on the outlet mass flow rate as well as the inlet and outlet temperatures, which are used to calculate an enthalpy value. These terms are combined to calculate the work, as shown by Equation 42.

\[
Work = \dot{m}_{actual} (h_{in} - h_{out})
\]

Equation 42. High Pressure Turbine Work
**Low Pressure Turbine**

After core air exits the HP turbine, it enters the LP turbine. The LP turbine produces power that drives the LP shaft, which in turn drives the fan. The Simulink model used to represent the LP Turbine is shown in Figure 11.

![Simulink Low Pressure Turbine Model](image)

**Figure 11. Simulink Low Pressure Turbine Model**

**Inputs:**
- NXT_In……………………………Molar Composition (non-dimensional)
- Molar Flow Rate (kmole/sec)
- Temperature (K)
- Inlet Mass Flow Rate………………kg/sec
- Outlet Pressure…………………..kPa
- Low Pressure Shaft Speed………RPM
- Bleed………………………………Mass Flow Rate (kg/sec)
- Temperature (K)

**Outputs:**
- Inlet Pressure……………………kPa
- NXT_Out…………………………Molar Composition (non-dimensional)
- Molar Flow Rate (kmole/sec)
- Temperature (K)
- Outlet Mass Flow Rate…………….kg/sec
- Work………………………………kW
Within the LP turbine model, several key equations are required to describe the relevant physics. The following relationships are modeled:

A. Outlet Mass Flow Rate

The LP turbine model contains a performance map that determines a corrected mass flow for a given shaft speed and expansion ratio. The map is represented by a 2D lookup table that contains a predetermined matrix for the specific LP turbine being used. Row and column vectors are also defined within the map, allowing interpolation within the matrix based on the input signals to the lookup table. These input signals are the expansion ratio and a corrected speed, shown below by Equation 43 and Equation 44 respectively.

\[
\text{Expansion Ratio} = \frac{P_{out}}{P_{in}}
\]

Equation 43. Low Pressure Turbine Expansion Ratio

\[
N_{\text{corrected}} = \left( \frac{N}{\sqrt{T_{in}}} \right) \left( \frac{\sqrt{T_{\text{std}}}}{N_{\text{design}}} \right) \times 100
\]

Equation 44. Low Pressure Turbine Corrected Shaft Speed

Using these two signals, the performance map interpolates within the predefined matrix to output a corrected mass flow rate. This corrected mass flow rate is used to calculate an actual mass flow rate using Equation 45.
\[ \dot{m}_{\text{actual}} = \dot{m}_{\text{corrected}} \frac{P_{\text{in}}}{P_{\text{std}}} \sqrt{\frac{T_{\text{std}}}{T_{\text{in}}}} \]

Equation 45. Low Pressure Turbine Outlet Mass Flow Rate

B. Inlet Pressure

A plenum volume located between the HP turbine outlet and the LP turbine inlet is modeled within the LP turbine to derive the inlet pressure. The mass flow rate entering this plenum volume is known from the HP turbine model. Conservation of mass dictates that the mass flow rate exiting the plenum volume must be equivalent to the outlet mass flow rate of the LP turbine, as specified by the performance map. With the incoming and outgoing mass flows of the plenum volume known, the dynamic pressure of the plenum volume can be calculated via integration of the ideal gas law, shown by Equation 46.

\[ P_{\text{inlet}} = \int \left( \frac{\dot{m}_{\text{in}} - \dot{m}_{\text{out}}}{V} \right) R \frac{T}{dt} \]

Equation 46. Low Pressure Turbine Inlet Pressure

C. Bleed Flow and Inlet Mass Flow Rate

As air enters the LP turbine, a bleed air stream is added to reduce the temperature of the core air. This bleed stream is fed by the bleed air removed at the HP compressor exit. Within the LP turbine model, a subsystem combines the LP turbine bleed air, derived within the HP turbine model, with the core air
entering the LP turbine from the HP turbine. The LP turbine bleed mass flow rate
calculation performed within the HP turbine model is shown by Equation 47.

\[ \dot{m}_{LPT \text{Bleed}} = 0.1680\left(\dot{m}_{\text{HP Compressor Bleed}}\right) \]

Equation 47. Low Pressure Turbine Bleed Air Mass Flow Rate

Two calculations are required to determine the resulting mass flow rate as well as
the temperature of the newly formed mixture that enters the LP turbine once the
bleed air and core air have merged. The required calculations for the mass flow
rate and temperature signals entering the LP turbine are shown by Equation 48
and Equation 49 respectively.

\[ \dot{m}_{LPT \text{Inlet}} = \dot{m}_{LPT \text{Bleed}} + \dot{m}_{\text{HPT Outlet}} \]

Equation 48. Low Pressure Turbine Inlet Mass Flow Rate

\[ T_{LPT \text{Inlet}} = T_{\text{HP Compressor Bleed}} \frac{\dot{m}_{LPT \text{Bleed}}}{\dot{m}_{LPT \text{Inlet}}} + T_{\text{HPT Outlet}} \frac{\dot{m}_{\text{HPT Outlet}}}{\dot{m}_{LPT \text{Inlet}}} \]

Equation 49. Low Pressure Turbine Inlet Temperature

It is worth noting that the NXT_In signal shown is the NXT signal from the HP
turbine outlet. A new NXT signal is formed within the LP turbine model using the
LP turbine inlet mass flow and temperature signals calculated by Equation 48 and
Equation 49 respectively. This new NXT signal is used within the LP turbine
model as required.
D. Outlet Temperature

The LP turbine model contains a performance map that determines an efficiency for a given shaft speed and expansion ratio. The efficiency performance map contains a matrix defining efficiencies for predetermined shaft speeds and expansion ratios. The signals for expansion ratio and normalized shaft speed are shown by Equation 43 and Equation 44 respectively. The efficiency term yielded from the performance map is then used to calculate the outlet temperature for the turbine model, shown by Equation 50.

\[
T_{out} = T_{in} \left[ 1 + \eta \left( \frac{P_{in}}{P_{out}} \right)^{\frac{1}{k}} \right]
\]

Equation 50. Low Pressure Turbine Outlet Temperature

E. Work

The work produced by the LP turbine is based on the outlet mass flow rate as well as the inlet and outlet temperatures, which are used to calculate an enthalpy value. These terms are combined to calculate the work, as shown by Equation 51.

\[
Work = m_{actual}(h_{in} - h_{out})
\]

Equation 51. Low Pressure Turbine Work
**Bypass Plenum Volume**

The bypass model determines how much fan mass flow enters the HP compressor. The air that bypasses the HP compressor, combustor, HP turbine, and LP turbine travels through a bypass duct and enters a mixer plenum volume at the nozzle inlet. The majority of the fan mass flow enters the bypass rather than the HP compressor. The Simulink model used to represent the bypass duct is shown in Figure 12.

![Figure 12. Simulink Bypass Plenum Volume Model](image)

**Inputs:**
- Compressor Mass Flow Rate……..kg/sec
- Fan Exit Pressure......................kPa
- Fan Mass Flow Rate.................kg/sec
- Fan_NXT_Out........................Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
- Mixer Pressure.......................kPa

**Outputs:**
- mdot_Bypass..........................kg/sec
- Bypass Volume Pressure..............kPa
- NXT_Out..............................Molar Composition (non-dimensional)
  - Molar Flow Rate (kmole/sec)
  - Temperature (K)
Within the bypass model, several key equations are required to describe the relevant physics. The following relationships are modeled:

A. **Outlet Mass Flow Rate**

The bypass flow rate is based on the bypass nozzle area, the density of the air entering the bypass, the inlet pressure of the bypass, and the exit pressure of the bypass. In general, mass flow is based on a density, a fluid velocity, and a cross sectional area the fluid is passing through, as shown by Equation 52.

\[ \dot{m} = \rho V A \]

*Equation 52. General Form of Mass Flow Rate*

A pressure differential exists due to a fluid velocity and density, as defined by Equation 53.

\[ \frac{1}{2} \rho V^2 = \Delta P = P_{inlet} - P_{outlet} \]

*Equation 53. General Pressure Differential*

Solving Equation 53 for the velocity and substituting this term into Equation 52 yields the bypass mass flow rate, as shown by Equation 54.

\[ \dot{m}_{Bypass} = A_{Bypass \ Nozzle} \sqrt{2\rho(P_{inlet} - P_{outlet})} \]

*Equation 54. Bypass Mass Flow Rate*

The inlet pressure is actually the fan outlet pressure and the outlet pressure is the nozzle inlet pressure.
B. Bypass Plenum Volume Pressure

The bypass plenum volume is modeled in a similar fashion to the other plenum volumes located between the various turbo-machine models. The bypass plenum receives air from the fan outlet and passes this bypass stream to the nozzle model. A mixer exists at the inlet of the nozzle model, as will be discussed in the next section, to mix the core air stream from the LP turbine outlet with the bypass air stream from the bypass plenum volume outlet. The mass flow rate entering the bypass is already known from Equation 54. Two different streams are exiting the bypass plenum volume. The first stream exits to the HP compressor. The second stream exits to the nozzle mixer. With the incoming and outgoing mass flows of the bypass volume known, the dynamic pressure of the plenum volume can be calculated via integration of the ideal gas law, shown by Equation 55.

\[ P_{Bypass} = \int \frac{(\dot{m}_{in} - \dot{m}_{out}) * R * T}{V} dt = \int \frac{(\dot{m}_{Fan} - \dot{m}_{Compressor} - \dot{m}_{Bypass}) * R * T}{V} dt \]

Equation 55. Bypass Plenum Volume Pressure
Nozzle

The nozzle is the final component in a turbofan engine flow path. Air from the LP turbine outlet and the bypass plenum volume are combined in the mixer volume before entering the nozzle. A converging-diverging nozzle creates the thrust needed to propel the aircraft forward. The Simulink model used to represent the bypass duct is shown in Figure 13.

![Simulink Nozzle Model](image)

Figure 13. Simulink Nozzle Model

**Inputs:**
- NXT_Core .................. Molar Composition (non-dimensional)
- Molar Flow Rate (kmole/sec)
- Temperature (K)
- Core Mass Flow Rate ............... kg/sec
- Environment .................. Altitude (feet)
- Mach Number (non-dimensional)
- Bypass Mass Flow Rate .............. kg/sec
- NXT_Bypass .................. Molar Composition (non-dimensional)
- Molar Flow Rate (kmole/sec)
- Temperature (K)
- Fan Mass Flow Rate ............... kg/sec

**Outputs:**
- Mixer Volume Pressure ............... kPa
- Thrust ................................ kN
Within the converging-diverging nozzle model, several key equations are required to describe the relevant physics. The following relationships are modeled:

A. Mixer NXT Stream

The mixer is located at the inlet of the nozzle. Two streams, one from the LP turbine outlet and one from the bypass plenum, mix before entering the converging-diverging nozzle as a single stream. In order to determine the NXT value for this new stream, several calculations need to occur. These calculations include a new molar flow rate, a new molar composition, and a new temperature. The derivation of these three terms is shown below.

The molar flow rate term for the mixer, $N_{\text{mixer}}$, is found by using the seven core and seven bypass NX terms (1 term per species), as shown by Equation 56.

$$N_{\text{Mixer}} = \sum_{i=1}^{7} \left[ (N_{\text{Core}} X_{\text{Core}_{i}}) + (N_{\text{Bypass}} X_{\text{Bypass}_{i}}) \right]$$

Equation 56. Mixer Volume Molar Flow Rate

With the molar flow rate of the mixture known, the new molar composition of the mixture is found using Equation 57.

$$X_{\text{Mixer}_{i}} = \frac{\sum_{i=1}^{7} \left[ (N_{\text{Core}} X_{\text{Core}_{i}}) + (N_{\text{Bypass}} X_{\text{Bypass}_{i}}) \right]}{(N_{\text{Core}} X_{\text{Core}_{i}}) + (N_{\text{Bypass}} X_{\text{Bypass}_{i}})}$$

Equation 57. Mixer Volume Molar Composition
The temperature of the new mixture is found by integrating the energy balance of streams entering and exiting the mixer plenum volume. First, enthalpy flows entering the mixer through the core and bypass streams are calculated. Enthalpy values for each species of the appropriate stream are added together to form a total enthalpy flow for that particular stream. The enthalpy calculations for the core and bypass streams are shown by Equation 58 and Equation 59, respectively.

\[ h_{\text{inCoreStream}} = N_{\text{Core}}T_{\text{Core}} \left[ \left( X_{\text{JP8}}C_{p_{\text{JP8}}} \right) + \left( X_{\text{CO}}C_{p_{\text{CO}}} \right) + \left( X_{\text{CO2}}C_{p_{\text{CO2}}} \right) + \left( X_{\text{H}_2}C_{p_{\text{H}_2}} \right) \\
+ \left( X_{\text{H}_2O}C_{p_{\text{H}_2O}}} \right) + \left( X_{\text{N}_2}C_{p_{\text{N}_2}}} \right) + \left( X_{\text{O}_2}C_{p_{\text{O}_2}}} \right) \right] \]

**Equation 58. Mixer Volume Inlet – Core Stream Enthalpy**

\[ h_{\text{inBypassStream}} = N_{\text{Bypass}}T_{\text{Bypass}} \left[ \left( X_{\text{CH}_4}C_{p_{\text{CH}_4}}} \right) + \left( X_{\text{CO}}C_{p_{\text{CO}}} \right) + \left( X_{\text{CO2}}C_{p_{\text{CO2}}} \right) \\
+ \left( X_{\text{H}_2}C_{p_{\text{H}_2}}} \right) + \left( X_{\text{H}_2O}C_{p_{\text{H}_2O}}} \right) + \left( X_{\text{N}_2}C_{p_{\text{N}_2}}} \right) + \left( X_{\text{O}_2}C_{p_{\text{O}_2}}} \right) \right] \]

**Equation 59. Mixer Volume Inlet – Bypass Stream Enthalpy**

An additional enthalpy calculation is performed for the mixed stream exiting the mixer volume, as shown by Equation 60.

\[ h_{\text{out}} = N_{\text{Mixture}}T_{\text{Mixture}} \left[ \left( X_{\text{JP8}}C_{p_{\text{JP8}}} \right) + \left( X_{\text{CO}}C_{p_{\text{CO}}} \right) + \left( X_{\text{CO2}}C_{p_{\text{CO2}}} \right) + \left( X_{\text{H}_2}C_{p_{\text{H}_2}}} \right) \\
+ \left( X_{\text{H}_2O}C_{p_{\text{H}_2O}}} \right) + \left( X_{\text{N}_2}C_{p_{\text{N}_2}}} \right) + \left( X_{\text{O}_2}C_{p_{\text{O}_2}}} \right) \right] \]

**Equation 60. Mixer Volume Outlet Enthalpy**
With the inlet and outlet energy streams known, a total energy is known for the mixer volume at any given time. This total energy $Q$, shown by Equation 61, will be used to determine a temperature of the mixture.

$$Q_{Net} = h_{in-core\ Stream} + h_{in-bypass\ Stream} - h_{out}$$

**Equation 61. Mixer Volume Energy**

In order to determine the temperature of the new mixture stream, a concentration, $C$, must first be found. The derivation of the concentration used in the mixer is shown below in Equation 62 through Equation 64. The concentration is defined as,

$$C = \frac{n}{V} = \frac{moles}{Volume}$$

**Equation 62. General Concentration**

Using the ideal gas law,

$$PV = nRT \rightarrow n = \frac{PV}{RT}$$

**Equation 63. Ideal Gas Law**

Substituting this value for $n$ into the definition of concentration and simplifying yields,
A temperature for the mixture is now found using Equation 65.

\[
T_{\text{Mixer}} = \int \frac{Q_{\text{Net}}}{V_{\text{Mixer}} * C_{p_{\text{Mixer}}} * C_{\text{Mixer}}} \, dt
\]

Equation 65. Mixer Volume Temperature

Values for the molar flow rate (N), molar composition (X), and temperature (T) of the new mixer stream are now combined to form a new NXT vector entering the nozzle.

**B. Mixer Plenum Volume Pressure**

The pressure within the mixer plenum volume is calculated using the same techniques applied elsewhere within the turbofan engine model. The mixer inlet mass flow rate is found by adding the core stream mass flow rate with the bypass stream mass flow rate. The nozzle model calculates a mass flow rate leaving the engine. Using conservation of mass, the flow rate exiting the nozzle must be equal to the flow rate exiting the mixer. With both inlet and outlet mass flow rates known for the mixer, integration of the ideal gas law yields the mixer plenum volume pressure, as shown by Equation 66.
C. Critical Pressure Ratio

The nozzle modeled in the turbofan engine model is of the converging-diverging type. As a result, several steps are required to determine mass flow rates, exit velocities, and thrusts of a particular nozzle. The first step is to calculate the critical pressure ratio. This term will be compared to the nozzle’s actual pressure ratio to determine whether the nozzle flow is choked or not. The critical pressure ratio is shown in Equation 67.

\[
\left( \frac{P_{\text{Outlet}}}{P_{\text{Inlet}}} \right)_{\text{Critical}} = \left( \frac{2}{k-1} \right)^{\frac{k}{k-1}}
\]

Equation 67. Nozzle Critical Pressure Ratio

The actual pressure ratio of the nozzle, \( \left( \frac{P_{\text{Outlet}}}{P_{\text{Inlet}}} \right) \), is calculated and compared to the critical pressure ratio. The two possible cases, choked flow and non-choked flow, are outlined below in Equation 68 and Equation 69 respectively.

\[
\left( \frac{P_{\text{Outlet}}}{P_{\text{Inlet}}} \right)_{\text{Critical}} > \left( \frac{P_{\text{Outlet}}}{P_{\text{Inlet}}} \right)_{\text{Actual}} = \text{Choked Flow}
\]

Equation 68. Nozzle Classification of Choked Flow
D. Nozzle Exit Mass Flow Rate and Velocity – Choked Flow Case

When the nozzle model has determined that the flow is choked, calculations for the exit mass flow rate as well as the velocity of this exit flow can be performed. The exit mass flow rate is shown by Equation 70.

\[
\dot{m}_{Exit} = \dot{m}_{Mixer} A_{Throat} \left( \frac{k}{RT_{Mixer}} \right)^{\frac{k+1}{2(k-1)}} \left( \frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}}
\]

Equation 70. Nozzle Outlet Mass Flow Rate – Choked Flow

In order to find the exit velocity, several terms must first be derived, including the exit Mach number, the exit temperature, and the speed of sound at the nozzle exit. The nozzle exit Mach number is represented by Equation 71.

\[
M_{Exit} = \sqrt{\frac{2}{k-1} \left( \frac{P_{Mixer}}{P_{Exit}} \right)^{\frac{k-1}{k}} - 1}
\]

Equation 71. Nozzle Outlet Mach Number – Choked Flow

Using the exit Mach number, the temperature of the air leaving the nozzle can be found using Equation 72.
\[
T_{\text{Exit}} = \frac{T_{\text{Mixer}}}{1 + M_{\text{Exit}}^2 \left( \frac{k-1}{2} \right)}
\]

Equation 72. Nozzle Outlet Temperature – Choked Flow

With the exit temperature known, the speed of sound at the exit is found with Equation 73.

\[
C_{\text{Exit}} = \sqrt{kRT_{\text{Exit}}}
\]

Equation 73. Nozzle Outlet Speed of Sound – Choked Flow

Finally, the velocity of air exiting the nozzle can be found using the speed of sound and Mach number results, as shown by Equation 74.

\[
V_{\text{Exit}} = M_{\text{Exit}} C_{\text{Exit}}
\]

Equation 74. Nozzle Outlet Velocity – Choked Flow

E. Nozzle Exit Mass Flow Rate and Velocity – Non-Choked Flow Case

When the nozzle model has determined that the flow is not choked, calculations for the exit mass flow rate as well as the velocity of this exit flow can be performed. The first step is to calculate the Mach number at the nozzle exit, represented by Equation 75.

\[
M_{\text{Exit}} = \sqrt{\frac{2}{k-1} \left( \frac{P_{\text{Mixer}}}{P_{\text{Exit}}} \right)^{\frac{k-1}{k}} - 1}
\]

Equation 75. Nozzle Outlet Mach Number – Non-Choked Flow
Using the exit Mach number, the temperature of the air leaving the nozzle can be found using Equation 76.

\[
T_{\text{Exit}} = \frac{T_{\text{Mixer}}}{1 + M_{\text{Exit}}^2 \left(\frac{k-1}{2}\right)}
\]

Equation 76. Nozzle Outlet Temperature – Non-Choked Flow

With the exit temperature known, the speed of sound at the exit is found with Equation 77.

\[
C_{\text{Exit}} = \sqrt{kRT_{\text{Exit}}}
\]

Equation 77. Nozzle Outlet Speed of Sound – Non-Choked Flow

The density of air exiting the nozzle is also found using the exit temperature, as shown by Equation 78.

\[
\rho_{\text{Exit}} = \frac{P_{\text{Exit}}}{RT_{\text{Exit}}}
\]

Equation 78. Nozzle Outlet Density – Non-Choked Flow

Finally, the mass flow rate exiting the nozzle is found using Equation 79.

\[
\dot{m}_{\text{Exit}} = M_{\text{Exit}}C_{\text{Exit}}\rho_{\text{Exit}}A_{\text{Exit}}
\]

Equation 79. Nozzle Outlet Mass Flow Rate – Non-Choked Flow
The exit velocity is represented by Equation 80.

\[ V_{\text{Exit}} = M_{\text{Exit}} C_{\text{Exit}} \]

Equation 80. Nozzle Outlet Velocity – Non-Choked Flow

F. Thrust

The thrust produced by the engine is based on the mass flows entering and exiting the engine, as well as the pressure difference between the nozzle and ambient air. The inlet mass flow rate, which is equivalent to the fan mass flow rate, is already known. The inlet velocity, however, must be calculated using Equation 81.

\[ V_{\text{Inlet}} = \text{Mach}_{\text{Aircraft}} \sqrt{kRT_{\text{Ambient}}} \]

Equation 81. Nozzle Inlet Velocity

Using the inlet velocity, the total engine thrust is represented by Equation 82.

\[ \text{Thrust} = (\dot{m}_{\text{Exit}} V_{\text{Exit}} - \dot{m}_{\text{Inlet}} V_{\text{Inlet}}) + A_{\text{Exit}} (P_{\text{Exit}} - P_{\text{Ambient}}) \]

Equation 82. Nozzle Thrust
**High Pressure Shaft**

The HP shaft connects the HP Turbine and the HP Compressor. Power from the HP turbine is transferred by the HP shaft to drive the HP compressor. The Simulink model used to represent the HP Shaft is shown in Figure 14.

![Figure 14. Simulink High Pressure Shaft Model](image)

**Inputs:**

- Load 1: …………………………………………………………….kW
- Load 2: …………………………………………………………….kW
- Load 3: …………………………………………………………….kW

**Outputs:**

- High Pressure Shaft Speed……………………………………..RPM

The HP turbine work signal represents a positive load and the HP compressor work signal represents a negative load. The third load signal is left blank but is ready to accept additional HP loads, such as an electrical generator or oil and fuel pumps. The HP shaft speed is the only calculation performed within the model and is given by Equation 83.

\[
RPM_{HP\, Shaft} = \frac{30 \pi}{\pi} \left[ \frac{Load_1 + \frac{RPM_{HP\, Shaft}}{N_{HP\, Design}}}{\int_{t_{HP\, Shaft}}^{} \omega_{HP\, Shaft} \, dt} \right] \frac{(Friction \ Loss)}{J_{HP\, Shaft}}
\]

**Equation 83. High Pressure Shaft Speed**
Low Pressure Shaft

The LP shaft connects the LP Turbine and the fan. Power from the LP turbine is transferred by the LP shaft to drive the fan. The Simulink model used to represent the LP Shaft is shown in Figure 15.

Figure 15. Simulink Low Pressure Shaft Model

Inputs:
- Load 1……………….. ……………………………………kW
- Load 2……………….. ……………………………………kW
- Load 3……………….. ……………………………………kW

Outputs:
- Low Pressure Shaft Speed……………………….………..RPM

The LP turbine work signal represents a positive load and the fan work signal represents a negative load. The third load signal is left blank but is ready to accept additional LP loads, such as an electrical generator or oil and fuel pumps. The LP shaft speed is the only calculation performed within the model and is represented by Equation 84.

\[
RPM_{LP Shaft} = \frac{30}{\pi} \int \frac{Load_1 + Load_2 + Load_3 + \left(\frac{RPM_{LP Shaft}}{N_{LP Design}}\right)^2}{J_{LP Shaft} * (\omega_{LP Shaft})} (Friction Loss) \ dt
\]

Equation 84. Low Pressure Shaft Speed
CHAPTER 4 – DYNAMIC COMPONENT COMPARISON RESULTS

Troubleshooting an entire engine model following development is nearly impossible due to the complex interactions between components. Consequently, comparing components on an individual basis leads to more efficient troubleshooting and verification before assembling the full engine model. In order to quantify the accuracy of the WSU engine model, each component has been compared to the respective component model from the previous T2T engine model. The results of these evaluations are shown in the following sections.

Component Baseline Results

In an effort to create a true comparison between the previous T2T engine and the WSU engine, common inputs have been used for both engine models. These inputs include aircraft altitude, Mach number, and fuel flow rate. The mission profile varies in altitude and Mach number, identical to the T2T mission profile used previously. The specified altitude and Mach number values are shown by Figure 16. To simplify the test stand, the AVS model and engine controller used in the T2T research are neglected. As a result, the required fuel flow rate for the engines is not calculated. Rather than calculate a required fuel flow, the fuel flow data from the original T2T model has been supplied through a lookup table. Figure 17 illustrates this actual fuel flow used during the T2T mission.
The previously used T2T engine is run through the same 7700 second mission profile shown by Figure 16. The fuel flow rate to the engine is defined by Figure 17. Data points are recorded for inlet and outlet conditions of each component as well as shaft speeds for both the high and low pressure spools. These results will serve as a baseline for future comparisons with the WSU engine. In addition, these results will be used as inputs for the WSU components in their respective test stands. As a result, it will be possible to show the WSU component produces similar outlet conditions for common inlet conditions. These inlet conditions will be provided in each test stand using lookup tables.

Figure 16. Engine Simulation Mission Profile
Component Comparison Results – Fan

The fan model requires inputs for outlet pressure, LP shaft RPM, and mission profile. Data from the previous T2T engine is used as inputs for the outlet pressure and LP shaft RPM. The mission profile from Figure 16 is also used. The outputs for comparison from the fan model include the outlet mass flow rate as well as the outlet temperature. The fan test stand is shown below in Figure 18.
The results of this simulation are shown in Figure 19. Both the mass flow and temperature results follow the T2T engine closely. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the mass flow rate and temperature results are 3.45% and 2.18%, respectively.

Figure 18. Simulink Test Stand - Fan

Figure 19. Comparison of Fan Outputs
Component Comparison Results – High Pressure Compressor

The HP compressor model inputs include inlet pressure, outlet pressure, inlet mass flow, inlet temperature, and HP shaft RPM. Just as the fan model, the HP compressor model outputs a mass flow and temperature. The HP compressor test stand is shown below in Figure 20.

Figure 20. Simulink Test Stand – HP Compressor

The output values are compared to the T2T results in Figure 21. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the mass flow rate and temperature results are 9.52% and 9.48%, respectively.
Component Comparison Results – Combustor

The combustor model inputs consist of an outlet pressure, a fuel mass flow rate, and an air flow rate with temperature. Each of these inputs is supplied using the T2T engine data points. The outputs of the combustor model include a temperature and mass flow rate of the outlet air, as well as an inlet pressure. The combustor test stand is shown in Figure 22. The results of the WSU combustor are shown in Figure 23. Both the mass flow rate and temperature are almost perfectly matched. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the mass flow rate and temperature results are 0.005% and 0.40%, respectively.
Component Comparison Results – High Pressure Turbine

Inputs to the HP turbine model include inlet mass flow rate and temperature, outlet pressure, and HP shaft speed. Each of these inputs is provided from the T2T engine data. Outputs of the HP turbine model consist of outlet mass flow rate, outlet temperature, and inlet pressure. The HP turbine test stand is shown in Figure 24.
The results of the outputs are shown in Figure 25. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the mass flow rate and temperature results are 3.18% and 1.74%, respectively.
Component Comparison Results – Low Pressure Turbine

Inputs to the LP turbine model include inlet mass flow rate and temperature, outlet pressure, and LP shaft speed. Once again, this data is provided from the baseline T2T engine run. Outputs of the LP turbine model consist of outlet mass flow rate, outlet temperature, and inlet pressure. The LP turbine test stand is shown in Figure 26.

Figure 26. Simulink Test Stand – LP Turbine

The results of the comparison are shown in Figure 27. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the mass flow rate and temperature results are 4.57% and 2.73%, respectively.
Component Comparison Results – Nozzle

The nozzle model inputs include the mission profile, data from the LP turbine outlet, data from the bypass outlet, and a fan mass flow rate. Each of these inputs is supplied from the T2T engine baseline simulation. The nozzle model outputs a thrust as well as an inlet pressure. The nozzle test stand is shown in Figure 28. The results of the comparison are shown by Figure 29. As the results show, the WSU nozzle inlet pressure follows the T2T results closely except for the 2000 – 3000 second range. From mission times of 2000 – 3000 seconds, Figure 16 shows the aircraft is in a level flight immediately following a large descent. During these transients, the WSU nozzle plenum volume captures the dynamics of the inlet pressure. The discrepancies between these results can be explained by the newly developed transient model capabilities. Over the 7700 data points recorded the average percent differences between the T2T and WSU
models for the nozzle inlet pressure and thrust results are 11.86% and 6.29%, respectively.

Figure 28. Simulink Test Stand – Nozzle

Figure 29. Comparison of Nozzle Outlet Conditions
Component Comparison Results – Bypass Plenum Volume

The bypass plenum volume receives air from the fan outlet. The Simulink model inputs include the HP compressor outlet mass flow, the fan outlet pressure, the fan outlet mass flow rate, the fan outlet NXT signal, and the mixer plenum volume pressure. Each of these inputs is supplied from the T2T engine baseline simulation. The bypass model outputs a mass flow rate, a plenum volume pressure, and a bypass NXT signal. The bypass volume test stand is shown in Figure 30.

![Simulink Test Stand – Bypass Plenum Volume](image)

Figure 30. Simulink Test Stand – Bypass Plenum Volume

The results of the output comparison are shown by Figure 31. Over the 7700 data points recorded, the average percent differences between the T2T and WSU models for the bypass plenum volume mass flow rate and pressure are 11.93% and 3.86%, respectively.
Figure 31. Comparison of Bypass Plenum Volume Outlet Conditions
CHAPTER 5 – FULL ENGINE COMPARISON RESULTS

The full WSU engine model is developed by combining the individual component models. The total simulation time required for the 7700 second T2T mission is of primary interest and the key gauge of accuracy for the WSU engine will be the thrust produced. Just as in the component comparisons, the previous T2T engine model is used as a benchmark to quantify both simulation time improvement as well as accuracy of the new engine. The following sections outline these results.

Test Stand Setup

Each engine model requires several inputs. In an effort to maintain a true comparison, these inputs are kept identical. Specifically, each engine requires an altitude, a Mach number, and a fuel flow rate for every time step in the simulation. The altitude and Mach number are shown below in Figure 32 and are the same values used in the component comparisons. The fuel flow rate was calculated by the AVS model during previous T2T simulations and is shown in Figure 33. Once again, these are the same values used in the individual component comparisons.

Important parameters, including temperatures, flow rates, and pressures are tracked throughout each component. Variations in temperatures, mass flow rates, and pressures throughout the engine are considered acceptable as long as the thrust produced matches the T2T engine. Differences in modeling and techniques and physical design
parameters are expected to cause differences through the engine components, but an overall thrust accuracy is desired.

![Simulation Mission Profile](image1)

**Figure 32. Simulation Mission Profile**

![Specified Fuel Flow Rate](image2)

**Figure 33. Fuel Flow Rate Input**

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**Full Engine Results**

The thrust produced by the WSU engine is the primary gauge of accuracy. The goal is for the WSU engine to be within 10% of the T2T averaged for the entire mission. The thrust comparison results are shown below in Figure 34. The average percent difference between the T2T and WSU models for the thrust results is 15.21%. Although larger than 10%, the decision was made to move forward and integrate the WSU engine with the full aircraft T2T model. Additional discussion of this decision will occur within the concluding remarks.

The simulation time required to complete the 7700 second T2T mission is of primary interest. The previous T2T engine required several hours to complete the mission. The WSU engine completes the mission in just 33 seconds (233 times faster than real time). This large reduction in simulation time should aid in reducing simulation times for the full T2T aircraft model.

![Comparison of Engine Thrusts](image-url)

*Figure 34. Thrust Comparison for Full Engine Models*
CHAPTER 6 – INTEGRATION OF WSU ENGINE AND T2T AIRCRAFT MODEL

Once the WSU engine model is verified to be acceptably accurate, a new T2T model is constructed. The purpose of the new engine model is to reduce the computation times required for a full T2T simulation. A new T2T aircraft model is created using the WSU engine. This new T2T model is run for a specified mission profile with critical parameters being tracked. These results are then compared to the original T2T version, which includes the original T2T engine simulation, to verify accuracy of the updated T2T model. Details of the T2T model, the engine integration, and the results of this comparison are discussed in the following sections. Computational times for the new T2T model are also compared to the original T2T model.

Tip-to-Tail Model Description

The full T2T model is a system-level thermal management aircraft model that has been developed in a multidisciplinary modeling and simulation environment. Individual subsystem models developed in MATLAB/Simulink have been combined to investigate the thermal management issues of a notional long range strike platform. Figure 35 shows a Simulink screenshot of this original vehicle-level T2T model. The first subsystem of interest in Figure 35 is the Aircraft Vehicle System (AVS) model, represented by the large blue block at the bottom center of the screenshot. The AVS model contains the mission profile data as well as the forces acting on the aircraft, such as weight, drag, and lift. The mission profile consists of predefined waypoints for Mach number and altitude at various mission times. The AVS model calculates a required thrust to maintain the desired mission profile and relays this thrust to the engine model.
The engine model is represented by the green block in the upper left corner of Figure 35. The aircraft in this effort utilizes four engines, each producing a maximum sea-level standard thrust of 20,000 lb., to meet the thrust demands of the mission. The engine controllers alter the fuel flow to the engine in order to produce the thrust demanded by the AVS model. The engine model also interacts with the vehicle’s TMS, which is divided into two parts: the Adaptive Power and Thermal Management System (APTMS) and the Fuel Thermal Management System (FTMS). Both the APTMS and FTMS models are represented by red blocks on the right side of Figure 35. An overview of each of these subsystems is provided below.
Adaptive Power and Thermal Management System Overview

The Adaptive Power and Thermal Management System (APTMS) contains the Integrated Power Package (IPP), an air cycle machine that cools the cockpit, air-cooled avionics, and liquid-cooled avionics. A majority of the thermal loads within the APTMS reject heat to the engine fan bypass air stream. The remaining APTMS heat loads are transferred to the FTMS and are ultimately rejected to the fuel. A schematic of the APTMS is displayed in Figure 36.

Figure 36. Schematic of Adaptive Power and Thermal Management System

The orange lines in Figure 36 represent the flow path of high pressure bleed air removed from the main engine high pressure compressor. After leaving the engine, the bleed air is cooled in the fan duct heat exchanger (HX). The air is then sent to one of two locations: The IPP or the Cockpit and Air-Cooled Avionics. There are two control valves that regulate the mass flow of air being sent to each of these two locations. The IPP speed
control valve, labeled as Point 1 in Figure 36, regulates the mass flow of high pressure bleed air from the engine compressor to the IPP combustor, and ultimately the IPP power turbine. When the control valve is fully open, all available bleed air is sent to the IPP’s combustor. The combustor burns the bleed air and JP-8 fuel to increase the enthalpy of the stream entering the IPP power turbine, resulting in a higher cooling capacity of the closed loop air cycle. As the control valve closes, overall mass flow of bleed air to the IPP combustor is reduced and the cooling capacity falls. The APTMS controller operates the IPP speed control valve such that the PAO oil temperature at the liquid-cooled avionics inlet is maintained to a set point of 60 °F. As the PAO oil temperature climbs above the set point, the controller opens the IPP speed control valve to increase the cooling capacity of the closed loop, thereby reducing the PAO oil temperature inside the liquid-cooled avionics loop.

If the IPP speed control valve has been fully opened and the PAO oil temperature at the liquid-cooled avionics inlet continues to climb above 60 °F to 65°F, a backup control valve is operated by the APTMS controller. The FTMS HX bypass control valve, labeled as Point 2 in Figure 36, regulates how much PAO oil is sent to the Air-PAO HX. As the valve closes, more of the PAO oil is sent to the HX, removing more heat from the APTMS closed loop. As the valve opens, additional PAO oil bypasses the Air-PAO HX and less heat is removed from the APTMS. If the IPP speed control valve is fully opened and the PAO oil temperature at the liquid-cooled avionics inlet continues to climb above 60 °F and reaches 65°F, the APTMS controller will begin to close the FTMS HX bypass control valve, increasing the amount of heat rejected from the APTMS to the FTMS.
which increases the cooling capacity of the closed loop, thereby reducing the PAO oil temperature inside the liquid-cooled avionics loop.

The third and final control valve within the APTMS is the APTMS cockpit control valve, labeled as Point 3 in Figure 36. This control valve regulates the amount of high pressure bleed air that flows from the main engine high pressure compressor to the cockpit and air-cooled avionics. The APTMS controller operates this valve so that the temperature of the air exiting the cockpit is maintained at 65°F. As the cockpit exit temperature increases above this set point, the APTMS controller opens the control valve, increasing the mass flow of cooling air being sent to the cockpit and air-cooled avionics, resulting in lower temperatures.

The APTMS also contains a closed air loop cycle, highlighted in blue in Figure 36, powered by the IPP. At the outlet of the IPP compressor, the closed loop air is at its highest temperature. The air then passes through a fan duct HX in the main engine where it is cooled. The air continues to the Air-PAO HX where it rejects additional heat to the FTMS. The air then expands across the IPP closed loop turbine and reaches its lowest temperature within the closed loop before absorbing heat from various heat loads within the APTMS. Heat is absorbed from the high pressure bleed air traveling to the cockpit and air-cooled avionics in two different Air-Air heat exchangers. Heat is also absorbed from the PAO oil loop cooling the liquid-cooled avionics in the PAO-Air HX. Finally, the closed loop air returns to the IPP compressor where it reaches its highest temperature and repeats the closed loop cycle.
**Fuel Thermal Management System Overview**

In addition to absorbing heat from the APTMS, the Fuel Thermal Management System (FTMS) removes heat from the engine shaft bearings, engine oil pumps, and fuel pumps. A schematic of the FTMS is displayed in Figure 37.

![Figure 37. Schematic of Fuel Thermal Management System](image)

The FTMS consists of the aircraft’s fuel tanks, several HX’s, the engine fuel pumps, and the PAO oil loop interface between the FTMS and APTMS. There are two primary fuel loops within the FTMS, as shown by Figure 37. The simplest loop removes fuel from the fuel tanks, cools the FADEC (engine controller) and the engine generator controller before returning to the fuel tanks. The second loop removes fuel from the fuel tanks and sends it to the PAO-Fuel HX. In this HX, heat from the APTMS is delivered to the FTMS via the PAO oil loop. The fuel then absorbs heat from the aircraft’s hydraulics, engine generators, and engine fuel pumps. The engine oil HX transfers heat from the engine oil to the fuel, with the primary heat source for the engine oil being the engine’s shaft bearings. At this point, a control valve determines how much of the fuel enters the engine and how much returns to the fuel tanks.
The two orange blocks in Figure 35 represent the electrical systems. The Robust Electrical Power System (REPS) and High Power Electric Actuation System (HPEAS) are solely modeled from a thermal standpoint. The only contributions from these systems are predefined heat loads, which are a function of mission time. Components of the HPEAS and REPS models include the actuators, generator, and avionics heat loads. The magenta block of Figure 35 contains all of the necessary controllers. The model includes controllers for several control valves within the APTMS and FTMS, as well as performance monitoring for TMS temperatures and set points. The final two light blue blocks in the upper left hand corner of Figure 35 represent the Environment and Analysis components of the system. The Environment block defines the atmosphere and the Analysis block enables the user to quickly plot the simulation results.

Each subsystem model is designed to interact with a generic spreadsheet that contains all of the pertinent subsystem variables. The end user is able to update physical parameters quickly and can include their own proprietary data if desired. Parameters of interest, such as temperatures, control valve positions, flow rates, and pressures, are stored as variables inside of the system controller block in Figure 35. They are then sent to the MATLAB workspace and are plotted upon the completion of each simulation. The specific parameters of interest will be discussed in detail in the results section.
Integration of Tip-to-Tail Model with New Engine Model

The engine model has several key interfaces with the full T2T aircraft model. The inputs and outputs for the engine model are shown in Figure 38.

As Figure 38 illustrates, the engine model requires five different input signals and outputs one signal. A description of these signals is outlined below.

**Environment**

The environment signal contains mission profile data. Specifically, this signal provides an altitude and Mach number at every time step through the 7700 second simulation. These values are specified using vectors and can be easily modified to create varying mission types. Both the altitude signal and Mach number signal are combined using a bus creator in Simulink to create the Environment signal, as shown in Figure 3. The altitude is specified using units of “feet” and Mach number is non-dimensional. The environment signal is used throughout the engine model to calculate air properties (temperature, pressure, density, etc.) as well as to determine air velocities entering the engine.
**Thrust Demand**

This signal represents the thrust being demanded by the engine controller. As previously mentioned, the AVS model calculates all forces on the aircraft which in turn determines a required thrust that the engine must produce to maintain the commanded mission profile. The thrust demanded signal enters the engine model and is sent out in the engine monitoring signal to the engine controller. This signal is then sent to the controller model which alters a fuel flow rate to match the demanded thrust at every point in the mission. In essence, the thrust demand signal passes through the engine model and is not used directly until it enters the engine controller.

**Engine Control**

This signal carries information from the aircraft controllers that pertains to the engine. Specifically, this signal relays the amount of bleed air being removed from the HP compressor to power the IPP. It also adds loads to the LP and HP shafts from other aircraft components such as the electrical generator. These additional loads reduced shaft speed which in turn alters the engine performance and must be accounted for. A signal also exists for surge control. This signal monitors the HP compressor performance maps to ensure the components do not operate in the surge region. If the engine is operating at a point that causes the HP compressor to surge, additional bleed air is removed from its outlet stream. The final component of the engine control signal is the fuel flow rate. The engine controller has determined the required fuel flow rate to match the demanded thrust and sends that value to the engine combustor through this signal. Within the engine model, this fuel flow rate is used to create a fuel NXT signal to be fed to the combustor model.
**FTMS Monitor**

This signal carries data from the FTMS model to the engine model. The only parameter of interest is the fuel temperature. This value is used to create the fuel NXT vector that enters the engine. The temperature of the fuel is constantly changing as heat loads from the TMSs are sent to the fuel.

**APTMS Monitor**

This signal is used with the engine model at the fan duct heat exchanger. Within the engine’s fan duct, a heat exchanger exists that provides a heat sink for the APTMS. The APTMS monitor signal is used to define the inlet conditions of APTMS air entering this heat exchanger.

**Engine Monitor**

This is the only output signal for the engine model. Within this bus, several individual signals exist to describe the engine’s overall performance.

1. **Engine Performance**

   This signal contains outlet conditions for each of the engine components, including mass flow rates, temperatures, and pressures.

2. **Fuel**

   This signal is the fuel flow rate into the engine. This is the same signal found within the “Engine Control” engine model input. Elsewhere in the T2T, the actual fuel flow is four times this signal since there are four engines for a single TMS.
3. *Fan HX Outlet*

   This signal contains the fan duct HX outlet conditions for the air returning to the APTMS model.

4. *Demanded Thrust*

   This signal is the thrust being demanded by the engine controller. As previously mentioned the thrust demanded signal enters the engine model and is sent out to the engine controller which alters a fuel flow rate to match the demanded thrust at every point in the mission.

**Unit Conversions**

The new engine model has been built using SI units. The majority of the T2T model, however, utilizes English units. As a result, special care is needed to ensure proper signal conversions. All signals entering the engine model are first sent to a unit conversion block. Within this model, all signals are converted to SI units. These signals then enter the actual engine model for simulation. Before the engine monitoring signal leaves the engine model, all signals are converted back to English units. This allows a much simpler integration within the full aircraft T2T.

**Updated Tip-to-Tail Model Comparison**

Once the new engine model is integrated into the full aircraft T2T model, a comparison must be completed to ensure the new T2T version is accurate. AFRL has requested that the following parameters be compared to verify accuracy:

1. Temperature of fuel entering engine
2. Mass of fuel in the fuel tanks

3. Temperature of fuel in the fuel tanks

The accuracy criterion for each of these three parameters is 10%. The average error between the T2T engine model full aircraft and the WSU engine model full aircraft for each of these parameters must be less than 10% for the full mission profile.

Two different simulations are completed in order to obtain the desired parameters for comparison. First, the full T2T model containing the original T2T engine is run for the same mission profile shown by Figure 32. Results for the three parameters of interest mentioned above are saved. Secondly, the full T2T model containing the WSU engine is run for the same mission with the same three parameters being tracked.

Plots illustrating the results of both simulations are shown below. The fuel temperature entering the engine, total mass of fuel in the fuel tanks, and the temperature of the fuel in the fuel tanks results are shown by Figure 39 through Figure 41 respectively.

![Engine Fuel Temperature](Figure 39. Comparison of Full T2T Models – Fuel Temperature Entering Engine)
Figure 40. Comparison of Full T2T Models – Mass of Fuel Remaining in Fuel Tanks

Figure 41. Comparison of Full T2T Models – Temp. of Fuel Remaining in Fuel Tanks
Using these results, percent differences between the original T2T engine results and the WSU engine results are calculated to quantify the comparison. The results obtained for the parameters of interest are shown below in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. % Error</th>
<th>Max. % Error</th>
<th>Avg. % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Fuel Temp. (°R)</td>
<td>2.8715e-006</td>
<td>5.6786</td>
<td>0.7602</td>
</tr>
<tr>
<td>Fuel Tank Mass (lbm)</td>
<td>2.1719e-006</td>
<td>34.2417</td>
<td>7.4072</td>
</tr>
<tr>
<td>Fuel Tank Temp. (°R)</td>
<td>1.2938e-005</td>
<td>0.3791</td>
<td>0.1955</td>
</tr>
</tbody>
</table>

Table 5. Results of Full Aircraft T2T Comparison

As the results in Table 5 show, the T2T model containing the WSU engine model performs exceptionally well. The largest error occurs in the fuel tank mass calculation. As Figure 40 shows, the WSU engine consumes significantly less fuel at the later stages of the mission. As a result, the error greatly increases at the end of the mission causing the average error to increase. Even still, the WSU model is within the desired 10% average error of accuracy, verifying that the WSU engine performs acceptably within the full aircraft T2T model.

The total simulation time required to complete the 7700 second mission is especially important. In fact, the sole motivation for this research is to develop an engine model that will allow faster design trade studies using the T2T tool. Unless the new T2T model runs significantly faster, the goal of the research has not been met. The simulation times for both T2T models are shown in Table 6.
### Table 6. Simulation Time Comparison for Original and WSU Engine Models

<table>
<thead>
<tr>
<th>Engine Used in T2T Model</th>
<th>Total Simulation Time (for 7700 second mission)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original T2T Engine</td>
<td>72,650 seconds</td>
</tr>
<tr>
<td>WSU Engine</td>
<td>375 seconds</td>
</tr>
</tbody>
</table>

As Table 6 shows, the WSU engine model greatly reduces the simulation time required to complete the 7700 second mission. In fact, the T2T model containing the WSU engine allows a 99.48% time reduction from the original version. As previously mentioned, both simulations have been completed on the same computer, eliminating any advantages due to computing power differences. These results demonstrate that the WSU engine model is highly effective in reducing the total simulation times required for the full aircraft T2T model, making the tool much more efficient for conducting design trade studies.
CHAPTER 7 – DESIGN TRADE STUDY

The T2T model has been developed to study the interactions between the propulsion, electrical, and thermal management subsystems in a typical aircraft. Currently, such vehicle-level interactions are not considered, leading to aircraft designs that are not truly optimized. Analysis of these subsystem interactions, however, may reveal major performance gain possibilities across the aircraft, improving the overall effectiveness of future platforms. The T2T model has been built as a modeling and simulation tool that can be used for quantifying these performance gains.

Now that the WSU engine has been integrated with the full T2T model, simulation times for running the model have been significantly reduced. As a result, the overall utility of the T2T tool has been increased dramatically. It is now possible for design groups to efficiently study how a design change in a particular subsystem affects the entire aircraft’s performance. In this section, a simple design trade study will be conducted to demonstrate the usefulness of this modeling and simulation tool. It is important to note that the purpose of this trade study is to demonstrate the capabilities of the T2T modeling tool. The main goal is to create an “apples-to-apples” comparison between different architectures and highlight the discovered subsystem interactions. As the results will show, the performance of the thermal management systems falls below desired levels. While future work will need to address these issues, for the purposes of this paper, proficient capturing of subsystem limitations and interactions is sufficient.
Integrated Power Package Design Trade Study – Electric Motor vs. Air Turbine

As previously discussed, the Integrated Power Package (IPP) is the part of the APTMS responsible for powering a closed loop air cycle that absorbs heat from the cockpit and avionics systems. The IPP consists of a power turbine that is driven by high pressure bleed air from the engine compressor, a closed loop compressor, and a closed loop turbine. All three of these turbo-machines are located on a single shaft. Preceding research utilizing the original full aircraft T2T model demonstrated that during low thrust mission segments, temperature limits within the aircraft systems are exceeded due to insufficient mass flow to the IPP power turbine. Under low thrust demands, the controller reduces the mass flow rate of fuel to the engine. This causes a reduction in the total mass flow rate of air through the engine. With less air passing through the engine, less HP compressor bleed air is available to power the IPP. This insufficient bleed air results in an IPP RPM lower than what the controller demands, causing temperatures to exceed limits.

One possible solution to this problem is utilizing an electrically driven IPP. Using a motor on the IPP shaft instead of a power turbine would eliminate the need for bleed air from the HP compressor and should prevent temperature limit violations at all points in a mission, even in low thrust demand scenarios. In addition, a fixed speed electric IPP will be examined. This trade study will determine how all aircraft systems are affected, if at all, by these new IPP configurations.

Bleed Air Power Turbine with Combustor – System Description

As previously discussed, the current IPP configuration requires HP compressor bleed air to drive the IPP power turbine which in turn drives the closed loop air cycle.
The flow diagram of this APTMS version is shown in Figure 42. The orange lines represent the flow of HP bleed air after leaving the main engine compressor. The blue line represents the closed loop air cycle being powered by the IPP. Blue points 1 and 2 are the only two locations where heat is rejected from the closed loop. Red points 1, 2, and 3 are locations where heat is added to the closed loop from the IPP heat loads (cockpit, liquid-cooled avionics, and air-cooled avionics). The green lines represent the flow of PAO oil used for cooling the liquid cooled avionics as well as transferring heat from the APTMS to the fuel in the FTMS.

The IPP speed control valve, located between the IPP power turbine and the main engine compressor, regulates the mass flow of high pressure bleed air from the main engine compressor to the IPP. When the control valve is fully open, all available bleed air is sent to the IPP’s power turbine and the cooling capacity of the closed loop air cycle is maximized. As the control valve closes, overall mass flow of bleed air to the IPP’s power turbine is reduced and the cooling capacity falls. The IPP speed control valve is operated to maintain a PAO oil temperature of 60°F in the liquid cooled avionics loop. A PI controller measures the actual temperature of oil entering the liquid cooled avionics, compares this value to the set point value of 60°F, and then operates the IPP speed control valve accordingly until the difference between the actual and set point temperatures is zero.

After the IPP speed control valve, the air enters a combustor before reaching the IPP power turbine. This combustor uses fuel from the main fuel tanks that is removed before reaching the engine. This combustor results in higher temperature flow entering the IPP power turbine for increased IPP performance, but it also increases the total fuel
consumption of the aircraft. One key component of the trade study will be comparing the fuel consumption for this bleed air version with an electric IPP, which uses no fuel for the IPP.

![Electric Motor – System Description](image)

Using an electric motor on the IPP shaft eliminates the need for a power turbine. All related signals and calculations involved with the IPP power turbine are removed. The flow diagram of this APTMS version is shown in Figure 43. A new controller is added within the APTMS to control how much power is delivered to the IPP motor. A controller already exists within the APTMS to determine what IPP shaft RPM is required to maintain sufficient cooling of the cockpit and avionics. The IPP motor controller
simply measures the difference between the actual IPP shaft RPM and the desired RPM and then modifies the flow of electric power to the IPP motor accordingly.

Figure 43. APTMS Flow Diagram – Electric Motor Configuration

The current version of the T2T aircraft model has limited electrical modeling. Future work will include higher fidelity modeling of the Robust Electrical Power System (REPS) and High Power Electric Actuation System (HPEAS), the two electrical systems included within the T2T model, but the current modeling has no electrical loads. The avionics and the actuators provide a heat load at various points in the mission that must be controlled by the TMS models, but no electrical loads exist. In addition, a Directed Energy Weapon (DEW) is included on the aircraft, requiring extremely large electrical
loads for short step changes during the mission. The first step is to include some electrical modeling so that the power available for the IPP electrical motor is known.

The actuators and avionics are assumed to be 25% efficient, with 75% of their electrical load being sent to the TMS as heat. The DEW is assumed to be 20% efficient, with 80% of its electrical load being sent to the TMS as heat. As a result, the already known heat loads for these components can be used to calculate the electrical loads throughout the mission, as shown by Equation 85.

$$P_{\text{Component}} = \frac{1}{1 - \eta} Q_{\text{Component}}$$

Equation 85. Actuator and Avionics Electrical Power

The total available electrical power in the aircraft will be provided by the engine generators. As previously mentioned, the current T2T requires four engines for a single aircraft. As a result, the total available power is defined as:

$$P_{\text{Generation Total}} = 4 * P_{\text{Engine Generator}}$$

Equation 86. Total Electrical Power Generation of Aircraft

The priority of available electrical power goes to the avionics, actuators, and DEW. The power available to the IPP electric motor is found as:

$$P_{\text{Available for IPP}} = P_{\text{Generation Total}} - P_{\text{Avionics}} - P_{\text{Actuators}} - P_{\text{DEW}}$$

Equation 87. Available Electrical Power for IPP Electric Motor
The IPP electric motor controller demands a power based on the difference between the commanded IPP shaft speed and the actual IPP shaft speed. A dynamic saturation is used in Simulink after the controller to ensure that the maximum power to the IPP electric motor doesn’t exceed the available power defined in Equation 87. The output of this dynamic saturation is the actual power being sent to the IPP motor. The IPP motor is assumed to have an efficiency of 95%, so only 95% of the power sent to the IPP motor does useful work on the IPP shaft.

The engine generators are not perfectly efficient and result in a heat load being produced. These components are assumed to be 95% efficient, with 5% of the power produced being released as heat. Once again, this is a heat load that must be absorbed by the TMS systems. The total heat load produced by the four engine generators is:

\[ Q_{Generators} = 0.05 \times (P_{IPP\ Motor} + P_{Avionics} + P_{Actuators} + P_{DEW}) \]

*Equation 88. Generator Heat Load*

The engine generators also place a mechanical load on the main engine LP shaft. A mechanical efficiency of 95% is assumed for the generator, so the mechanical load placed by each generator on its respective engine LP shaft is:

\[ P_{Mechanical} = -\frac{1}{0.95} \left[ \frac{1}{4} (P_{IPP\ Motor} + P_{Avionics} + P_{Actuators} + P_{DEW}) \right] \]

*Equation 89. Generator Mechanical Load per Engine*
Simulation Comparisons – Points of Interest

In order to complete the proposed design trade study, three cases will be examined. The first case consists of the original APTMS architecture, where the IPP shaft is driven by a power turbine that runs off of combusted bleed air from the main engine compressor. The second case will use a variable speed electric motor to drive the IPP shaft. The third and final case will once again use an electric motor to drive the IPP shaft, but this time the shaft speed will be fixed. The IPP design speed of 60,000 RPM has been selected as the fixed speed to be analyzed.

For all three cases, the same T2T mission profile used in the previous sections is employed. One of the primary points of interest in these comparisons will be the total fuel consumption for the mission. In addition, because the IPP is responsible for the cooling within the APTMS, temperatures in this system will be monitored to determine what effect each architecture has on the aircrafts ability to regulate temperatures in the liquid cooled avionics, air cooled avionics, and cockpit.

It is anticipated that the all electric version IPP architectures will require larger generators. The total weight of the aircraft will be updated to account for the larger generators, electric motor, and removal of the power turbine. The different aircraft weight is likely to alter the required thrust for the engines, so these values will be tracked as well.
Case 1: Bleed Air Power Turbine with Combustor – Simulation Results

The first case simulated consists of the full T2T aircraft model with the IPP being driven by the bleed air power turbine. The architecture for this case was illustrated by Figure 42. Some of the critical parameters for this case are outlined below in Table 7.

<table>
<thead>
<tr>
<th>Number of Engines per Aircraft</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Generators per Aircraft</td>
<td>4</td>
</tr>
<tr>
<td>Individual Generator Power Rating</td>
<td>310 kW (415.72 HP)</td>
</tr>
<tr>
<td>Generator Power Density</td>
<td>1 HP/lbm</td>
</tr>
<tr>
<td>IPP Combustor Weight</td>
<td>15 lbm</td>
</tr>
<tr>
<td>IPP Power Turbine Weight</td>
<td>33 lbm</td>
</tr>
</tbody>
</table>

Table 7. Key Parameters – Case 1 of Design Trade Study

The total weight of the generators for Case 1 is found to be:

\[
Weight_{Generators} = 4 \left[ (415.72 \text{ HP}) \left( \frac{1 \text{ lbm}}{\text{HP}} \right) \right] = 1,662.88 \text{ lbm}
\]

Equation 90. Case 1 – Generator Weight

The total weight of the IPP power turbine components is then:

\[
Weight_{Power\ Turbine} = Weight_{IPP\ Comb} + Weight_{IPP\ P.T} = 15\text{lbm} + 33\text{lbm} = 48\text{lbm}
\]

Equation 91. Case 1 – Power Turbine Component Weight

Thus, the total weight of the generators and IPP power turbine components is:

\[
Weight_{Total} = 1,662.88\text{lbm} + 48\text{lbm} = 1,710.88\text{lbm}
\]

Equation 92. Case 1 – Total Generator and Power Turbine Weight
The total weight of the aircraft, minus the fuel, is defined as 55,000 lbm (including generators and power turbine components). Using this weight and the mission profile illustrated in Figure 32, the thrust demand signal from the AVS model can be found, as shown by Figure 44.

![Figure 44. Case 1 – Thrust Demand Results](image)

For case 1, the only electrical loads are those of the avionics, actuators, and DEW. The total electrical generation available is provided by the four engine generators, each rated at 310 kW. Figure 45 shows how much power is used and how much power remains for additional functions.

Each generator places a mechanical load on the LP shaft of its respective engine. The mechanical load placed on a single engine is shown by Figure 46.
Figure 45. Case 1 – Electrical Load Results

Figure 46. Case 1 – Generator Mechanical Load on Each Engine
Each generator also creates a heat load that the TMS systems must absorb. As previously mentioned, it is assumed that 5% of the total electrical load is sent to the TMS systems as heat. This heat load is shown by Figure 47.

![Total Generator Heat Load](image1.png)

**Figure 47. Case 1 – Total Generator Heat Load**

![Liquid-Cooled Avionics Inlet Temperature](image2.png)

**Figure 48. Case 1 – Liquid-Cooled Avionics Inlet Temp.**
The liquid-cooled avionics inlet oil temperature is shown in Figure 48. In order to investigate the cause of the temperature violations, the IPP shaft speed has been shown in Figure 49. During the segments of the mission that experience a temperature violation, the IPP fails to meet the shaft speed specified by the controller.
As Figure 50 shows, when the IPP fails to meet the speed specified by the controller, there is insufficient mass flow being sent to the IPP power turbine. Even with the IPP speed control valve fully open, the engine is not providing enough high pressure bleed air to properly drive the IPP power turbine, resulting in lower than required IPP shaft speed, leading to temperature violations in the liquid-cooled avionics. A solution to these temperature violations will be discussed further in the comparison portion of the trade study. Discovering subsystem interactions similar to this engine/TMS result is the primary goal of using the full aircraft T2T model.

The temperature of the air entering the air-cooled avionics is shown by Figure 51. The blue line represents the minimum allowable air temperature of the inlet air in order to prevent freezing. The air cooled avionics temperature remains above these limits at every point in the mission.

![Air-Cooled Avionics Inlet Temperature](image)

**Figure 51. Case 1 – Air-Cooled Avionics Inlet Temperature**
The temperature of the air exiting the cockpit is shown in Figure 52. The temperature limit for the cockpit is shown to be violated throughout the entire mission. The main goal of this trade study will be to see how the different cases compare and not necessarily how to prevent these temperature violations from occurring.

The final parameter of interest for this first case is the total fuel consumption. From start to finish of the T2T mission, the aircraft with a bleed air power turbine with combustor architecture consumes 28,605 lbm of fuel.
Case 2: Variable Speed Electric Motor – Simulation Results

The second case simulated consists of the full T2T aircraft model with the IPP being driven by a variable speed electric motor. The combustor prior to the IPP power turbine as well as the power turbine itself are removed and replaced with a single electric motor. The architecture for this case was illustrated by Figure 43. The generators have been optimized so that IPP shaft speed set point is met with virtually no additional power available. Some of the critical parameters for this case are outlined below in Table 8.

| Number of Engines per Aircraft | 4 |
| Number of Generators per Aircraft | 4 |
| Individual Generator Power Rating | 1,030 kW (1,381.25 HP) |
| Generator Power Density | 1 HP/lbm |
| IPP Motor Power Rating | 4,016.3 kW (5,385.95 HP) |
| IPP Motor Power Density | 1 HP/lbm |

Table 8. Key Parameters – Case 2 of Design Trade Study

The total weight of the generators for Case 2 is found to be:

\[
Weight_{Generators} = 4 \left[ (1,381.25 \text{ HP}) \left( \frac{1 \text{ lbm}}{\text{HP}} \right) \right] = 5,525 \text{ lbm}
\]

Equation 93. Case 2 – Generator Weight
The weight of the electric motor is:

\[
Weight_{Electric\,Motor} = (5,385.95\, HP) \left(1\frac{lbm}{HP}\right) = 5,385.95\, lbm
\]

Equation 94. Case 2 – Electric Motor Weight

Thus, the total weight of the generators and IPP electric motor is:

\[
Weight_{Total} = 5,525\, lbm + 5,385.95\, lbm = 10,910.95\, lbm
\]

Equation 95. Case 2 – Total Generator and Electric Motor Weight

From Equation 92, the total weight of the generator and IPP power turbine components for Case 1 is shown to be 1,710.88 lbm. Using this value, the previous weight of the aircraft (55,000 lbm), and the new total weight of the IPP drive components for Case 2, it is possible to determine the new weight of the aircraft for Case 2:

\[
Weight_{Aircraft} = 55,000\, lbm + 10,910.95\, lbm - 1,710.88\, lbm = 64,200.07\, lbm
\]

Equation 96. Case 2 – Total Aircraft Weight

As Equation 96 shows, the variable speed electric motor results in a total aircraft weight increase of 17\% compared to the bleed air power turbine with combustor architecture. Using this weight and the mission profile illustrated in Figure 32, the thrust demand signal from the AVS model can be found, as shown by Figure 53:
For Case 2, the electrical loads include the avionics, the actuators, and the electric motor that drives the IPP shaft. The total electrical generation available is provided by the four engine generators, each rated at 1,030 kW. Figure 54 shows how much power is used and how much power remains for additional functions.

Each generator places a mechanical load on the LP shaft of its respective engine. The mechanical load placed on a single engine is shown by Figure 55.
**Figure 54. Case 2 – Electrical Load Results**

**Figure 55. Case 2 – Generator Mechanical Load on Each Engine**
Each generator also creates a heat load that the TMS systems must absorb. As previously mentioned, it is assumed that 5% of the total electrical load is sent to the TMS systems as heat. This heat load is shown by Figure 56.

![Figure 56. Case 2 – Total Generator Heat Load](image)

Once again, the liquid cooled avionics inlet temperature is plotted. As Figure 57 shows, the temperature is properly controlled to remain below the 60 °F temperature limit except for one portion of the mission. Near a mission time of 1400 seconds, the temperature quickly spikes, eventually reaching a maximum value of 85.43 °F 1500 seconds into the mission. The temperature returns to an acceptable value at a mission time of 1900 seconds. In order to evaluate the cause for the temperature violation, the IPP shaft speed has been plotted in Figure 58.
Figure 57. Case 2 – Liquid-Cooled Avionics Inlet Temp.

Figure 58. Case 2 – IPP Shaft Speed

As Figure 58 shows, the IPP shaft meets the set point shaft speed called for by the controller throughout the entire mission. During the temperature violation portion of the
mission, the IPP shaft speed saturates at the maximum speed of 60,000 RPM. This shows that between mission times of 1400 and 1900 seconds, the maximum speed of the IPP does not provide sufficient cooling for the APTMS. In order to provide sufficient cooling, the design speed of the IPP must be increased or a different IPP is required. Because the IPP meets the set point speed for the entire mission, the generators and electric motor for driving the IPP have been shown to be sufficient for this architecture.

The temperature of the air entering the air-cooled avionics is shown by Figure 59.

![Air-Cooled Avionics Inlet Temperature](image)

**Figure 59. Case 2 – Air-Cooled Avionics Inlet Temperature**

The blue line represents the minimum allowable air temperature of the inlet air in order to prevent freezing. The air cooled avionics temperature remains above these limits at every point in the mission.

The temperature of the air exiting the cockpit is shown in Figure 60. Once again, the temperature limit for the cockpit is shown to be violated throughout the entire
mission. The main goal of this trade study will be to see how the different cases compare and not necessarily how to prevent these temperature violations from occurring.

![Cockpit Exit Temperature](image)

**Figure 60. Case 2 – Cockpit Exit Temperature**

The final parameter of interest for Case 2 is the total fuel consumption. From start to finish of the T2T mission, the aircraft with variable speed electric motor IPP architecture consumes 22,828 lbm of fuel.
Case 3: Fixed Speed Electric Motor – Simulation Results

The third and final case simulated consists of the full T2T aircraft model with the IPP being driven by an electric motor at a constant speed. The design speed of the IPP has been chosen as the fixed speed for this case (60,000 RPM). Once again, the architecture for this case was illustrated Figure 43. The generators have been optimized so that IPP shaft speed set point is met with virtually no additional power available. Some of the critical parameters for this case are outlined below in Table 9.

<table>
<thead>
<tr>
<th>Number of Engines per Aircraft</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Generators per Aircraft</td>
<td>4</td>
</tr>
<tr>
<td>Individual Generator Power Rating</td>
<td>1,240 kW (1,662.87 HP)</td>
</tr>
<tr>
<td>Generator Power Density</td>
<td>1 HP/lbm</td>
</tr>
<tr>
<td>IPP Motor Power Rating</td>
<td>4,016.3 kW (5,385.95 HP)</td>
</tr>
<tr>
<td>IPP Motor Power Density</td>
<td>1 HP/lbm</td>
</tr>
<tr>
<td>IPP Fixed Shaft Speed</td>
<td>60,000 RPM</td>
</tr>
</tbody>
</table>

Table 9. Key Parameters – Case 3 of Design Trade Study

The total weight of the generators for Case 3 is found to be:

\[ Weight_{Generators} = 4 \left[ (1,662.87 \, HP) \left( \frac{1 \, lbm}{HP} \right) \right] = 6,651.48 \, lbm \]

Equation 97. Case 3 – Generator Weight
The weight of the electric motor is:

$$\text{Weight}_{\text{Electric Motor}} = (5,385.95 \text{ HP}) \left( \frac{1 \text{ lbm}}{\text{HP}} \right) = 5,385.95 \text{ lbm}$$

Equation 98. Case 3 – Electric Motor Weight

Thus, the total weight of the generators and IPP electric motor is:

$$\text{Weight}_{\text{Total}} = 6,651.48 \text{ lbm} + 5,385.95 \text{ lbm} = 12,037.43 \text{ lbm}$$

Equation 99. Case 3 – Total Generator and Electric Motor Weight

From Equation 92, the total weight of the generator and IPP power turbine components for Case 1 is shown to be 1,710.88 lbm. Using this value, the previous weight of the aircraft (55,000 lbm), and the new total weight of the IPP drive components for Case 3, it is possible to determine the new weight of the aircraft for Case 3:

$$\text{Weight}_{\text{Aircraft}} = 55,000 \text{ lbm} + 12,037.43 \text{ lbm} - 1710.88 \text{ lbm} = 65,326.55 \text{ lbm}$$

Equation 100. Case 3 – Total Aircraft Weight

As Equation 100 shows, the fixed speed electric motor results in a total aircraft weight increase of 19% compared to the bleed air power turbine with combustor architecture. Using this weight and the mission profile illustrated in Figure 32, the thrust demand signal from the AVS model can be found, as shown by Figure 61:
For Case 3, the electrical loads include the avionics, the actuators, and the fixed speed electric motor that drives the IPP shaft. The total electrical generation available is provided by the four engine generators, each rated at 1,240 kW. Figure 62 shows how much power is used and how much power remains for additional functions.

Each generator places a mechanical load on the LP shaft of its respective engine. The mechanical load placed on a single engine is shown by Figure 63.
Figure 62. Case 3 – Electrical Load Results

Figure 63. Case 3 – Generator Mechanical Load on Each Engine
Each generator also creates a heat load that the TMS systems must absorb. As previously mentioned, it is assumed that 5% of the total electrical load is sent to the TMS systems as heat. This heat load is shown by Figure 64.

![Total Generator Heat Load (4 Engines)](image)

**Figure 64. Case 3 – Total Generator Heat Load**

As Figure 65 shows, the temperature is properly controlled to remain below the 60 °F temperature limit except for one portion of the mission. At a mission time of 1400 seconds, the temperature quickly spikes, eventually reaching a maximum value of 71 °F 1600 seconds into the mission. The temperature returns to an acceptable value at a mission time of 1900 seconds. This temperature violation will be discussed further in the comparison portion of the trade study.

For Case 3, the IPP actually provides too much cooling throughout the majority of the mission. As Figure 65 shows, there are many segments of the mission that send the liquid cooled avionics temperature below freezing. Should this IPP drive method be used,
a different APTMS architecture will be required to take on additional heat to prevent these low liquid cooled avionics inlet temperatures.

![Liquid-Cooled Avionics Inlet Temperature](image)

**Figure 65. Case 3 – Liquid-Cooled Avionics Inlet Temp.**

The temperature of the air entering the air-cooled avionics is shown by Figure 66.

![Air-Cooled Avionics Inlet Temperature](image)

**Figure 66. Case 3 – Air-Cooled Avionics Inlet Temperature**
The air-cooled avionics temperature falls below limits that prevent freezing within the avionics. At some point, a new APTMS architecture will be required to provide additional heat to prevent freezing from occurring within the air-cooled avionics.

The temperature of the air exiting the cockpit is shown in Figure 67. Once again, the temperature limit for the cockpit is shown to be violated throughout the majority of the mission. The main goal of this trade study is to see how the different cases compare and not necessarily how to prevent these temperature violations from occurring.

![Figure 67. Case 3 – Cockpit Exit Temperature](image)

The final parameter of interest for Case 3 is the total fuel consumption. From start to finish of the T2T mission, the aircraft with fixed speed electric motor IPP architecture consumes 21,892 lbm of fuel.
Summary of Key Simulation Results – Overall Comparison

Now that the three cases have been outlined, some of the key results are compared on single plots. The final architectures of the three cases are outlined below in Table 10.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Case 1 Power Turbine</th>
<th>Case 2 Variable Speed Electric Motor</th>
<th>Case 3 Fixed Speed Electric Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Engines</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Number of Generators</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Generator Power Rating</td>
<td>310 kW</td>
<td>1030 kW</td>
<td>1,240 kW</td>
</tr>
<tr>
<td>IPP Motor Power Rating</td>
<td>N/A</td>
<td>4016 kW</td>
<td>4016 kW</td>
</tr>
<tr>
<td>IPP Fixed Shaft Speed</td>
<td>N/A</td>
<td>N/A</td>
<td>60,000 RPM</td>
</tr>
<tr>
<td>Empty Aircraft Weight</td>
<td>55,000 lbm</td>
<td>64,200 lbm</td>
<td>65,327 lbm</td>
</tr>
</tbody>
</table>

Table 10. Summary of Trade Study Key Parameters

The primary comparisons of interest are the APTMS temperature results and the overall fuel consumption by the aircraft for the mission. The liquid-cooled avionics inlet temperature is shown below by Figure 68.

Using the original architecture (Case 1) as a baseline, it is possible to determine the average percent difference in the liquid-cooled avionics inlet temperature across the entire mission. These differences have been calculated using absolute temperature (°R). The results of this analysis are shown in Table 11.
A comparison of the air-cooled avionics inlet temperature for all three cases is shown below by Figure 69. Once again, using the original architecture (Case 1) as a baseline, it is possible to determine the average percent difference in the air-cooled avionics inlet temperature across the entire mission for Case 2 and Case 3. These values have been determined using absolute temperature (°R). The results of this analysis are shown in Table 12.
A comparison of the cockpit exit temperature for all three cases is shown below by Figure 70. Once again, using the original architecture (Case 1) as a baseline, it is possible to determine the average percent difference in the cockpit exit temperature across the entire mission for Case 2 and Case 3. These values have been determined using absolute temperature (°R). The results of this analysis are shown in Table 13.
The final comparison of interest is the total fuel consumption of the aircraft during the mission. The results of this comparison are illustrated in Figure 71. Table 14 shows the percentage of fuel saved for each mission for Case 2 and Case 3 compared to the original architecture of Case 1.
Figure 71. Design Trade Study Comparison – Fuel Consumption

<table>
<thead>
<tr>
<th>IPP Drive Mechanism</th>
<th>Fuel Savings (lbm)</th>
<th>Fuel Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2 – Variable Speed Electric Motor</td>
<td>5777</td>
<td>20.1958</td>
</tr>
<tr>
<td>Case 3 – Fixed Speed Electric Motor</td>
<td>6713</td>
<td>23.4679</td>
</tr>
</tbody>
</table>

Table 14. Fuel Savings Comparison
Additional Analysis – Engine Controller Evaluation

The design trade study has shown that the most fuel efficient architecture is a fixed speed electric motor driving the IPP. As the temperature results have shown, however, this method causes many of the temperatures to drop below practical limits throughout large portions of the mission. Therefore, the adoption of this architecture will require additional work to develop new methods for adding heat during segments of the mission that have excessively low temperatures within the APTMS. An example of a possible architecture is to add a loop that brings heat to the APTMS from the engine when necessary in order to prevent the avionics inlet temperatures from freezing.

Another point of interest has arisen from the design trade study. The analysis has shown that a fixed speed electric motor operating at the IPP design speed of 60,000 RPM is more fuel efficient than the variable speed electric motor that operates at lower RPM’s for the majority of the mission. With lower IPP shaft speeds, lower mechanical loads are placed on the engine LP shaft, which intuitively should reduce the fuel consumption of the engine. In order to examine the validity of these results, some additional analysis needs to be performed. Specifically, by analyzing the bleed air quantity from the main engine that is used to prevent surging of the HP compressor, it will be possible to determine whether or not the engine controls utilized are efficient and accurate.
The amount of bleed air from the HP compressor, as specified by the main engine controller, has been illustrated in Figure 72. As this plot shows, the Case 3 architecture results in a lower bleed air requirement for the majority of the mission. The engine controller utilized is a simple proportional-integral (PI) controller and may not be complex enough for this application. Without an appropriate engine controller, the fuel consumption results for the Case 2 to Case 3 comparison may not be accurate. It is possible that the fuel advantages of Case 3 over Case 2 are due to this difference in bleed air. In order to determine whether or not the previous fuel consumption results are valid, an additional trial is required.

Case 3 is run a second time, now using the same bleed air values as Case 2 throughout the entire mission, effectively removing the engine controller from the equation. This new case will be called Case 4. Because the purpose of the bleed air is to prevent surging in the compressor, the larger bleed value of Figure 72, Case 2, was
needed as the common value. The Case 2 bleed air results were fed into the Case 3 engine model using a lookup table. The resulting Case 4 bleed air should be identical to the Case 2 bleed air, as shown by Figure 73.

![Engine HPC Bleed Air Comparison](image)

**Figure 73. Engine Controller Verification – HP Compressor Bleed Air Results**

With identical bleed air values being sent to the engine HP compressor, a true comparison can be made for the fuel consumption. Case 4 results in a total fuel consumption of 21,947 lbm. This value is compared to the other 3 cases in Figure 74. A comparison of the fuel savings is also shown in Table 15.

As these results show, even when feeding in the same bleed air as Case 2, the fixed speed electric motor IPP is still a more efficient architecture. The difference between Case 3 and Case 4 does, however, suggest that a more complex engine controller may need to be built in the future. The current PI controller may be too simple and may
not be sufficiently accurate for completing more complex design trade studies of the aircraft at a vehicle level.

![Figure 74. Engine Controller Verification – Fuel Consumption Results](image)

<table>
<thead>
<tr>
<th>IPP Drive Mechanism</th>
<th>Fuel Savings (lbf)</th>
<th>Fuel Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2 – Variable Speed Electric Motor</td>
<td>5777</td>
<td>20.1958</td>
</tr>
<tr>
<td>Case 3 – Fixed Speed Electric Motor</td>
<td>6713</td>
<td>23.4679</td>
</tr>
<tr>
<td>Case 4 – Fixed Speed Electric Motor (Case 2 Bleed Air)</td>
<td>6658</td>
<td>23.2757</td>
</tr>
</tbody>
</table>

Table 15. Engine Controller Verification – Fuel Savings Comparison
**Additional Analysis – Case 1 IPP Power Turbine Inlet Temperature Limit**

As the Case 1 results showed, specifically in Figure 48, the liquid-cooled avionics inlet oil temperature exceeded the set point value of 60 °F at several points throughout the mission. It was shown in Figure 50 that the cause of this was insufficient mass flow to the IPP power turbine, resulting in an IPP shaft speed below the speed called for by the controller. In an effort to eliminate these temperature limit violations, additional analysis has been performed using the Case 1 architecture.

The Case 1 architecture contains a combustor that increases the enthalpy of the high pressure bleed air entering the IPP power turbine. The purpose of the combustor is to increase the temperature of the air entering the IPP power turbine, allowing better performance from the IPP for mission segments with low bleed air availability. For equal bleed air mass flow rates being sent to the power turbine, a higher temperature air stream will provide more energy for the IPP power turbine, thereby increasing the cooling performance of the APTMS. Due to material limitations, however, the IPP power turbine inlet temperature was limited to a value of 3140 °F (2000 K) for the Case 1 results. This version of Case 1 will be referred to as Case 1a from this point forward.

In an effort to increase the enthalpy at the power turbine inlet, the temperature limit was increased until the liquid-cooled avionics was properly controlled for the later stages of the mission. The resulting power turbine inlet temperature has been found to be 5840 °F (3500 K). This version of Case 1 will be referred to as Case 1b from this point forward.
A comparison of the liquid-cooled avionics inlet temperature results for both Case 1a and Case 1b is shown in Figure 75. As these results show, the temperature violations near the end of the mission in Case 1a have been eliminated in Case 1b, but an issue still exists near 1500 seconds into the mission for both cases.

![Figure 75. Case 1a/1b Comparison- Liquid-Cooled Avionics Inlet Temp.](image)

The IPP combustor results for Case 1a are shown in Figure 76. As Figure 76 shows, the set point for the IPP power turbine inlet temperature saturates at a value of 3140 °F between mission times of 4500 and 7300 seconds. Because of this limit, not enough energy enters the IPP power turbine, resulting in the Case 1a temperature spikes in Figure 75. The IPP combustor results for Case 1b are shown in Figure 77.
Figure 76. Case 1a – IPP PT TIT and Combustor Fuel Mass Flow Rate

Figure 77. Case 1b – IPP PT TIT and Combustor Fuel Mass Flow Rate
As Figure 77 shows, the set point for the IPP power turbine inlet temperature now saturates at a value of 5840 °F. As a result, more energy enters the IPP power turbine than in Case 1a, resulting in increased cooling capacity in the later segments of the mission, thereby producing the reduced temperature values of Case 1b for Figure 75.

Even with the increased IPP power turbine inlet temperature limit, the IPP still fails to sufficiently cool the liquid-cooled avionics near the 1500 second mark in the mission. In fact, both Case 1a and Case 1b follow similar temperature profiles during this mission segment. In order to determine the cause of this temperature violation, the IPP shaft speed needs to be evaluated. The Case 1b IPP shaft speed is shown below in Figure 78.

Near the mission time of 1500 seconds, the controller is calling for an IPP shaft speed of 60,000 RPM. The IPP is ramping up to that speed but then drops off, likely due
to controller gains. Just as with the all electric IPP versions, the design speed of 60,000 RPM does not appear sufficient for cooling the liquid-cooled avionics. Because the IPP cannot exceed 60,000 RPM, the temperature climbs above the set point.

In conclusion, this additional analysis of the Case 1 architecture has shown that the current T2T model is capturing the subsystem interactions. In addition, the tool has shown that determining limitations of various architectures is also possible, as was found with the IPP combustor temperature limit.

**Additional Analysis – Case 3 Electric Power Transfer**

The generators used in all three cases of the design trade study were optimized so that the aircraft electrical systems could be powered with almost no additional power left over. For all three architectures, the aircraft’s electrical loads included the avionics, the actuators, and the Directed Energy Weapon (DEW). The DEW consists of a 1 MW electrical load step change at five points during the early stages of the mission. For the cases covered up to this point, the generators were made large enough so that the IPP electric motor could be powered sufficiently throughout the entire mission, even during the DEW firings. In an effort to analyze energy transfer between the aircraft subsystems, an additional version of the Case 3 architecture (fixed speed electric motor IPP) will be run, this time with smaller generators that prevent the IPP electric motor from receiving sufficient electrical power. Not only does this demonstrate additional capabilities of the T2T modeling tool for capturing subsystem interactions, but it also reveals the benefits of transient analysis in the design of future aircraft platforms.
The first version of the fixed speed electrically driven IPP, Case 3, utilized four 1240 kW generators to produce the needed electrical power for the avionics, actuators, DEW, and IPP electric motor. A new version of Case 3, referred to as Case 5 from this point forward, will use smaller generators so that the IPP motor experiences a power deficit during the firings of the DEW. For simplicity, the Case 2 generator rating of 1030 kW is chosen. The Case 2 results showed that this generator rating was sufficient for driving the IPP to its design speed of 60,000 RPM for a brief moment when the DEW was not being utilized. The Case 5 analysis will determine how the IPP shaft speed and associated APTMS temperatures change during the DEW transients.

The electrical loads for the aircraft in Case 5 are shown below in Figure 79. The five spikes in power consumption early in the mission correspond to the DEW firings. During these transients, no electrical power remains for the IPP electric motor.

![Figure 79. Case 5 – Electrical Load Results](image-url)
During the DEW firings, insufficient electrical power is available for the IPP electric motor. As a result, the IPP shaft speed falls below the desired speed of 60,000 RPM, as shown in Figure 80.

![IPP Shaft Speed](image.png)

*Figure 80. Case 5 – IPP Shaft Speed*

With the DEW firings being quick bursts of high electrical energy, the IPP electric motor is only experiences a deficit of electrical power for short periods of time. The inertial effects of the IPP allow the IPP shaft speed to remain reasonably close to the design speed of 60,000 RPM.

The liquid-cooled avionics temperature for Case 5 is shown below in Figure 81. Even with the IPP shaft speed falling below design speed, the liquid-cooled avionics temperature shows no significant change during the DEW firings.
Similarly, the air-cooled avionics temperature experiences no significant temperature transient due to the DEW firing, as shown by Figure 82.
Finally, the cockpit temperature is shown by Figure 83. Once again, the DEW firings do not significantly impact the performance of the APTMS.

![Cockpit Exit Temperature](image.png)

**Figure 83. Case 5 – Cockpit Exit Temperature**

As the Case 5 results have shown, reducing the generator size appears to have no significant impact on the performance of the APTMS. The temperature results for Case 5 look almost identical to the results obtained in Case 3. This analysis has demonstrated the benefit of transient modeling, especially for the design optimization process. It has been shown that energy usage diversion mechanisms allow a reduction in generator size and, subsequently, overall aircraft weight, without sacrificing TMS performance.
CHAPTER 8 – SUMMARY, CONCLUSION, AND RECOMMENDATIONS

The newly developed WSU engine model has been shown to be very effective at reducing the total simulation times required to run the full aircraft T2T model. Although the comparison study between the previous T2T engine model and the WSU engine model shows a thrust difference of 15.21%, the full T2T model performs significantly more accurately. The integration of the full aircraft T2T model with the WSU engine model impacts three significant parameters, including the engine fuel temperature, the mass of fuel in the fuel tanks, and the temperature of the fuel within the fuel tanks. When compared to the original T2T engine model and full aircraft T2T model integration, the average percent errors for these three parameters were just 0.7602%, 7.4072%, and 0.1955% respectively. Since these values are all well within the desired accuracy of 10%, the WSU engine model is proven to be sufficiently accurate when integrated with the full T2T aircraft model.

The overall goal of the project, reducing computation times for the full T2T aircraft model, has been met as well. After integrating the WSU engine with the full T2T aircraft model, the computation time for a 7700 second mission was reduced from 72,650 seconds to just 375 seconds, a 99.48% reduction. This reduction in computational time results in incredible gains in the usefulness of the T2T aircraft model and is especially beneficial for the future conduction of design trade studies.
Future work should focus on improving the accuracy of the WSU engine model even further. Although the full T2T results are less than 10% from the original T2T results, the WSU engine itself has room for improvement. As the individual test stand results showed, some of the new components are greater than 10% from the original T2T engine components. These results are once again shown by the summary in Table 16.

<table>
<thead>
<tr>
<th>Component Model</th>
<th>Average Percent Error Across 7700 Second Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass Flow Rate</td>
</tr>
<tr>
<td>Fan</td>
<td>3.45</td>
</tr>
<tr>
<td>HP Compressor</td>
<td>9.52</td>
</tr>
<tr>
<td>Combustor</td>
<td>0.005</td>
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<tr>
<td>HP Turbine</td>
<td>3.18</td>
</tr>
<tr>
<td>LP Turbine</td>
<td>4.57</td>
</tr>
<tr>
<td>Nozzle</td>
<td>N/A</td>
</tr>
<tr>
<td>Bypass</td>
<td>11.93</td>
</tr>
</tbody>
</table>

Table 16. Summary of WSU Engine Component Accuracy

The largest errors found on a component basis occur for the nozzle and bypass plenum volume models (nearly 12%). This comes as no surprise considering that the nozzle and bypass models were two of the most complex models within the original T2T engine model. At least some of the large simulation time reductions in the WSU engine model were due to simplification of these models, likely the cause of these higher than desired error values. It is worth noting that the mass flow of the bypass plenum volume is driven
by the bypass pressure, which is within 4% of the original T2T engine, leading one to believe that the new bypass plenum mass flow rate should be accurate as well. This may show that the simplistic method used for calculating the bypass plenum volume mass flow rate is not sufficient for this application and that future work should focus on implementing more robust modeling techniques in the bypass model.

A simple design trade study has been conducted to demonstrate the usefulness of the WSU engine model when integrated with the original full aircraft T2T model. The trade study considered three different architectures for driving the IPP, the unit responsible for cooling the liquid-cooled avionics, air-cooled avionics, and cockpit. The first case examined the current architecture which consists of high pressure bleed air from the main engine compressor being combusted before entering a power turbine which drives the IPP shaft. The second case replaced the combustor and power turbine with a variable speed electric motor to drive the IPP. The third case replaced the combustor and power turbine with a fixed speed electric motor to drive the IPP.

As the trade study results have shown, the most fuel efficient design is to use a fixed speed electric motor to drive the IPP shaft. In fact, this architecture resulted in a fuel savings of over 23% for each mission compared to the original architecture. This method appears to be the best option of the three from a mission-cost standpoint, but several hurdles exist to apply the concept on an actual aircraft. First, the power generation required to drive the IPP shaft to 60,000 RPM consists of each engine generator having a power of 1240 kW. In addition, a 4016 kW electric motor is required. Assuming power densities of 1 HP/lbm (although 2 HP/lbm power densities have been mentioned as a possibility) the total aircraft weight increases by 10,300 lbm compared to the original
architecture. The additional weight may prove unrealistic for military applications. In addition, the availability of generators and electric motors of this size for aviation applications is unknown.

The purpose of the trade study was to demonstrate the newfound capabilities of the full T2T model, specifically due to the WSU engine model integration. Although several problems were illustrated within the thermal management system results, the T2T model was able to capture key subsystem interactions. This trade study was set up with the intent of showing a true comparison between three different architectures and successfully met this goal. As the results have shown, however, none of the current architectures were able to completely control the APTMS temperatures throughout the mission. Each case showed that the current IPP design speed of 60,000 RPM was insufficient for certain parts of the mission. Future work will need to focus on these temperature violations, but the primary goal of capturing an “apples-to-apples” comparison has successfully been performed.

The fixed speed electric motor IPP drive also resulted in many of the APTMS temperatures reaching extremely low values. In order to prevent freezing within various components, including the liquid-cooled and air-cooled avionics, the APTMS architecture will need to be modified even further. Additional trade studies should address these freezing issues and how heat from the engine can be used to increase APTMS temperatures as needed. Any additional loops that bring heat to the APTMS components during mission segments with unnecessarily low component temperatures will result in additional weight and complication, possibly reducing the fuel efficiency benefits of this IPP drive architecture.
It was also shown that the current engine controller used within the full aircraft T2T model may be overly simplified. The PI controller has been shown to be inaccurate, specifically with specifying demand bleed air mass flow rates from the engine HP compressor. Analysis was performed to show that with identical bleed air mass flow rates, the fixed speed electric motor IPP drive is still the more efficient architecture from a fuel consumption standpoint. Future work should look into the development of a more robust and accurate engine controller. This will allow the accurate completion of more and more complex design trade studies.

Analysis of the Case 1 architecture demonstrated that the new T2T modeling and simulation tool is adequately capturing the subsystem interactions. In addition, the tool has shown that determining limitations of various architectures is also possible, as was found with the IPP combustor temperature limit. Although increasing the IPP power turbine inlet temperature limit to 5840 °F was unrealistic from a materials standpoint, the exercise demonstrated that the modeling tool has the ability to accurately and efficiently demonstrate key subsystem interactions.

Finally, Case 5 demonstrated the new T2T model’s ability to capture transient behavior with the DEW firing. Even with insufficient electrical power to drive the IPP to the required speed, the APTMS maintains sufficient control of the cockpit and avionics temperatures. This analysis has shown that utilizing energy usage diversion between the aircraft subsystems results in significant design benefits. By diverting the electrical energy from the IPP electric motor to the DEW for short transients, it was discovered that the IPP inertial effects were sufficient for maintaining proper temperature control. This
allows smaller generators to be used, reducing overall aircraft weight and further optimizing aircraft design.

The development of the WSU engine has greatly reduced the simulation time required for the full aircraft T2T model to complete a mission, improving the utility of the tool. Future analysis using this tool may be able to capture other subsystem interactions not examined in the design trade study studied here, allowing conceptual designers and research groups to optimize future aircraft from a vehicle-level. As these results have shown, the study of subsystem interactions uncovers relationships that may otherwise be overlooked when optimizing the aircraft and it’s subsystems at a subsystem-level.
BIBLIOGRAPHY


