Power/Thermal Interaction within an Adaptive Turbine Engine

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Power/Thermal Interaction within an Adaptive Turbine Engine

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

By

Andrew K. DeSomma
B.S., Ohio State University, 2015

2019
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY
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Abstract
DeSomma, Andrew K. M.S.M.E. Department of Mechanical and Materials Engineering, Wright State University, 2019. Power/Thermal Interaction within an Adaptive Turbine Engine.

Usually power take off (PTO) with a two-spool turbofan engine has been accomplished via the high pressure (HP) shaft and bleed air from the high-pressure compressor (HPC). The PTO is used to run various aircraft components such as generators and hydraulic pumps, which also produce waste heat. To better understand the coupled transient nature of balancing engine thrust, power take off and thermal management, a transient variable cycle three stream turbofan engine model has been developed to investigate the integrated behavior. The model incorporates many dynamic features including a third-stream heat exchanger as a heat sink for thermal management and HP/LP shaft PTO. This paper describes a method of controlling HPC surge margin and maintaining the desired thrust while extracting power using both the HP and LP spools. The transient interactions as both PTO and 3rd stream heat rejection are simultaneously applied to the transient variable cycle engine model utilizing different control effectors were investigated.

The rate of transient heat rejection was found to impact surge margin. Rapidly applied heat loads caused larger surge margin transients than heat loads applied more gradually despite the same maximum heat rejection. Optimal PTO profiles between the LP and HP shaft to minimize the amount of fuel used for a given PTO amount and flight envelope were also investigated. Finally, a notional mission was simulated with varying flight parameters and dynamic PTO based on optimal PTO profiles along with heat generation and afterburner. The controls were found to be sufficient to successfully run the mission however such simplified controls could induce numerical instabilities in certain mission profiles. This shows that while these simple controls are sufficient for these notional test runs more sophisticated controls will be necessary for a proper generic engine model.
Nomenclature

\( A_n(t) \) - Actual value to be compared to set point

APU - Auxiliary Power Unit

Dry - Afterburner off.

HP - High Pressure

HPT - High Pressure Turbine

I_n - Integral gain

IGV - Inlet Guide Vane

LP - Low Pressure

LPT - Low Pressure Turbine

MEA - More Electric Aircraft

NPSS - Numerical Propulsion System Simulation

P_n - Proportional gain

PTO - Power Take Off

Q - Heat to be rejected

SFC - Specific Fuel Consumption

SLS - Sea Level Static, Altitude = 0ft, Mach = 0.0

SM - Surge Margin

Sp_n - PI controller set point

TC - Time Constant

VCE - Variable Cycle Engine

u_n(t) - PI controller output

Wet - Afterburner on
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1. Introduction

As technology advances so does capability and engineering requirements and the next generation of aircraft including combat aircraft are no exception. One of the main engineering concerns is increased power and thermal management requirements. A visual aid showcasing this trend in military aircraft is shown in Figure 1. Power and thermal management requirements for current and future military aircraft as they relate to capability. Note the break in the power & thermal axis above the F-22, this showcases the significant jump in power need and thermal rejection requirements that will accompany the next generation of aircraft design.¹

![Power and thermal management requirements for current and future military aircraft as they relate to capability.](image)

**Figure 1.** Power and thermal management requirements for current and future military aircraft as they relate to capability.

Additional constraints that mainly affect military aircraft can further complicate matters. These include the need to maintain low observability and high survivability and resistance to damage. These additional constraints result in limitations in available heat sinks (large exterior heat sinks generate large thermal signatures and are easy to damage). Composite skins and
stealth materials also preclude the use of such heat sinks which further complicates the thermal management problem.

Furthermore, the push to more electric aircraft (MEA) architectures necessitates the need for additional electrical power generation on the aircraft. Typically the two main sources of power on an aircraft are the engines and auxiliary power unit (APU). However, if an APU is the primary source of electricity, as the demands for electrical power increase so does the size and weight of the APU. This increases the empty weight of the aircraft and reduces the payload as well as occupying space that could be used for other aircraft systems or fuel. Thus it is desirable for the APU to be as light and compact as possible for use in emergency situations or in high load situations where it is supplemental with main engine power generation.

Engine power take off (PTO) is the primary source of power for many aircraft. It is used to drive generators, hydraulic pumps and other systems necessary for proper aircraft operation. Historically PTO from engines whose primary purpose is thrust (i.e. not turboshfts, turboprops etc.) has been taken from the high pressure (HP) shaft for dual shaft designs. In addition, high pressure compressor (HPC) bleed air is also used as a form of power take off, either to drive a separate turbine or as a source of high pressure air. PTO has typically been considered steady state.

PTO is primarily taken off of the HP shaft for several reasons, one is mechanical simplicity as the shafts are nested with the LP shaft being inside the HP shaft so accessing the LP shaft creates complications and adding the additional gearing and generator systems adds bulk and weight to the engine as well as expands the failure modes. Another reason is that the HP shaft is the one spun up for engine start and thus the necessary connections are already there, and the generator is simply used as a motor (in electrically started engines) to spin up the engine for
startup. These mechanical complexities are not investigated in this paper as the model is strictly numerical however it demonstrates the theoretical feasibility of these approaches in future engine design.²

1.1. Problem Overview

In typical engine design analysis, the PTO effects are turned on at engine start and remain for the duration of the mission, therefore transient effects are not investigated. This research utilizes an adaptive turbine engine model developed in Simulink® to investigate the effects of transient PTO. Normally, power is not taken off of the low-pressure shaft, but this option may provide the opportunity to more efficiently manage the thrust and power generation aspects of the propulsion system. Ultimately, it is desired to determine the most efficient way to extract the power out of the engine while allowing the engine to maintain the desired thrust in a stable manner.

Compressor surge, also known as compressor stall is when a compressor is unable to maintain the pressure differential across it to prevent flow moving backwards through the compressor. This is obviously detrimental to compressor operation and to the engine operation as a whole and can lead to loss of power, engine damage or even the total loss of the aircraft.¹¹ Due to these dire consequences, engines are designed with a specific surge margin (SM) to operate within using controls to actively maintain that surge margin. In this paper surge margin is presented as a percentage based on shaft speed, pressure ratio across the compressor and mass flow rate of air through the compressor. Note that these factors are all normalized. When the surge margin reaches 0% that indicates a surge condition. The equation that governs the surge margin is shown in Equation 1.
\[
SM = 100\% \left( \frac{PrnSurge \cdot Mn}{MnSurge \cdot Prn} - 1 \right)
\]

**Equation 1.** Compressor surge margin calculation.

Where PrnSurge and MnSurge are the pressure ratio and mass flow rate at the surge condition respectively. These are determined from lookup tables based on the shaft speed and inlet guide vane angle. For a more detailed analysis of compressor operation please refer to Eastbourn’s thesis. In practical terms for this research it means that as power is extracted from the shafts or as pressure is increased downstream of the compressor the surge margin will decrease. Thus, the limit of how much energy that can be extracted from the engine is dependent on how effectively the controls can maintain that surge margin.

As aircraft technology and capability improve so does the need for power for various subsystems. In addition, the heat loads from these subsystems correspondingly increase and need to be dissipated. This can be a significant aerospace engineering challenge as areas on the aircraft capable of sufficiently dissipating the heat become restricted. A three-stream variable cycle engine (VCE) has been proposed as a propulsion option, which has capabilities that potentially can help to alleviate these power and thermal issues. This model incorporates a heat sink in the 3rd stream as a potential sink for the thermal loads. The effect of this heat dissipation on overall engine performance is investigated however the actual physics of the 3rd stream heat exchanger are not. This research is strictly focused on how the interaction between engine shaft power take off and thermal load heat rejection affect engine performance.
1.2. Review of Relevant Literature

1.2.1. Simmons

In 2009 Ronald J. Simmons submitted his Ph. D. dissertation to The Ohio State University. The focus of his research was a steady-state Numerical Propulsion System Simulation (NPSS) based model of a three-stream Variable Cycle Engine (VCE). The dissertation goes into the history of VCE research from the early days of jet engine research in the 1950’s all the way to modern day. The concept of flow holding was introduced which could reduce or eliminate inlet spillage drag at the expense of possibly lowering engine efficiency thus a balance between drag and efficiency would be required to achieve optimum performance. To achieve this, he described the idea of a three-stream VCE engine that would be able to actively modulate air flow through the engine by controlling the inlet area of various components. The third stream has the additional benefit of being a potential heat sink for engine components which must be considered with the air flow controls. The NPSS architecture studied is shown in Figure 2.

Figure 2 NPSS VCE architecture
This model was then used to find the optimal way to operate the variable geometry controls as well as investigating different engine configurations of the engine under different static flight conditions both on and off design. These investigations found that substantial fuel savings could be achieved with only three variable control features, the high-pressure turbine (HPT) inlet area, modulated cooling of the turbine blades, and a variable third-stream nozzle. However due to the generic nature of the model in this paper it incorporates as many variable geometry features as is feasible.

1.2.2. Corbett  

In 2011 Michael Corbett submitted his master’s thesis to Wright State University on the effects of large-scale transient loading and waste heat rejection on a three-stream variable cycle engine. This thesis explains the history and underlying physics of the three-stream architecture and its advantages and disadvantages compared to low and high bypass ratio turbofans. It then goes into how power is extracted from the engine via bleed air and shaft power extraction and their uses as well as the overall effect on the performance of the engine. Corbett’s research also utilized an NPSS VCE model with a similar architecture to what Simmons used and went into the development of the various components integrated into the engine model. Corbett’s model utilized a controller based in Simulink® the controller made use of a set of lookup tables created from steady state operating points. This allowed for transient operation and flow holding investigation however they were quite limited.

The engine was run over three generic missions and it was found that at low thrust settings a greater proportion of total engine airflow traveled through the third-stream bypass compared to higher thrust settings. It was also found that under certain flight conditions the temperature of the third-stream could exceed the temperature of the waste heat to be extracted,
this would require a refrigeration cycle to elevate the waste heat which would require a significant amount of power. There was also a correlation between the mass flow rate through the heat exchanger and the pressure drop across the third stream with a higher mass flow resulting in a higher pressure drop. This can possibly cause a problem if the fan is not able to keep the nozzle pressure above ambient however in testing the nozzle pressure became near ambient at ground idle conditions and never actually dipped below ambient. This shows that the design of the 3rd stream HX will be critical in the design of the fan and 3rd stream nozzle to prevent air backflow. This paper also finds that the amount and rate of change of expected heat into that HX will also need to be considered.

1.2.3. Faidi

In 2012 Anis Faidi submitted his thesis to the Department of the Air Force Air University at Wright-Patterson Air Force Base titled “Effect of Accessory Power Take-Off Variation On a Turbofan Engine Performance”. For his research he also utilized the NPSS system for turbofan engine modeling and focused on the performance effects of taking power off via bleed air from the HPC and LPC as well as taking the equivalent amount of power off of the HP shaft and LP shaft respectively. For these tests he ran the simulations at an altitude of 35,000ft and a Mach number of 0.8 in either of two modes, constant fuel flow or constant HPT inlet temperature.

His results showed that bleeding air from the HPC was the much less efficient method of power take off in terms of fuel use when compared to the other three methods. It was also found that extracting power off of the HP shaft increased the HPT inlet temperature compared to the LPC bleed and LP shaft extraction however the temperature increase was minor and deemed to not be a problem.
He also investigated the performance of the fan, low pressure compressor and high-pressure compressor when the different forms of power extraction was applied. His results suggest that none of the four would have a problem on the LP spool shaft maximum speed limit but extracting HPC bleed air or from the LP shaft could cause a problem with LP shaft speed when high amounts of power are being extracted or when the engine is at a high throttle setting. These findings coincide with my own showing that available power take off is greatly reduced when the engine is running at max settings.

1.2.4. Eastbourn

In 2012 Scott Eastbourn submitted a master’s thesis to Wright State University on “Modeling and Simulation of a Dynamic Turbofan Engine Using MATLAB/Simulink®” The thesis discusses the motivations and reasoning for using MATLAB/Simulink®. It reduces complexity without sacrificing accuracy and thus improves computation time over other systems such as NPSS. A dynamic mixed-flow turbofan engine model was created for the use of a full vehicle-level model known as a “Tip-to-Tail” (T2T) model. This T2T model incorporated the power and thermal management systems in order to simulate the power/thermal interactions of the different subsystems in a generic aircraft. This engine model incorporated several dynamics such as shaft inertial dynamics and air flow volume dynamics which both increase fidelity and reduce algebraic constraints. Eastbourn goes into great detail on the component models of the engine and comparisons with other components that were previously modeled. These comparisons showed that the components performed as intended.

Utilizing this new engine model in the Tip-to-Tail model significantly decreased computation time which was the original goal of the research. To confirm this a design trade study was done with the T2T model using a notional mission profile. This engine model was
then used by Buettner as a basis in order to create the three-stream engine and many of the
details and features in the two-stream model were incorporated into his.

1.2.5. Buettner \textsuperscript{9,10}

In 2017 Robert Buettner submitted a master’s thesis titled “Dynamic Modeling and
Simulation of a Variable Cycle Turbofan Engine with Controls” to Wright State University.
Buettner built upon Eastbourn’s work by taking the mixed-flow turbofan engine model and
adding new components such as a low-pressure compressor and third-stream bypass duct to
create a variable cycle three-stream engine. The first subsystem added was an afterburner into
the engine however for the purposes of this paper it is disabled and only acts as a pressure drop.
He also incorporated variable geometry maps into the engine allowing for variable inlet guide
vanes (IGV) into the fan, LPC, LPT and HPT, however other than verifying that they work those
IGV’s were fixed in the engine. Developing the variable geometry maps required an automated
system to convert the maps from the Air Force’s AGATE model into a form useable in
Sinulink\textsuperscript{®}. There was some loss in fidelity near the surge line, however because the controllers
are set to maintain a 12\% surge margin it was determined to not be a significant issue. The fuel
controllers were also modified to allow for the future addition of flow holding capability
however the control systems to actually achieve flow holding were not yet implemented.
Controllers were also implemented controlling the core and third-stream nozzle. Note that no
controller was implemented to control the HPC surge margin however for the notional mission
run it was determined to not be an issue. The resulting engine architecture is shown in Figure 3.
Three-Stream Engine architecture
The engine was run over a notional mission of varying altitudes, Mach numbers and thrusts and was shown to be capable of successfully executing the mission without surges. The mission was also run with PTO of up to 500kW on both the HP and LP shafts and while the uncontrolled SM of the HPC fluctuated it did not come close to surging, so it was deemed a success. Still it showed that surge margin is a limiting factor in power taken off of an engine. A heat exchanger was also installed in the third stream and was tested over the mission with both a constant and sinusoidal mass flow rate to verify that they work correctly. Buettner notes a probable interaction between the power take off and thermal rejection into the third stream however does not investigate it. This paper continues directly from Buettner’s work and dives specifically into these power/thermal interactions.

2. Approach

The general architecture of the VCE model is the same as Buettner’s model shown in Figure 3. Three-Stream Engine architecture (Note that the yellow stars indicated variable geometry controls.) Air enters the fan where it can take 3 paths through the engine. The first route is through the core of the engine where it passes through the fan, LPC, HPC, burner, HPT, LPT, afterburner and core nozzle. This is the core flow. The second route goes through the fan
and LPC but then bypasses the HPC, burner and turbines to recombine with the core flow in the mixer which is just before the afterburner. The third route only passes through the fan and bypasses the rest of the engine through the 3rd stream duct before being exhausted through the 3rd stream nozzle. Flow through the 3rd stream is significantly cooler then the air flowing the other routes and thus is a candidate for a heat sink of engine systems.

The third-stream nozzle and core nozzle control the fan and low-pressure compressor (LPC) surge margins respectively. The nozzles control surge margin by adjusting their area, this directly affects the pressure upstream of the nozzle and thus the pressure across the compressors. The low-pressure turbine (LPT) and high-pressure turbine (HPT) inlet guide vanes (IGV) are found to be effective at controlling HPC surge margin. This is due to the inlet guide vanes controlling both the efficiency and mass flow rate of the turbines. The fan and LPC IGV’s are currently not controlled and set to fixed positions. The HPC currently does not have variable inlet guide vanes. Details on the various engine components are discussed in Appendix A.

The model was set up in Simulink having the engine components organized into individual subsystems. The components are connected with the pressures feeding backwards starting from the nozzles and propagating backward throughout the engine. The dynamic effects of the model also improve computation time by reducing algebraic constraints. Variable geometries are controlled via PI controllers. The fan and LPC are on the same shaft powered by the LPT, while the HPC is on a separate shaft powered by the HPT. Therefore, when a percentage of power is being taken off of the LP shaft it is a percentage of the work being done by both the fan plus the LPC. For example, if both the fan and LPC are using 500kW for a total of 1MW and 10% is being taken off of the LP shaft then the amount of PTO taken off the LP shaft is 100kW.
It should be noted that in the interests of computational efficiency all air properties are considered to be uniform throughout a subsystem (i.e. no CFD calculations). The engine model is purely numerical and does not take into account mechanical complexities such as shaft vibration or thermal soak although the latter is a planned addition to the model. In addition, complete combustion is assumed for both the main burner and afterburner as long as sufficient oxygen is available. If sufficient oxygen is not available, the unburnt fuel is simply passed through the engine unreacted (no incomplete burning).

2.1. Controller overview

Surge margin controls include the third-stream nozzle and core nozzle which controls the fan and LPC surge margin. In addition, HPC bleed and HPT and LPT IGV controls were developed that all control the HPC SM. All of the controls utilize PI controllers tuned to maintain a 12% SM. While the engine is equipped with an afterburner all of these tests were run with it disabled (i.e. dry).

PI controllers are a feedback control system widely used in industry. They are a simple mathematical system that attempts to control a given signal to a set point by finding the difference between the signal and set point (the error) and trying to minimize that difference via proportional and integral means. The proportional component issues a correcting signal in proportion to the error so the higher the error the more it tries to correct however it is prone to fluctuations and overcorrections. The integral component takes into account past errors, the longer an error has persisted the stronger the correction signal. This means that the signal is relatively weak at the beginning of an error but can become extremely strong after time has passed and is slow to respond if the error switches sides. These two methods sum together to
create the corrective signal. Tuning these controllers involves changing the gains which are multiplicative constants on their respective signals.

Tuning a PI controller is non-trivial and especially with complicated systems like this engine with many controllers working simultaneously mistuning can result in fluctuations and numerical instabilities that preclude proper engine operation. There is also a derivative term that can be used to make a PID controller where the derivative issues a corrective signal based on the rate of change of the error and acts as a damping effect to the control signal. One of the quirks of Simulink however is that adding the derivative term slows the model down significantly and introduces instabilities into the system. For this reason, the derivative is omitted and thus without the damping term tuning the P and I terms becomes even more critical.

As an example, the core nozzle controller maintains the LPC surge margin at 12% by comparing the current value to the 12% baseline. The error is used to change the core nozzle position according to Equation 2. How this controller looks in Simulink is shown in Figure 4. Core nozzle PI controller The turbine inlet guide vane and HPC bleed controllers operate in a similar matter although obviously controlling the inlet guide vane angle and HPC bleed respectively. The fuel controllers for the main burner and afterburner use cascading PI controllers which are detailed in Buettner’s thesis. Diagrams of these controllers can be found in Appendix D.

\[
\begin{bmatrix}
  u_1(t) \\
  u_2(t) \\
  \vdots \\
  u_n(t)
\end{bmatrix}
= 
\begin{bmatrix}
  P_1 \\
  P_2 \\
  \vdots \\
  P_n
\end{bmatrix}
\times
\begin{bmatrix}
  Sp_1 - A_1(t) \\
  Sp_2 - A_2(t) \\
  \vdots \\
  Sp_n - A_n(t)
\end{bmatrix}
+ 
\begin{bmatrix}
  I_1 \\
  I_2 \\
  \vdots \\
  I_n
\end{bmatrix}
\times
\int
\begin{bmatrix}
  Sp_1 - A_1(t) \\
  Sp_2 - A_2(t) \\
  \vdots \\
  Sp_n - A_n(t)
\end{bmatrix}
\, dt
\]

Equation 2. PI Controller equations
Where \( u_n(t) \) is the controller output for a specific controller, \( P_n \) and \( I_n \) are the proportional and integral gains, for the corresponding controller respectively. \( Sp_n \) is the setpoint of a particular controller and \( A_n \) is the actual value that setpoint compares to. The controller output is limited to the physical constraint of the object being controlled (20% to 100% of max area for nozzles, 61° to 75° for inlet guide vanes). A first order transfer function with a 1 second time constant was added to each actuator to emulate the dynamics of the physical movement of the control surface. All controllers in the VCE model use this logic. Note: the derivative factor of the PI controller is 0 as it can induce instability in the system.

**Figure 4. Core nozzle PI controller**

The engine was sized to a dry thrust of 24,000 lbf at sea level static (SLS). This was accomplished resizing the design mass flow rate on all of the components. Consistent resizing was also applied to resize plenum volumes and nozzle areas. This is possible because all of the engine components were already correctly sized relative to each other. This resizing reduced the dry SLS engine thrust from the initial 36,400 lbf when the engine was developed by Buettner to 24,000 lbf. Other than the thrust, resizing of the engine had no other effects on engine performance.
3. Testing and results

3.1 Effect of PTO with no Surge Margin controls

To get an idea of what effect PTO has on engine surge margin, a test was run with the HPC bleed disabled and both core and third-stream nozzles fixed at a position that provides a 12% surge margin at conditions with no PTO. The conditions are 30,000 ft and Mach 0.8. Under these conditions, the max dry thrust of the engine is 10,500 lbf. This and further tests are run at 90% of the engine’s maximum thrust (9,500 lbf). 90% was chosen arbitrarily because at 100% the engine is already at the limits of the fuel controllers and thus is not able to compensate for the power extraction. In other words, the engine was already going all out, and any PTO would result in a drop in thrust. All tests are run on a 1000 second mission segment which allows for transient and steady state effects to be investigated using minimal computational resources. Note the first 100 seconds are reserved for startup transients and thus are not considered part of the test. The typical PTO profile used is shown in Figure 5. Absolute and percentage PTO profiles taken off the LP and HP shafts The PTO is 6% HP and 10% LP. A 10 second ramp up and down between PTO on and off is used to allow for the controls to compensate for the transients. A constant 100 horsepower (74.57 kW) PTO on the HP shaft is used to model customer PTO. The customer PTO is in effect even during no PTO tests.
Figure 5. Absolute and percentage PTO profiles taken off the LP and HP shafts

The LP and HP PTO are offset to allow for the investigation of having only LP PTO, only HP PTO and both as well as the transient interactions between them. There is negligible difference between when LP leads or when HP leads. The resulting effects on the surge margin for the fan, LPC and HPC are shown in Figure 6. Effect of PTO on surge margin with no controls.
3.2 Nozzle controls and HPC bleed

A PI controller that controls the HPC surge margin and tries to maintain it at 12% was then developed. It simply controls a small valve that bleeds air downstream of the HPC thus lowering the HPC pressure ratio and increasing the surge margin. The test was performed at the same flight conditions as the no control test in the previous section and with the same PTO profile with the HPC bleed and nozzle controls enabled. Note that there is a constant customer bleed of 0.59 kg/s, this is equivalent to 2% of the total HPC mass flow at cruise. The effect on the surge margins is shown on Figure 7 and the HPC bleed profile is shown in Figure 8.

**Figure 6.** Effect of PTO on surge margin with no controls.

The PTO decreases the surge margin of all three components. This is due to PTO causing a reduction in corrected shaft speed, which in turn reduces the compressors surge margin. Fuel burn over the duration of the mission is compared - the baseline with no PTO uses 1440 lbm of fuel versus 1550 lbm with PTO.
Figure 7. Effect of controls on surge margins

(Note: transients at 100, 300, 700, and 900s.)

Figure 8. HPC bleed
The HPC bleed controller does indeed maintain the surge margin. However, the total fuel used was 1600 lbm, while the no control test used only 1550 lbm under the same conditions and PTO profile. This is due to energy being used to compress the bleed air that is not recovered by the turbine resulting in a net loss of energy and efficiency. So, the question is, is there a more efficient way to control HPC surge margin?

3.3 Adding turbine IGV controls

Another method to control HPC surge margin is with inlet guide vanes (IGV) for the turbines. Varying the IGV angle has two effects on the engine, it affects the efficiency, and the corrected mass flow rate of the turbine. Changing the efficiency alters the power that is extracted from the airflow and thus the power that is able to be utilized by the compressors, and the mass flow rate governs the pressure ratio across the compressors. Both events effectively control the surge margin of the HPC. When combined with the variable geometry nozzles, the compressor SM in the engine can be effectively controlled. However, the turbines have to be oversized from their original design mass flow rate in order to accommodate the additional mass flow. The turbines were resized to have a design mass flow rate 10% higher. This was so that at cruise condition, 30,000 ft Mach 0.8, 9,450 lbf of thrust and no PTO the IGV angle was about 68° which is midway in the allowable range. Note: resizing changes the design mass flow rate, not the actual flow rate of air through the engine.

The optimum control configuration of the HPT and LPT IGV is determined at steady state with no PTO where one turbine is oversized with an active IGV PI controller while the other remains at the original design configuration with a fixed IGV angle of 61°. Finally, both turbines were resized and given active controls. Both sea level static (0 ft, M 0), and cruise
(30,000 ft, M 0.8) operation was analyzed. The results are shown in Table 1. Turbine configuration tests at sea level static

**Table 1.** Turbine configuration tests at sea level static

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<th>Configuration</th>
<th>Dry Thrust [lbf]</th>
<th>Fuel [lbm]</th>
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</thead>
<tbody>
<tr>
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<td>3900</td>
</tr>
<tr>
<td>HPT 10% oversized</td>
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<tr>
<td>Both 10% oversized</td>
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**Table 2.** Turbine configuration tests at cruise

<table>
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<th>Fuel [lbm]</th>
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<td>10500</td>
<td>1600</td>
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</table>

The conclusion is that utilizing both HPT and LPT oversizing results in the best overall performance. There is a small decrease in thrust (~4%) but a significant decrease in fuel burn is achieved. Based on these results both the HPT and LPT are oversized and IGV controlled for the next analysis.

To confirm that the variable turbine IGVs are capable of controlling the HPC SM under PTO and allow the engine to complete the mission, a test at cruise (30,000 ft, M 0.8) with a thrust of 9,450 lbf was analyzed. The PTO profile used is given in Figure 9. PTO profiles (9%
(1.3MW) HP, 23% (1.8MW) LP for a total of 3.1MW) The thrust profile, shaft speeds, and fuel usage are shown in Figure 10. Thrust, shaft speed and fuel usage. (Note first 100 seconds are for startup transients before it reaches steady state for the test).

**Figure 9.** PTO profiles (9% (1.3MW) HP, 23% (1.8MW) LP for a total of 3.1MW)
Figure 10. Thrust, shaft speed and fuel usage. (Note first 100 seconds are for startup transients before it reaches steady state for the test).

So, even with a PTO load of ~3 MW thrust is maintained throughout the mission. Note: the corresponding increase in fuel use when PTO is on. The surge margins for the mission are shown in Figure 11 and the controls are shown in Figure 12 and 13.
Figure 11. Engine surge margins.

Figure 12. Nozzle controls
The controls are able to successfully maintain surge margin throughout the mission. The total fuel use for the mission is 1620 lbm. To compare with HPC bleed the IGV’s were fixed at ~68° so that with no PTO they maintain a 12% surge margin. The same flight conditions and PTO profiles were analyzed. A total fuel use of 1690 lbm means that more fuel was used with HPC bleed than with variable turbine inlet guide vanes. So, variable turbine inlet guide vanes are a more effective and efficient method of HPC surge margin control than HPC bleed. Therefore, all further results use only the IGV’s to control HPC surge margin with a constant customer HPC bleed enabled. Full fuel and nozzle controls are also enabled. It was found that when both IGV and bleed controls are enabled the bleed controller remains at 0 until the IGV control saturates at 61° so it effectively improves control of HPC SM beyond what the IGV can do alone and only effects fuel use in those special circumstances, however that condition is never reached in these tests so the HPC bleed controller can be disabled.
3.4 Optimal PTO profiles

Due to the coupled nature of turbine system the ratio of power being taken off the HP and LP spools can have a substantial effect on engine performance. Taking more power off of the HP results in less power being taken off the LP and vice versa. Thus, there is an optimum ratio for power take off, but is this ratio fixed or is it dependent on other factors such as altitude, Mach number, thrust, total amount of PTO and so on. The first question tackled is what combination of PTO allows for the highest total PTO achievable by the engine while maintaining the required thrust and preventing compressor surges. A MATLAB script was developed that varies the HP and LP total at different altitudes and Mach numbers. Three altitudes (10, 20 and 30 kft) and Mach numbers (0.3, 0.5, and 0.8) at 90% of the maximum thrust was analyzed. The results of this max thrust analysis is shown in Table 3 and in Figure 14 through 16.

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Table 3. Max PTO analysis
Figure 14. Max HP PTO profile.

Figure 15. Max LP PTO profile.

Figure 16. Max PTO ratio
It is clear from these results that by utilizing both shafts and HPC SM control substantial power can be extracted from the engine while maintaining thrust and preventing compressor surges. Several trends are also apparent, such as the total amount of PTO able to be extracted is much greater at lower altitudes which is to be expected from the increased air density. Also, at lower altitudes a larger portion of the PTO is extracted from the LP shaft. This is due to that at low altitudes and high Mach numbers a greater proportion of total engine thrust is produced by the core. This leads to high total power extraction from the LP shaft, however subsequent testing shows that this method is highly inefficient.

3.5 Set PTO Profiles

While finding out how much power it is possible to extract from the engine is interesting and shows the limits of the engine no real-world mission would be run with such requirements. A more practical analysis would be to find what ratio of HP to LP results in the most efficient extraction of a set amount of PTO. Again, three altitudes and three Mach numbers were run at 90% of maximum thrust and any result that could not maintain that thrust or caused a surge was rejected. This time however instead of checking to find the maximum PTO a 2MW total between the HP and LP shafts was set and the combination with the lowest fuel burn was selected. The program used to find these values is shown in Appendix B. The optimized results are given in. And the resultant HP and LP profiles are shown in Figure 17 through 19. Note the extra 74.57kW is from the 100hp constant HP PTO.
Table 4. 2MW profiles

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Figure 17. HP PTO profile.  
Figure 18. LP PTO profile.  
Figure 19. PTO ratio
Several trends can be seen here as well. At low altitudes it is advantageous to take more power off of the HP shaft while at higher altitudes favoring the LP shaft is more fuel efficient. Whereas Mach number has a smaller impact on ratio but slightly favors HP as Mach number increases.

To illustrate the fuel efficiency advantage of this ratio a comparison was done where 2MW was taken off first using the optimum ratio for a 1000 second mission and then attempting to take the 2MW off of only the HP shaft for another 1000 second mission. In both cases the total 2MW is taken off for the entirety of the mission except for the first 100 seconds which again are reserved for startup transients. The Altitude, Mach number and Thrust conditions were the same as the previous test. The results of this comparison are shown in Table 5.

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This comparison illustrates the fuel savings over the conventional HP only PTO. As expected, the fuel savings are greater at higher altitudes where a greater proportion of PTO is taken off of the LP shaft. The 2 NA’s are where the engine was unable to extract 2MW off of the
HP shaft. This shows that in addition to the fuel savings, dual shaft PTO can allow for greater amounts of power extraction than is available by conventional methods. Similar trends were found with PTO’s of different magnitudes.

3.6 Effects of heat rejection into the 3rd stream

The effect of heat rejection into the 3rd stream on engine performance was next investigated. The feasibility of adding a heat exchanger to the 3rd stream for aircraft thermal management is analyzed. The actual physics of the heat exchanger was not examined (i.e. volume, mass, etc.). An ideal heat exchanger was assumed with the energy being added directly into the 3rd stream. Initially, a study similar to the effect of PTO on SM with controls disabled was conducted with the addition of heat added to the 3rd stream.

Tests were run at 30,000ft, Mach 0.8 with a desired thrust of 9,500 lbf. Core nozzle, 3rd stream nozzle and turbine inlet guide vanes were fixed to maintain a 12% SM with no PTO. Power was then taken off as follows, 500kW was taken off the HP shaft over a 10 second interval at 300 seconds into the mission where it remains for the duration of the mission. An additional 74.57kW (100hp) is constantly taken off the HP shaft for a total of 574.57kW. At 600 seconds 500kW was subsequently taken off the LP shaft in the same manor so that at 610 seconds into the mission a total of 1.074MW is being taken off the engine. This PTO profile was chosen so as to minimize transients caused by PTO so that transients produced from the addition of heat could be better identified. In addition, around 0.59kg/s of bleed air is extracted off the HPC as customer bleed. This is equivalent to 2% of HPC mass flow with no PTO. Full fuel controllers were enabled that try to maintain the desired thrust. Afterburner was disabled (dry operation).
Heat (also known as Q in thermodynamic terminology) is generated from PTO by taking the work extracted from each shaft, multiplying it by an efficiency factor and then running it through a first order transfer function that smooths the signal at a rate dependent on the time constant of that transfer function. In this test the multiplier is 1 so when 500kW of power is extracted 500kW of heat is added to the 3rd stream after it has been delayed by the transfer function. A shorter time constant means that the heat reaches its maximum value in a shorter period of time.

An example of the PTO and a 1x multiplier for resulting heat generation with a 300s time constant (TC) is shown in Figure 20.
**Figure 20.** Example PTO and resulting Q.

This profile was run with varying thermal time constants from 5 seconds to 300 seconds. The resulting impact on surge margin is shown in Figure 21.

Adding heat to the 3\textsuperscript{rd} stream increases the temperature which subsequently increases the pressure in accordance to equation 3. However, it was determined experimentally that the second term in that equation was negligibly small and thus could be neglected.

\[
\frac{\partial P}{\partial t} = \frac{R \cdot T \cdot (\dot{m}_\text{in} - \dot{m}_\text{out})}{V} + \frac{P}{T} \cdot \frac{dT}{dt}
\]
Equation 3. Plenum volume pressure

The temperature also affects the density of the air out of the nozzle which then also affects the mass flow. This culminates in an increase in pressure ratio across the fan which lowers its surge margin. Since the exit to the fan is also the entrance to the LPC it also decreases the pressure ratio across the LPC which increases its surge margin. There is negligible effect (less than 1%) on the HPC. Another consequence is that the additional heat causes the 3rd stream to behave like an impromptu burner that increases the total engine thrust by about 113 lbf/MW. Due to this additional thrust the engine also does not need to work as hard to achieve the required thrust.

The results show that a shorter time constant increases the magnitude of the surge margin transients before the return to steady state and is unsurprisingly most pronounced in the fan. This shows that the nozzles and other surge margin controllers need to consider the anticipated rate of thermal transients to be rejected to the engine. A high thermal load suddenly put onto the engine could cause it to surge even if the steady state load would allow it to perform normally. This shows the importance of transient modeling in engine design.
Figure 21. Effects of TC on SM with no controls.
3.7 2MW profiles with Q

The 2MW PTO profiles were investigated again with a 2x inefficiency meaning that the heat produced is double what the PTO is, so if 1MW is being taken off 2MW of heat is being rejected into the 3rd stream. This is to account for additional heat generated through APU’s and other sources. This heat is run through a 300s time constant to represent the propagation of heat through the various aircraft subsystems. The results are shown in Table 6 and Figure 22 through 24.

Table 6. 2MW profiles with heat rejection.

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Figure 22. HP PTO profile with Q.

Figure 23. LP PTO profile with Q

Figure 24. PTO ratio with Q
There are slight differences in the LP to HP ratio compared to the no Q result but overall the difference is negligible. To illustrate the comparison between profiles with and without heat rejection the Mach 0.8 results showing the PTO at different altitudes are presented in Figure 25 and 26.

Figure 25. M=0.8 percent
This illustrates the high dependence of PTO on altitude. Note that the HP percentage does not vary much while the actual is decreasing, this shows that the supplemental thrust means that the core of the engine produces slightly less thrust and thus less power is available to be extracted off of the HP shaft. The addition of heat slightly decreases the amount extracted from the HP and slightly increases the amount from the LP but overall has negligible effect on optimal PTO ratios.

3.8 Full mission profile

As a final stress test of the engine a notional 15,000 second mission was developed with varying altitudes and Mach numbers from SLS to 30,000ft Mach 0.8. Thrust was also varied
throughout the mission including areas where the demanded thrust exceeds the maximum dry thrust of the engine. This mission was designed to emulate a notional real-world mission with taxi, takeoff, cruise, attack, decent and final landing. Full controls were enabled as well as the afterburner so when the mission reaches those high thrust demands the afterburner is enabled for full wet operation. This is shown by a corresponding jump in fuel usage.

A 2MW PTO demand was set for the duration of the mission, however using the information in table 6 a lookup table was developed that dynamically allocates the PTO between the HP and LP shafts depending on the mission conditions to allow for optimum power extraction. The PTO was also set to scale depending on the operating thrust so that if the engine is demanding less than 90% thrust the PTO is also correspondingly decreased. This PTO is then ran through a 2x multiplier with a 300s time constant as before and the resulting heat is dumped into the 3rd stream. The results of this mission are shown in Figure 27.

![Flight Profile](image)

**Figure 27.** Flight profile altitude and Mach number.
Figure 28. Full mission thrust, shaft speed and fuel profile. Note the increase in fuel use at around 7000 and 10000 seconds. This is where the afterburner is enabled.
Figure 29. Dynamic PTO and resulting heat rejection. Note the change in PTO proportions as a function of the flight profile and the reduction in total PTO when the thrust is less than 90%.
Figure 30. Full mission surge margins. Note the LPC transients when the flight profile and thrust is rapidly changed.
Figure 31. Full mission nozzle positions.

Figure 32. Full mission turbine IGV positions. The HPC bleed controller was enabled however it never activated as IGV’s never saturated.
This mission thus shows that all the control systems are able to properly operate over a wide range of mission conditions with both wet and dry operation as well as compensate for dynamically changing PTO and heat rejection. Around 8000 seconds into the mission there is a rapid increase in demanded thrust along with a corresponding decrease in LPC SM as the controllers are just barely able to prevent surging. The test was rerun with the PTO starting at the same time as the thrust increase and the combined transients were too significant for the controllers to compensate for and the LPC surged. This reaffirms that when and how PTO is taken off of the engine can have significant effects on performance that are not seen in steady state modeling. Significant tuning to the fuel and surge margin controllers was required to make this mission possible however, and there are conceivably other mission profiles that would require further tuning. Thus, while these simplified controllers are able to perform this notional mission there is probably no “one size fits all” configuration and thus for practical real-world applications a more sophisticated control system would need to be utilized.

4. Conclusions

Using a transient adaptive three-stream turbofan engine developed in Simulink® the power/thermal interactions of power take off were investigated and allowed for several conclusions to be made. It was found that taking power off of both the low pressure and high pressure shafts is an effective way to extract power off of the engine. High pressure compressor bleed air is an inefficient and less effective method for controlling HPC surge margin and having variable inlet guide vanes for the turbines is much more effective and efficient. While this study did not investigate the mechanical complexities of taking power off of both shafts nor the significant challenges required to articulate the turbine inlet guide vanes it nonetheless demonstrates the theoretical feasibility of these approaches.
The optimum ratio of LP to HP PTO for a given total power extraction varies at different altitudes and Mach numbers but that ratio can probably be interpolated. The optimal PTO for various altitudes and Mach numbers is not a linear relationship. Larger profiles would increase the accuracy of this interpolation. This would allow for power to be efficiently taken off throughout a mission as flight conditions change. It was found that for a given Mach number amount of power to be extracted on the LP spool increases with altitude while power to the HP spool decreases. Likewise for a given altitude as the Mach number is increased there is a distinct decrease in the LP power extraction and increase in HP extraction. This is due to the change in mass flow split between the core and bypasses resulting in a change in shaft work between the HP and LP shafts.

Rejecting heat through the 3rd stream increases thrust and decreases specific fuel consumption. Its effect on surge margin is most pronounced on the fan with negligible effect on the HPC. Analysis of transients with different thermal time constants showed that shorter time constants and thus a more rapid onset of heating can have a significant impact on fan surge margin. Controls for the fan thus must be able to respond accordingly, if a rapid thermal transient is anticipated the controls must be expected to react not only rapidly, but be able to handle a wider range of surge margin conditions (ie a nozzle must be designed to open wider then it would have to in a steady state configuration).

A full mission was then simulated to verify the feasibility of the control systems and their interaction with PTO and resulting heat rejection. The controls had to be significantly tuned to make this mission possible and further tuning might be required for other mission profiles. Thus while the simplified PI controllers used in this engine work well enough, for practical real world applications more sophisticated controllers will be needed.
4.1.1. Future Work

As stated above, for these studies a perfect heat exchanger was assumed as a feasible liquid to air heat exchanger model was not available. Once a heat exchanger is incorporated into the model it will improve the accuracy of the simulation and would allow for integration into a full tip-to-tail model of an aircraft. This would allow for full aircraft power/thermal studies to be done with actual subsystem heat generation instead of a time constant estimation.

Improved PTO profiles over a wider range of flight conditions would likely improve the accuracy of the interpolation. Flight profiles at different thrust levels and total power being taken off could also be considered, although generating several large profiles would take a considerable amount of time.

Improvements to the engine model is an ongoing process. Additional controllers could be implemented into the engine to achieve flow holding. This could include fan and LPC IGV controls or even new variable geometry components like a variable geometry mixer which would actively control the mass flow rate of the core bypass flow to the core. More complicated controllers such as neural nets might be needed to handle the complex interaction of these systems.

Longer term projects include things like the implementation of thermal soak, which is the effect of thermal expansion on the blade clearances of compressors and turbines and the resulting impact on efficiency. The ultimate goal of this development is to produce an adaptive transient variable cycle 3-stream engine capable of flow holding and supersonic operation while having a high degree of physics fidelity. This will allow for rapid trade studies to be conducted under a myriad of test conditions with a high degree of confidence in the results.
Appendix A – Turbofan Engine Components

The three-stream variable cycle turbofan engine is comprised of various components, each component is made into its own Simulink subsystem for ease of navigation. At the time of this writing, the current engine architecture is shown in Figure 33. Note most of the details of the subsystems are from Eastbourn’s thesis.

Figure 33 Current VCE architecture

The gas flows between subsystems are arranged as vectors containing a molar flow rate (N), the molar composition of the flow as mole fractions (X), and the temperature of the flow (T). This vector, called an NXT vector, is summarized in Table 7. NXT vector composition
Table 7. NXT vector composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Vector Index</th>
<th>Name</th>
<th>Chemical Formula</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1</td>
<td>Molar Flow Rate</td>
<td>N/A</td>
<td>kmol/s</td>
</tr>
<tr>
<td>X</td>
<td>2</td>
<td>JP-8 Equivalent</td>
<td>C_{10.3}H_{20.5}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Carbon Monoxide</td>
<td>CO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Carbon Dioxide</td>
<td>CO_{2}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Hydrogen</td>
<td>H_{2}</td>
<td>N.D.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Water Vapor</td>
<td>H_{2}O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Nitrogen</td>
<td>N_{2}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Oxygen</td>
<td>O_{2}</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>9</td>
<td>Temperature</td>
<td>N/A</td>
<td>K</td>
</tr>
</tbody>
</table>

A.1 Governing Equations for compressors

The VCE has three separate compressor sections, in order is the Fan, LPC and HPC. All three of them share the same governing equations however their actual properties are governed by several performance maps that are unique to each compressor. The one difference is that for the fan the inlet pressure is calculated from the ambient environment according to equation 4.

\[
P_{\text{inlet}} = P_{\text{ambient}} + \frac{1}{2}P_{\text{ambient}}[Mach\sqrt{\gamma_{\text{ambient}}R_{\text{ambient}}T_{\text{ambient}}}]^2
\]

Equation 4. Fan inlet pressure

These maps determine the corrected mass flow rate, surge margin, and efficiency. They are represented by 2D lookup tables that contains a predetermined matrix for the specific 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, shaft speed, and inlet guide vane angle. The normalized pressure ratio and shaft speed are shown by equations 5 and 6.
\[ P_{\text{normalized}} = \frac{P_{\text{out}}}{(P_{\text{in}}) (P_{\text{design}})} \]

**Equation 5.** Compressor normalized pressure ratio

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

**Equation 6.** Compressor normalized 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.

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

**Equation 7.** Compressor 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. These are also used in the compressor efficiency maps and the efficiency is used to determine the outlet temperature of the compressor according to equation 8.

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

**Equation 8.** Compressor outlet temperature

The work absorbed by the compressors 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 compressor model, as shown by equation 9.

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

**Equation 9.** Compressor work

The surge margins are determined from Equation 1.

**A.2 Governing Equations for the combustor**

The pressure across the combustor is modeled as a fixed pressure drop governed by equation 10.

\[
P_{Inlet} = 1.1067(P_{Outlet})
\]

**Equation 10.** Combustor pressure drop

The major concern for the combustor was 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 which is done by summing the enthalpies of the specific components according to equation 11 where i is the species (JP-8, CO, CO$_2$, H$_2$, H2O, H$_2$O$_2$).

\[
h = \sum Cp_i N_i
\]

**Equation 11.** Enthalpy calculation

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 CO2 and H2O as the sole products of the reaction. The equation governing the combustion process is shown in equation 12.

$$C_{10.3}H_{20.5} + 15.425O_2 \rightarrow 10.3(CO_2) + 10.25(H_2O)$$

**Equation 12.** Combustion equation

In conceptual terms, this shows that for every kmole of JP-8 fuel entering the combustor, 15.425 kmoles of O2 will be consumed, 10.3 kmoles of CO2 will be produced, and 10.25 kmoles of H2O will be produced. These products are then combined with the incoming air stream to yield the molar composition of the combusted mixture. The energy of the combustion process is determined by the combustion values for the relevant species (JP-8, CO2, and H2O) which is used to determine the heat produced. This heat is then fed into an energy balance with the enthalpy flow of the incoming air and fuel streams and the outlet 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).

The total specific heat of the outgoing stream is required to determine the stream temperature. To find this the molar composition of the stream is found and used to find the
specific heat of the individual species. The molar composition of the stream is shown in equation 13 and the specific heat in equation 14.

\[ X_i = \frac{N_i}{\sum N_i} \]

**Equation 13. Molar composition**

\[ C_{p_{outlet}} = \sum C_{p_i} X_i \]

**Equation 14. Specific Heat**

The outlet temperature also depends on the molar concentration, shown in equation 15.

\[ C = \frac{P_{Inlet}}{RT_{Outlet}} \]

**Equation 15. 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). Finally, the temperature of the combustor outlet stream can be found using equation 16.

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

**Equation 16. Combustor outlet temperature**

Where V is combustor volume and \( Q_{net} \) is given by equation 17.

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

**Equation 17. Q net**

The heat of reaction is found using equation 18.
\[
\text{Heat of Reaction} = -N_{C_{10.3}H_{20.5}}h_{f_{C_{10.3}H_{20.5}}} - N_{CO}h_{f_{CO}} + \\
(10.3N_{C_{10.3}H_{20.5}} + N_{CO})h_{f_{CO_2}} + (10.25N_{C_{10.3}H_{20.5}} + N_{H_2})h_{f_{H_2O}}
\]

\textbf{Equation 18.} Heat of reaction

With the outlet temperature of the combustor now known, the final NXT vector signal leaving the combustor can be defined. The outlet mass flow rate of the combustor is found using the NXT vector and the molecular weights of the constituent species shown in equation 19. Where \(M_i\) is the molecular weight of the species.

\[
\dot{m}_{out} = N \sum X_i M_i
\]

\textbf{Equation 19.} Mass flow out of combustor

\textbf{A.3 Governing equations of the turbines}

The VCE has two separate turbines, the high-pressure turbine which is immediately after the combustor and drives the high-pressure shaft, and the low-pressure turbine which is after the high-pressure turbine and drives the low-pressure shaft. Like the compressors they are governed by similar equations however each has a separate turbine map that defines their operation. Each turbine has maps that determines the efficiency and corrected mass flow rate for a given shaft speed, pressure ratio across the turbine and inlet guide vane angle. The equations for the pressure ratio and corrected shaft speed are shown in equations 20 and 21 respectively.
Pressure Ratio = \frac{P_{out}}{P_{in}}

**Equation 20.** Turbine pressure ratio

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

**Equation 21.** Turbine corrected shaft speed

These signals are then used by the performance maps to find the corrected mass flow rate, which is subsequently used to find the actual mass flow rate through the turbines in accordance to equation 22.

\[ m_{actual} = m_{corrected} \frac{P_{in\,std}}{P_{std}} \frac{T_{std}}{T_{in}} \]

**Equation 22.** Turbine outlet mass flow rate

The inlet pressures to the turbines are determined from a plenum volume calculation from the combustor outlet and the HP turbine outlet respectively. The mass flow rates entering the plenum volumes are known and thus conservation of mass dictates that the mass flow rate exiting the plenum volume must be equivalent to the outlet mass flow rate 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 as shown by equation 23. (Note there are actually 2 terms in the equation however the 2\textsuperscript{nd} term was
experimentally determined to be insignificant due to low thermal transients as shown in Equation 3).

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

**Equation 23.** Turbine inlet pressure

The outlet temperatures from the turbines is determined by the efficiency performance map. This map interpolates the shaft speed and pressure ratio and inlet guide vane angle to find the turbine efficiency. This efficiency is then used to calculate the turbine outlet temperature as shown in equation 24.

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

**Equation 24.** Turbine outlet temperature

The work produced by the turbines is based on the outlet mass flow rate as well as the inlet and outlet temperatures, which are used to calculate the enthalpy values. These enthalpies are then used to find the work as shown in equation 25.

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

**Equation 25.** Turbine work

**A.4 Bypass plenum volumes**

The engine model has two bypass plenum volumes. The core bypass flows air from the LPC, and bypasses the HPC, burner, and turbines to merge with the core flow in the mixer just before the afterburner and core nozzle. The 3rd stream bypass flows air from the fan to an exhausted nozzle bypassing the rest of the engine entirely. These models determine the mass flow of air through these streams and their pressure. The core bypass is assumed to be adiabatic
with no change in flow temperature while for the third stream the only change in temperature is due to the third-stream heat exchanger. The mass flow rate through the respective bypass ducts is calculated from equation 26.

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

**Equation 26.** Bypass mass flow rate

The inlet pressure for the core bypass is the exit pressure from the LPC, and the inlet pressure for the 3rd stream bypass is the exit pressure from the fan. The pressure out of the plenum volumes is calculated from equation 27.

\[
P_{\text{bypass}} = \int \frac{(\dot{m}_{\text{in}} - \dot{m}_{\text{out}}) * R * T_{\text{bypass}}}{V_{\text{bypass}}} \, dt
\]

**Equation 27.** Bypass plenum volume pressure

Due to the anticipated thermal transients from the heat exchanger the 3rd stream uses Equation 3. Plenum volume pressure, however, it was found experimentally that even with thermal transients the 2nd term in the pressure calculation was negligible. Thus equation 27 is sufficient for all plenum volume pressure calculations.

**A.5 Mixer**

The mixer combines the core stream from the LP turbine and core bypass stream from the core bypass plenum volume and creates a single uniform stream for entrance into the afterburner and then the core nozzle. 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 molar flow rate term for the mixer, \( N_{\text{mixer}} \), is found by summing the core and bypass NX terms as shown in equation 28.
\[ N_{\text{Mixer}} = \sum \left[ (N_{\text{Core}}X_{\text{Core}i}) + (N_{\text{Bypass}}X_{\text{Bypass}i}) \right] \]

**Equation 28.** Mixer volume molar flow rate

With the molar flow rate of the mixer known, the new molar composition can be found with equation 29.

\[ X_{\text{Mixer}i} = \frac{\sum \left[ (N_{\text{Core}}X_{\text{Core}i}) + (N_{\text{Bypass}}X_{\text{Bypass}i}) \right]}{(N_{\text{Core}}X_{\text{Core}i}) + (N_{\text{Bypass}}X_{\text{Bypass}i})} \]

**Equation 29.** Mixer volume molar composition

The temperature of this new mixture is found from integrating the energy balance of the streams entering and exiting the mixer plenum volume. This is done by calculating the enthalpy of the core and core bypass streams using equations 30 and 31. Where i is the species (JP-8, CO, CO\textsubscript{2}, H\textsubscript{2}, H\textsubscript{2}O, H\textsubscript{2}O\textsubscript{2}).

\[ h_{\text{inCoreStream}} = N_{\text{Core}}T_{\text{Core}} \sum (X_iCp_i) \]

**Equation 30.** Mixer inlet core stream enthalpy

\[ h_{\text{inBypassStream}} = N_{\text{Bypass}}T_{\text{Bypass}} \sum (X_iCp_i) \]

**Equation 31.** Mixer inlet bypass stream enthalpy

The enthalpy is also calculated for the mixed stream exiting the mixer as shown in equation 32.

\[ h_{\text{OutMixture}} = N_{\text{Mixture}}T_{\text{Mixture}} \sum (X_iCp_i) \]

**Equation 32.** 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 33, will be used to determine a temperature of the mixture.

$$Q_{Net} = h_{inCoreStream} + h_{inBypassStream} - h_{out}$$

**Equation 33.** Mixer total energy

In addition, the concentration, $C$, must be found to calculate the mixer temperature. $C$ is found using equation 34.

$$C_{Mixer} = \frac{P_{Mixer}}{R T_{Mixer}}$$

**Equation 34.** Mixer concentration

The final mixture temperature is thus found using equation 35.

$$T_{Mixer} = \int \frac{Q_{Net}}{V_{Mixer} * C_{pMixer} * C_{Mixer}} dt$$

**Equation 35.** Mixer volume temperature

The values for the outlet molar flow rate ($N$), molar composition ($X$), and temperature ($T$) of the outlet stream are then combined into the outlet NXT vector entering the afterburner. The pressure of the mixer plenum volume is calculated in the same manner as the other plenum volumes using an integration of the ideal gas law as shown in equation 36. The mixer inlet mass flow rate is the sum of the core mass flow rate and the core bypass mass flow rate.

$$P_{Mixer} = \int \frac{(m_{in} - m_{out}) * R * T_{Mixer}}{V_{Mixer}} dt$$

**Equation 36.** Mixer volume pressure
A.6 Afterburner

The afterburner comes directly after the mixer. When engaged it automatically activates when the engine is unable to produce the demanded thrust. The logic of the activation and control system is detailed in Buettner’s thesis. The mechanics of the afterburner closely follow the combustor system with the main difference is that the afterburners NXT is from the mixer. When the afterburner is not running either when it is not engaged or simply not activated at that point in the mission it acts as a simple adiabatic pressure drop before the core nozzle.

A.7 Nozzles

The engine model also has two nozzles. The core nozzle is the final component in the core and core bypass flow paths. Air from the LP turbine outlet and the bypass plenum volume are combined in the mixer volume before entering the nozzle. The 3rd stream nozzle is the final component of the 3rd stream flow path. Both consist of converging-diverging nozzles which combined create the total thrust of the engine. Several steps are required to determine the mass flow rates, exit velocities and thrusts of the nozzles. Both nozzles use the same governing equations.

The first step is to calculate the critical pressure ratio, this is then compared to the actual pressure ratio of the nozzle to determine if the nozzle flow is choked or not. If the actual pressure ratio is less than the critical pressure ratio then the nozzle is choked, otherwise the flow is non-choked. The critical pressure ratio is shown in equation 37.

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

**Equation 37.** Nozzle critical pressure ratio
If the nozzle is choked the exit mass flow is determined by equation 38.

\[
\dot{m}_{\text{Exit}} = P_{\text{in}} A_{\text{Throat}} \sqrt{\frac{\gamma}{R T_{\text{in}}}} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}
\]

**Equation 38.** Nozzle outlet mass flow rate for choked flow

In order to find the nozzle exit velocity the exit Mach number and the exit temperature must first be found. The Mach number is found from equation 39.

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

**Equation 39.** Nozzle outlet Mach number for choked flow

The temperature of the nozzle exit velocity is then found with equation 40.

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

**Equation 40.** Nozzle outlet temperature for choked flow

The final exit velocity can then be found using equation 41.

\[
V_{\text{Exit}} = M_{\text{Exit}} \sqrt{\gamma R T_{\text{Exit}}}
\]

**Equation 41.** Nozzle outlet velocity for choked flow

If the nozzle was determined to be non-choked a slightly separate set of calculations are performed. The Mach number, temperature and velocity of the exit are performed the same as with choked flow however the mass flow rate is determined by equation 42.

\[
\dot{m}_{\text{Exit}} = M_{\text{Exit}} \sqrt{\gamma R T_{\text{Exit}}} \frac{P_{\text{Exit}}}{R T_{\text{Exit}}} A_{\text{Exit}}
\]

**Equation 42.** Nozzle outlet mass flow rate for non-choked flow
The final thrust produced by the engine is based on the mass flows entering and exiting the engine through both the core and 3\textsuperscript{rd} stream bypass nozzles as well as the pressure differences between the nozzles and the ambient air. The inlet mass flow rate is the fan mass flow rate and the inlet velocity are calculated using equation 43.

\[ V_{\text{Inlet}} = Mach_{\text{Aircraft}} \sqrt{yRT_{\text{Ambient}}} \]

**Equation 43.** Nozzle inlet velocity

Thus, the total thrust is found from equation 44.

\[ Thrust = \left( m_{\text{Exit core}} V_{\text{Exit core}} + m_{\text{Exit bypass}} V_{\text{Exit bypass}} - m_{\text{Inlet}} V_{\text{Inlet}} \right) + A_{\text{Exit core}} (P_{\text{Exit core}} - P_{\text{Ambient}}) + A_{\text{Exit bypass}} (P_{\text{Exit bypass}} - P_{\text{Ambient}}) \]

**Equation 44.** Nozzle thrusts

**A.8 Shafts**

The engine model is equipped with two separate shafts that simulate the rotational inertia of the internal engine components. The HP shaft connects the HP turbine to the HP compressor. Power from the HP turbine is transferred by the HP shaft to drive the HP compressor. The LP shaft connects the LP turbine to the LP compressor and fan. Power is extracted from the LP turbine and is transferred by the LP shaft to drive both the LP compressor and fan. Both shafts use the same governing equation shown in equation 45.

\[ RPM_{\text{Shaft}} = 30 \int \frac{\sum \text{Load}_i + \left( \frac{\text{RPM}_{\text{Shaft}}}{N_{\text{Design}}} \right)^2 (\text{Friction Loss})}{I_{\text{Shaft}} (\omega_{\text{Shaft}})} \, dt \]

**Equation 45.** Shaft speed
Where $I$ is the moment of inertia of the shaft and $\text{Load}_i$ are the different loads placed on the shaft with driving forces such as from the turbines being positive and extractions from compressors and other PTO are negative. Loads are in kW.
Appendix B – How to use the engine model

Hello! This is a more lighthearted how to guide to use the engine. I personally find retaining information easier when it is presented in a more personable manner and I hope it helps you as well. It might seem daunting at first but I will do my best to walk you through the intricacies of the engine model so soon you too will be generating data for your own research in turbofan engines. I assume you have at least some familiarity in MATLAB/Simulink and if not Dr. Roberts will graciously provide you with a tutorial (tip when building your own version of his fuel cell remember the initial conditions of the integrators).

Ok so to begin you need to know how to load the engine. The engine is located on the R drive under the folder “Adaptive Turbine Engine” and inside that there will be another folder labeled 3 stream engine v(number) you will want to pick the latest version. Once inside there will be a lot of files, don’t worry many of them just store parameters for when you load the engine. Click on the file named “OpenThreeStream_ForCSV.m” this is the main loading function for the engine. Note near the top there is a variable called “resizing_factor” changing this value is how you can resize the engine to arbitrary thrust values but more on that later, hit run.

Behold the engine! Simulink should pop up, if not double click “ThreeStream_Engine_V_E_3.slx” in the folder. Once it is up take a note of the large block with the beautifully rendered diagram of the engine, that is the engine model itself. Around it are support systems and readouts. If you want to jump right in and make sure it works, make sure that the simulation time at the top of the screen is set to 1000 and the simulation mode is set to Accelerator. It can run on normal but it takes longer and trying rapid accelerator causes Simulink to hang for a while before finally saying that it can’t build a target so don’t bother with it. Once the model has run click on the green “Double click to Plot Results” button to pull up the results.
of that mission. I will go into detail about those plots later, let’s first analyze the stuff around the engine.

Starting from the top and going clockwise is fuel readouts showing total fuel and fuel rate in kg and lbm. The two subsystems Fuel_Flow and Fuel1 simply add the fuel from the main burner and afterburner and establish the properties of the fuel respectively. You probably won’t be messing much with them.

Top right is the engine monitor, this is the primary place where variables and engine parameters are output to MATLAB for post processing (i.e. graphing). If you want to modify the graphing function (more on that later) and you need to know where a specific value is, look in the bus in the monitor section. Elements in a signal are listed in the numeric order they appear on the bus, for example the fan surge margin is the 11th signal on the Engine.Fan bus so to call it in MATLAB you would use Engine_Fan(11).

Under the engine monitor are displays of engine readouts such as turbine inlet temperature (TIT), rotation rates of the HP and LP shafts, the core nozzle inlet temperature and the fan mass flow rate. To the right of the engine model are the specific fuel consumption and thrust displays.

The lower right is the control panel subsystem inside it can look pretty daunting but most of the controls are to set constants. Starting from the top and working your way down.

Pseudo-Constant Thrust Demand – This sets the constant thrust in the cruiseConditionSetPoint subsystem, you will most likely not be controlling thrust this way so you can ignore it.

3rd Stream Nozzle Control – This sets the value of the 3rd stream nozzle when it is set to fixed. It
does nothing when the 3\textsuperscript{rd} stream controller is enabled. It is currently set to maintain a 12\% surge margin on the fan with no PTO at 30k ft M0.8 and a thrust of 9,450lbf. Note that even when the controller is disabled it is still enabled for the first 100 seconds of the mission because of startup transients.

Fan IGV Angle – This controls the inlet guide vane angle of the fan. The IGV angle controls the mass flow rate and efficiency of the fan and could possibly be used for flow holding. It’s controllers currently do not work so it is best to keep it at its lowest value (ie fully open).

LPC IGV Angle – Same as the fan IGV angle but for the LPC. As with the fan keep it fully open. To establish flow holding you might need to oversize the Fan and LPC like I did the turbines in which case choosing a different IGV angle could be needed.

Fan IGV Selector – Controls the Fan IGV controller, does not currently work, leave at constant.

LPC IGV Selector – Same as fan, controller does not currently work, leave as constant.

HPT IGV Angle – Controls IGV angle of the HPT. Since the HPT is oversized it is set to maintain a 12\% SM on the HPC at the same conditions as the 3\textsuperscript{rd} stream nozzle fixed value.

LPT IGV Angle – Same as HPT IGV angle but for the LPT.

HPT IGV Constant or Variable – Sets the HPT IGV controller, controller is enabled when set to variable. Note that even when set to constant the controller is enabled for the first 100 seconds due to startup transients.

LPT IGV Constant or Variable – Same as HPT only for the LPT controller.

Afterburner Logic – Sets afterburner controller, when disabled afterburner will not run and all
missions will be dry. When enabled afterburner will activate when dry condition cannot achieve required thrust. Drastically increases fuel consumption.

3rd stream nozzle control – Sets 3rd stream nozzle controller. When set to constant it uses value set by the 3rd Stream Nozzle Control knob but controller is still enabled for the first 100 seconds due to startup transients.

Core nozzle controller – Sets core nozzle controller similar to the 3rd stream and turbine IGV controllers. Again, when set to constant controller is still enabled for the first 100 seconds.

Variable HP PTO Control – Enables use of the PTO profile set in the Engine_Request and power take off subsystem. Note that even when set to Zero the Constant HP PTO will still apply.

Variable LP PTO Control – Same as the HP PTO controller, again even when set to Zero the constant LP PTO will still apply.

Constant HP PTO – Constant amount of power taken off of HP shaft, enabled even when other PTO is disabled. Currently set to 74.57kW, (100hp)

Constant LP PTO – Same as the constant HP PTO but on the LP shaft, currently set to 0.

Third Stream HX Control – Enables heat exchanger model for the 3rd stream. When uninstalled the system assumes a perfect heat exchanger and heat is dumped directly into the 3rd stream.

HPC Bleed Control – Sets the HPC bleed controller. When set to constant the only bleed air is from the customer bleed. When set to Variable a controller bleeds air to maintain 12% HPC SM in addition to the customer bleed.

Customer Bleed – This sets the constant customer bleed air from the HPC. It is currently set to 2% of HPC mass flow rate at cruise.
So that is the control panel out of the way, remember that those knobs control constants in the model, even the switches control constants going to multiport switches and it might be more effective just to change the constants directly rather than having to mess with knobs.

Directly below the engine model is the 3rd stream HX along with more readouts. As stated above the HX is currently disabled. This is because the current version only works as an air/air HX and thus requires impractical sizes in order to dissipate the megawatts of heat this engine can produce. When you try to change the fluids to something more sensible such as JP8 or H2O the model either runs extremely slowly or straight up breaks. Try to get Dr. Roberts to help you fix it as he is the one who wrote it and his programming style is…esoteric. Note that with the HX disabled the Q in goes straight into Q_fan which goes straight to the 3rd stream inside the engine.

To the left of the HX is the Hot fluid in subsystem. This takes the heat from PTO and uses it to heat a fluid to go into the HX. Since the HX is disabled however this subsystem simply sends the heat from the PTO heat generator to the HX. Note that inside it you can use a manual switch to enable a constant heat flow into the HX that is independent of PTO.

Lower left of the engine is the PTO heat Generation subsystem. This subsystem takes the amount of power taken off of the shafts and generates heat by multiplying the PTO by an efficiency factor and running it though a time constant, both are specified in the block parameters. Note the manual switch coming from it which allows missions to be run both with and without PTO heat.

Above and to the left of the engine are the two plotting buttons. The green one on the left simply plots the functions for you, while the light blue one to the right plots the functions and generates a MATLAB.fig file in the current folder (most likely the folder the model is in but
could change depending on what MATLAB is currently set as) with the name “Test_figures” followed by the date and time of creation. Both of these buttons call the Post_Analysis.m file, and if you are wondering how they work (It took me a while to figure it out myself) right click on the button and hit properties and then go to Callbacks, it calls the OpenFcn function.

Above the plot buttons is the Engine_Request and power take off subsystem. In it is quite a lot but the main things you have to work with is the power take off profiles. These are stored in the repeating tables, note that there are 4 tables but only 2 shafts. This is because there are two ways I have tested to take power off the engine, a percentage of actual shaft power, and an absolute power take off. The absolute simply takes the power directly off the shaft, if you want 1MW off of the LP shaft that is what you are getting. The percentage takes a set percentage off of the total work on that shaft, so if the fan and LPC combined are both using 10MW and you pull 10% of that, you will actually be pulling 1MW off of the shaft (Note fan and LPC work is added together while HPC stands alone). This is a less precise and realistic method of taking power off however it has the benefit of being more stable for the engine. Remember to have the correct PTO type selected with the manual switches, you can easily see what you have selected when you plot the mission. There is also the optimum ratio subsystem where you feed it in a single PTO profile and using the ratios found in Table 6 automatically determines the needed ratio between HP and LP.

When taking significant absolute amounts of power off of the engine it can cause major transients in the engine. I have found the solution to those transients to be increasing the moment of inertia of the shafts. In fact, I encourage you to reduce the moment of inertia of the shafts and see how the integrator in the core nozzle breaks and play the “follow the insane signal” game to see how signals propagate throughout the engine (hint, look at how compressor efficiency is
impacted by shaft transients). Another note to the right in this subsystem if the bleed control subsystem. This is where the constant customer bleed is set.

Above the Engine Request and Power take off subsystem are the main engine controllers. This includes the main and afterburner fuel controllers, the core nozzle controller, 3rd-stream nozzle controller, the turbine IGV controllers, and the inactive fan and LPC controllers. All of the controllers use the same PI controller system and can possibly be tuned to reduce instabilities and improve performance. However tuning controllers is more of an art then a science and with this many controllers all working together it could become quite an undertaking. I have found that sometimes doing the opposite of what your gut feeling tells you can be the right call. For example, for the full mission shown above I had numerous numerical instabilities with surge margin, so the gut feeling would be to lower the coefficients of the respective surge controllers, but instead the solution was to increase the coefficients of the main burner thrust-to-EPR controller. When dealing with instabilities try tweaking that first, but also use multiplication factors so you can easily revert to the previous value.

At the top left is the cruiseConditionSetPoint subsystem. It is in this subsystem that you set your mission parameters. There are two repeating tables for Altitude, Mach number and thrust demand. One is for test missions and the other is for the full mission used by Buettner to test the engine. Note the test missions are 1000s long while the full mission is 7700 long, remember to set the simulation time accordingly along with making sure the PTO profiles (if you are using them) match. The engine is particularly finicky with startup conditions, I find that it works best if you start each mission at the same conditions and ramp up or down to the test conditions over a 100 second time frame. The engine likes to start at sea level (0 alt) at M0.3 with a high thrust (currently set to 30,000 lbf which is higher than the engine can produce so it
runs flat out). As long as you start at those conditions you should not have to worry about startup transients breaking the engine.

Inside the engine model itself are all of the major components of the engine. It can be pretty daunting at first but remember there is nothing magical happening here, it is all just math, and hence why I recommend playing the “find the insane signal” game. Just put down displays and scopes everywhere so you can figure out how signals are created and modified. Remember pressure is generated at the nozzles of the engine and propagates forward while temperatures and mass flows propagate from the front. It will take some time, but you will get it. Remember that all of the values in this engine are arbitrary, until we actually have a real-world model to base this one off of we can use whatever values we want, just try to make sure they are reasonable. I suggest playing with those values a bit, increase or decrease a design mass flow or temperature for a component and see what happens. When you do change it I would recommend simply multiplying the original value by a number so that you can easily delete the multiplication factor and go back to the original value. This is your engine now, do not treat any system or value as gospel, Buettner made mistakes, I made mistakes, you will make mistakes, just remember to keep a backup to revert to for when things go really bad.

Speaking of modifying the engine, resizing the engine to an arbitrary thrust can be done quite easily with the resizing factor. Typically, an engine is sized to sea level static (SLS) so in the cruiseConditionSetPoint subsystem set the altitude to 0 and the Mach commands to 0. It might not like starting at 0 Mach so for the Mach Commands repeating table set the output values to [0.3 0 0]. Set the thrust to be something absurdly high like 50,000lbf so that the engine is running flat out. Make sure the afterburner is off (dry operation) and that the PTO is off (except for the constant customer PTO) and that all of the surge margin controls are enabled
(Core nozzle, 3rd stream nozzle, both turbine IGV controllers). Run the mission and if the resulting thrust is higher then what you want to lower the resizing_factor and run the loading script again and run again, if it is a lower thrust then you want, increase the resizing_factor. With a bit of trial and error you should be able to meet your target thrust within a few tries. The resizing_factor is simply a multiplication factor of the design mass flow rates and volumes of the various engine components. Note that the resizing factor is not just in the engine but is in the Post_Analysis function as well to scale the compressor maps, if you remove the resizing factor you will need to remove it from that function as well.

When you hit the plot results button a large amount of graphs pop up and it can be pretty daunting itself but like everything else with the engine there is nothing magic or archaic about it and you will get used to it with time. The first tab to pop up is the Flight Profile tab, this simply shows the altitudes and Mach numbers the engine flew over the mission, pretty self-explanatory. The F_C tab shows the total pressures, total temperatures and mass flows through the fan and LPC. The HPT_LPT tab shows the same thing as the F_C tab but for the high-pressure and low-pressure turbines, the mass flow graph also shows the flow through the core and 3rd stream bypass. Speaking of bypass, the Bypass tab details the pressures, temperatures and bypass ratios of those bypasses.

The PTO Loads tab shows what the loads on each shaft are over time. It shows the PTO both in absolute power being taken off, and as a percentage of the total power on the shaft. If you take power off in absolute mode the percentage graph will be “wobbly” and vice versa if you take power off in percentage mode. The Fan HX tab shows the heat rejection and pressure drop into the 3rd stream. The heat rejection comes directly from the PTO heat Generation subsystem.
The HX Temps tab details the 3rd stream HX, until a proper HX is installed this won’t be of much use.

The performance tab shows the thrust, shaft speeds and fuel usage. Part of the criteria for a successful mission is maintaining the required thrust. If you see dips in the thrust when PTO is put on then that means that it is more than the engine can handle for that mission and you need to reduce the power being taken off. Surge Margin Tracking is also an important aspect of the mission. The controllers are set to maintain a 12% surge margin of all three, but some deviations are allowed due to transients. The main thing to look out for is if any of them reach 0 at any part of the mission. If the surge margin reaches 0 that means that the engine has surged, and the mission is not viable. Since PTO has a major effect on surge margin consider the amount of power being taken off.

HPC bleed control, this shows the status of HPC bleed both as an absolute mass flow rate and as a percent of total mass flow through the HPC. This controller will most likely be disabled in the majority of tests and thus the absolute bleed will be constant while the percentage can vary due to a change in HPC mass flow. IGV control shows the position of the HPT and LPT IGV’s throughout the mission. Note they have to stay between 61 and 75, if you see them peg at one value or another that means that they will not be able to effectively maintain HPC SM and thus the mission is probably outside of the operational bounds of the engine.

Efficiencies, this shows the compressor and turbine efficiencies, they should typically be around 90%. Nozzles shows the core and 3rd stream nozzle area they have a minimum value of 0.1 and a maximum value of 1. Again, like the IGV’s if you see these pegged it most likely means that the mission is outside the bounds of the engine, either change the mission or change the engine parameters. Work shows the Fan and LPC work on the LP shaft.
The Fan, LPC and HPC maps are another way to show surge margin. The red curved line is the surge line, if the compressor line ever crosses it that means the engine has surged. Most of the time however you will probably use the Surge Margin Tracking tab.

The Post_Analysis function itself is simply a series of plot functions. It was written in an older version of MATLAB and thus some of its commands can look a bit archaic, but it is not that complicated on its own. Feel free to add or edit any graph you wish in order to convey the information you want. A note if you want to add in a new to workspace block to output a new signal, in the Sample time section of the block parameters block put “Data_Sample.Value” if you leave it as default the results will be skewed and won’t line up.

Last but not least are the PTO optimization functions that I wrote. The older one is called “Max_PTO_profile_test_optimized” and when run it finds the ratio of HP and LP PTO in order to find the maximum amount that can be extracted from the engine at given Altitudes, Mach numbers and Thrust demands. The other is called “set_PTO_profile_test_optimized” where you set the total amount of PTO you want taken off and it finds the optimal ratio at different altitudes, Mach numbers and thrust demands. Both have step by step instructions on how to set up the model for them to run. Note the max PTO function uses the percentage PTO while the set PTO function uses the absolute PTO. If you find bugs, feel free to fix them. I am constantly finding and fixing bugs in my code and I cannot guarantee I won’t pass some on to you.

Good luck! It is a daunting task, but I know you are up for it. If you need help Dr. Wolff and Roberts should be able to give advice. If you get frustrated take a break, let the problem mull around in your head for a while, you might get an AHA or “why didn’t I think of that sooner?”. Just don’t get discouraged and remember, this is fine!

Also, don’t forget to bring a towel!
Appendix C – PTO optimization code

% This program finds the optimal power take off profile ratios between the
% LP and HP shafts at given altitudes, mach numbers and thrusts. It
% optimizes results based on fuel use and ensures that for the results the
% engine is capable of
% maintaining thrust and does not surge.

% Test of the power/thermal interactions of the three stream engine
% This test is designed to run with the ThreeStream_Engine_V_E_3
% Written by Andrew DeSomma for Wright State University
% Preparation
% 1. Set Simulation time to 1000 seconds.
% 2. In control panel set
%    Fan IGV Angle to 0
%    LPC IGV Angle to 0
%    LPT IGV Angle to 0
%    HPT IGV Constant or Variable - Variable
%    Afterburner Logic - Disabled
%    3rd stream nozzle control - Variable
%    Core Nozzle Controller - Variable
%    HP PTO Control - Variable
%    LP PTO Control - Variable
%    Third Stream HX Control - Uninstalled for direct heat injection to the
%    3rd stream, Installed to use HX, note only matters if PTO Heat is
%    turned on - see below
%    HPC Bleed Control - Constant
% 3. Set the manual switch to the right of the PTO Heat Generation
%    subsystem up for PTO heat to the 3rd stream, or down for no heat.
% 4. In the cruise condition set point subsystem set the Altitude Commands
%    repeating table time values to [0 100 1001] and output values to [0
%    Alt_cmd Alt_cmd]
% 5. Set the Mach Commands repeating table time values to [0 100 1001]
%    and the output values to [0.3 Mach_cmd Mach_cmd]
% 6. Set the Thrust Commands repeating Table time values to [0 100 1001]
%    and the output values to [30000 Thrust_cmd Thrust_cmd]
% 7. In the Engine_Request and power take off subsystem set the
%    HP_Load_Commands (kW) absolute repeating table time values to [0 100 110
%    700 710 1000]
%    and the output values to [0 0 HP_PTO HP_PTO 0 0]
% 8. Set the LP_Load_Commands (kW) absolute repeating table time values to [0
%    300 310 900 910 1000]
%    and the output values to [0 0 LP_PTO LP_PTO 0 0]
% 9. Make sure the appropriate repeating tables are selected with manual
%    switches.
% 10. Make sure there is no file named Temp_Save in the main folder if you
%    do not want to continue from a previous test.

% The output will be in the form of 2 surface plots, one for the LP PTO
% percentage and the other for the HP PTO percentage. These plots will be
% saved under the file name "PTO_figures" followed by the date and time of
% completion in the same folder this program is in.
% The other main output is the variable "PTO_profile" which contains a list
% of all of the envelopes used. It is saved in a file called "PTO_Profiles"
% followed by the date and time.
%---------------------------------------------------------------------------
tic

warning off; %disables simulink warnings
% checks to see if a temp save exists and if so load from it
if exist('Temp_Save.mat','file') > 0
  load('Temp_Save');
  thrust_error = false;
  disp('Temp save found, loading parameters');
  A_start = A_save;
  M_start = M_save;
else
  count = 1;
  time_running(count) = toc;
  Mach_profile = [0.3 0.5 0.8];
  Altitude_profile = [10000 20000 30000]; % ft
  Test_thrust_percent = 0.9; % Percentage of max thrust to test at 0.9 is 90%

  % Maximum PTO
  Max_PTO = -2000; % kW
  if Max_PTO > 0
    Max_PTO = -Max_PTO;
  end
  Mach_profile = sort(Mach_profile); % Makes sure profile is in ascending order
  Altitude_profile = sort(Altitude_profile);
  assert(Test_thrust_percent < 1, 'Test thrust must be less then 100% of max thrust');
  assert(min(Mach_profile) >= 0, 'Mach must be above 0');
  assert(min(Altitude_profile) >= 0, 'Altitude must be above 0');

  disp('Finding thrust profile')
  Max_Thrust_profile = zeros(length(Mach_profile),length(Altitude_profile));
  Test_Thrust_profile = zeros(length(Mach_profile),length(Altitude_profile));
  Full_fuel = zeros(length(Mach_profile),length(Altitude_profile));
  Full_SFC = zeros(length(Mach_profile),length(Altitude_profile));
  thrust_error = false;
  Thrust_cmd = 50000;
  HP_PTO = 0;
  LP_PTO = 0;

  for M = 1:length(Mach_profile)
    Mach_cmd = Mach_profile(M);
    if thrust_error == true
      break;
    end
    for A = 1:length(Altitude_profile)
      Alt_cmd = Altitude_profile(A);
      try
        simOut = sim(Model_Name, 'SimulationMode', 'Accelerator'); % start simulation
Engine_Monitoring = simOut.get('Engine_Monitoring');
Time = simOut.get('Time');
Elements = 500:1:length(Time);
Actual_thrust = Engine_Monitoring(Elements,1)*224.81;
Max_Thrust_profile(M,A) = mean(Actual_thrust(45000:55000));

Fuel = simOut.get('Fuel') * 2.20462; % lbm
Full_fuel(M,A) = Fuel(end);
Engine_Monitoring = simOut.get('Engine_Monitoring');
SFC = ((Engine_Monitoring(Elements,5)*3600)/0.4536) ... %

(lbm/hr)/lbf
./((Engine_Monitoring(Elements,1))*224.81);
Full_SFC(M,A) = mean(SFC(45000:55000));

message = ['At ',num2str(Alt_cmd),' ft and Mach: ','num2str(Mach_cmd),', 'The max thrust is: ',num2str(Max_Thrust_profile(M,A))];
disp(message);
catch
    error_message = ['At ',num2str(Alt_cmd),' ft and ','num2str(Mach_cmd),', 'Mach The engine broke for some reason!'];
disp(error_message);
thrust_error = true;
break;
end
if thrust_error == false
    save('Temp_Save','Mach_profile','Altitude_profile','Test_thrust_percent','Max_PTO','Max_Thrust_profile','Full_fuel','Full_SFC','Fuel_weight','Temp_weight','Mass_flow_weight');
end

PTO_profile = {'Alt','Mach','Max Thrust','Test Thrust','HP PTO%','LP PTO%','LP PTO Abs','LP PTO Abs','Total PTO','LP_abs/HP_abs','SFC','PTO/SFC','Fuel used','Baseline SFC','Baseline fuel','Purt throttle SFC','Purt throttle fuel'};
PTO_profile(end+1,:) = {'[Ft]', ' ', '[lbf]','[lbf]',' ', '',' ',' ',' ',' ','[Kw]',' ','',' ',' ',' ',' ',' ',' ',' ',' ',' ','[lbm/hr]/[lbf]','[Kw]/([lbm/hr]/[lbf])','[lbm]','[[lbm/hr]/[lbf]','[lbm]','[([lbm/hr]/[lbf])']};
LP_PTO_abs_matrix = zeros(length(Mach_profile),length(Altitude_profile));
HP_PTO_abs_matrix = zeros(length(Mach_profile),length(Altitude_profile));
LP_PTO_matrix = zeros(length(Mach_profile),length(Altitude_profile));
HP_PTO_matrix = zeros(length(Mach_profile),length(Altitude_profile));
A_start = 1; % starting variables so if loaded the loops will start where they left off
M_start = 1;
A_save = 1;
M_save = 1;

disp('Finding baseline fuel and SFC')
Baseline_fuel = zeros(length(Mach_profile),length(Altitude_profile));
Baseline_SFC = zeros(length(Mach_profile),length(Altitude_profile));

for M = 1:length(Mach_profile)
Mach_cmd = Mach_profile(M);
if thrust_error == true
    break;
end
for A = 1:length(Altitude_profile)
    Alt_cmd = Altitude_profile(A);
    Thrust_cmd = Max_Thrust_profile(M,A)*Test_thrust_percent;
    try
        simOut = sim(Model_Name, 'SimulationMode', 'Accelerator'); % start simulation
        Engine_Monitoring = simOut.get('Engine_Monitoring');
        Time = simOut.get('Time');
        Elements = 500:1:length(Time);
        Actual_thrust = Engine_Monitoring(Elements,1)*224.81;
        Test_Thrust_profile(M,A) = mean(Actual_thrust(45000:55000));
        Fuel = simOut.get('Fuel') * 2.20462; % lbm
        Baseline_fuel(M,A) = Fuel(end);
        SFC = ((Engine_Monitoring(Elements,5)*3600)/0.4536)... % (lbm/hr)/lbf
            ./(Engine_Monitoring(Elements,1))*224.81);
        Baseline_SFC(M,A) = mean(SFC(45000:55000));
        message = ['At ',num2str(Alt_cmd),' ft and Mach: ',num2str(Mach_cmd),', The baseline SFC is: ',num2str(Baseline_SFC(M,A))];
    disp(message);
    catch
        error_message = ['At ',num2str(Alt_cmd),' ft and ',num2str(Mach_cmd),', Mach The engine broke for some reason!'];
        disp(error_message);
        thrust_error = true;
        break;
    end
end
save('Temp_Save','PTO_profile','LP_PTO_matrix','HP_PTO_matrix','time_running',
'Mach_profile','Altitude_profile',
'count','Max_Thrust_profile','Test_Thrust_profile','Test_thrust_percent','Max_PTO',
'A_save','M_save','Full_SFC','Full_fuel','Baseline_fuel','Baseline_SFC','Fuel_weight','Temp_weight','Mass_flow_weight');
end
if thrust_error == false
    disp('Finding optimal PTO ratios');
    for M = M_start:length(Mach_profile)
        Mach_cmd = Mach_profile(M);
        for A = A_start:length(Altitude_profile)
            if A_start == length(Altitude_profile) % if it loads in the middle of an alt check
                A_start = 1;
            end
            Alt_cmd = Altitude_profile(A);
Thrust_cmd = Test_Thrust_profile(M,A);
PTO_test_count = 0;
Fuel_check = 99999;
Test_check = 99999999999;
PTO_check = false;
Addition_check = false;

for percent = 0:0.01:1
    HP_PTO = Max_PTO * percent;
    LP_PTO = Max_PTO * (1 - percent);
    try
        simOut = sim(Model_Name, 'SimulationMode', 'Accelerator'); % start simulation
        % get all of the parameters
        Time = simOut.get('Time');
        Engine_Monitoring = simOut.get('Engine_Monitoring');
        Engine_Fan = simOut.get('Engine_Fan');
        Engine_LP_Compressor = simOut.get('Engine_LP_Compressor');
        Engine_HP_Compressor = simOut.get('Engine_HP_Compressor');
        Engine_Combustor = simOut.get('Engine_Combustor');
        Engine_HPT = simOut.get('Engine_HPT');
        Engine_LPT = simOut.get('Engine_LPT');
        Engine_LP_Shaft = simOut.get('Engine_LP_Shaft');
        Engine_HP_Shaft = simOut.get('Engine_HP_Shaft');
        Engine_Afterburner = simOut.get('Engine_Afterburner');
        Engine_Nozzle = simOut.get('Engine_Nozzle');
        Engine_Bypass = simOut.get('Engine_Bypass');
        Engine_Third_Stream = simOut.get('Engine_Third_Stream');
        Engine_Third_Stream_Nozzle = simOut.get('Engine_Third_Stream_Nozzle');
        HPC_Bleed = simOut.get('HPC_Bleed');
        HP_Load = simOut.get('HP_Load');
        LP_Load = simOut.get('LP_Load');
        Q_in = simOut.get('Q_in');
        HX_T_in = simOut.get('HX_T_in');
        HX_T_out = simOut.get('HX_T_out');
        Q_Fan = simOut.get('Q_Fan');
        Third_Stream_Pres_Drop = simOut.get('Third_Stream_Pres_Drop');
        Engine_SFC = simOut.get('Engine_SFC');
        Fuel = simOut.get('Fuel'); % kg
        Elements = 500:1:length(Time);
        Demanded_thrust = Engine_Monitoring(Elements,2);
        Actual_thrust = Engine_Monitoring(Elements,1)*224.81;
        Fan_work = Engine_Fan(Elements,6);
        LPC_work = Engine_LP_Compressor(Elements,6);
        HPC_work = Engine_HP_Compressor(Elements,6);
        Third_stream_mass_flow = Engine_Third_Stream(Elements,2);
        % kg/s
        Third_stream_temp = Engine_Third_Stream(Elements,5); % kelvin
        Third_stream_mass_flow_avg = mean(Third_stream_mass_flow(45000:55000));
        Third_stream_temp_avg = mean(Third_stream_temp(45000:55000));
Fan_work_avg = mean(Fan_work(45000:55000));
LPC_work_avg = mean(LPC_work(45000:55000));
HPC_work_avg = mean(HPC_work(45000:55000));
HPC_work_avg = (HPC_work(45000)+HPC_work(50000)+HPC_work(55000))/3;
Demanded_thrust(45000:55000);
thrust_difference = mean(Actual_thrust(45000:55000) -
(lbm/hr)/lbf
SFC = (((Engine_Monitoring(Elements,5)*3600)/0.4536)/%
lbm/hr)/lbf
SFC_avg = mean(SFC(45000:55000));
LP_PTO_Load = -LP_Load(Elements,1);
HP_PTO_Load = -HP_Load(Elements,1);
LP_PTO_abs = mean(LP_PTO_Load(45000:55000));
HP_PTO_abs = mean(HP_PTO_Load(45000:55000));
LP_PTO_percent = -
(HP_PTO_abs/(Fan_work_avg+LPC_work_avg))*100;
HP_PTO_percent = -(HP_PTO_abs/HPC_work_avg)*100;
Total_PTO = LP_PTO_abs + HP_PTO_abs;
PTO_efficiency = Total_PTO/(SFC_avg); % kW/(lbm/hr)/lbf
% make sure the PTO load meets required thrust within
% 10 lbf and no surges
if (thrust_difference < 10) &&
(min(Engine_Fan(Elements,11)) >0) && (min(Engine_LP_Compressor(Elements,11))
> 0) && (min(Engine_HP_Compressor(Elements,11)) > 0)
if Fuel(end) < Fuel_check % Optimize for fuel use
Fuel_check = Fuel(end);
PTO_profile_addition = {Alt_cmd Mach_cmd
Max_Thrust_profile(M,A) Thrust_cmd HP_PTO_percent LP_PTO_percent HP_PTO_abs
LP_PTO_abs LP_PTO_abs/HP_PTO_abs Total_PTO SFC_avg PTO_efficiency
Fuel(end)*2.20462 Baseline_SFC(M,A) Baseline_fuel(M,A) Full_SFC(M,A)
Full_fuel(M,A)}
    LP_PTO_matrix(M,A) = LP_PTO_percent;
    HP_PTO_matrix(M,A) = HP_PTO_percent;
    LP_PTO_abs_matrix(M,A) = LP_PTO_abs;
    HP_PTO_abs_matrix(M,A) = HP_PTO_abs;
    PTO_check = true;
    Addition_check = true;
else
    PTO_check = false;
end
end
end
end
% if the test fails 3 times then the optimal value has
% probably passed and break
if PTO_check == false
    PTO_check_count = PTO_check_count +1;
end
if PTO_check == true
    PTO_check_count = 0;
end
if PTO_check_count == 3
    break;
end
catch
    error_message = ['At ',num2str(Alt_cmd),', ft and ',num2str(Mach_cmd),', Mach The PTO loads ',num2str(HP_PTO_abs),', HP and ',num2str(LP_PTO_abs),', LP broke the engine.'];
    disp(error_message);
    
end
message = ['Alt: ',num2str(Alt_cmd),', Mach: ',num2str(Mach_cmd),', HP_PTO: ',num2str(HP_PTO_abs),',kW LP_PTO: ',num2str(LP_PTO_abs),',kW'];
    disp(message);
    count = count + 1;
    time_running(count) = toc;
    message = ['Iteration: ',num2str(count-1),', last run time: ',num2str(time_running(count)-time_running(count-1)),', Total run time: ',num2str(max(time_running))];
    disp(message);
end
if Addition_check == true
    PTO_profile(end+1,:) = PTO_profile_addition;
end
if A < length(Altitude_profile) % save it so the system starts up
    where it left off
    A_save = A + 1; % A is finished, start on A + 1
    M_save = M;
    elseif A == length(Altitude_profile) % unless it is the last A, then
    move to next M
    A_save = 1;
    M_save = M + 1;
end
save('Temp_Save','PTO_profile','LP_PTO_matrix','HP_PTO_matrix','HP_PTO_abs_matrix','LP_PTO_abs_matrix','time_running','Mach_profile','Altitude_profile',
     'count','Max_Thrust_profile','Test_thrust_percent','Max_PTO',
      'A_save','M_save','Full_SFC','Full_fuel','Baseline_fuel','Baseline_SFC','Fuel_weight','Temp_weight','Mass_flow_weight');
end
end

File_Name=[num2str(-Max_PTO),'.kW',datestr(now, 'dd-mmm-yyyy HH-MM-SS PM')];
%put a timestamp on the file name
save(File_Name,'PTO_profile','LP_PTO_matrix','HP_PTO_matrix','HP_PTO_abs_matrix','LP_PTO_abs_matrix','time_running','Mach_profile','Altitude_profile');

if length(Mach_profile) > 1 && length(Altitude_profile) > 1
    PTO_fig(1) = figure(1);
surf(Altitude_profile,Mach_profile,HP_PTO_matrix,'EdgeColor','k','LineStyle',
     '-', 'FaceColor','interp');
xlabel('Altitude [ft]');
Appendix D – Controller diagrams

Figure 34. Core Nozzle Controller

Figure 35. 3rd Stream Nozzle Controller

Figure 36. HPC Bleed Controller
Figure 37. HPT IGV Controller

Figure 38. LPT IGV Controller

Figure 39. Main Burner Controller
Figure 40. Afterburner Controller. Note, additional information on afterburner controls can be found in Buettner’s thesis.
5. References


