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Vehicle Level Transient Aircraft Thermal Management Modeling and Simulation

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Vehicle Level Transient Aircraft Thermal Management Modeling and Simulation

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

By:

Adam B. Donovan
BS Mechanical Engineering, Wright State University, 2015

2016
Wright State University
July 29, 2016

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Adam B. Donovan ENTITLED Vehicle Level Transient Aircraft Thermal Management Modeling and Simulation BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Mechanical Engineering

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Abstract

Donovan, Adam B. M.S.M.E. Department of Mechanical Engineering, Wright State University, 2016. Vehicle Level Transient Aircraft Thermal Management Modeling and Simulation.

Many advances in technology are expected to increase the capabilities of next generation aircraft, and these advances will increase the thermal load on the aircraft as well. In order to assess and account for these increased thermal loads, three studies were performed: a fuel pump trade study, a high energy pulsed system (HEPS) implementation study, and a legacy vehicle environmental control system (ECS) study. The fuel pump study addresses the effect of the implementation of a centrifugal fuel pump versus a variable displacement fuel pump. Traditionally, aircraft designers have used a centrifugal fuel pump over a piston based pump based primarily on mass, volume, cost, and reliability. This study considers specific excess power (SEP), fuel burn and thermal margin and shows the piston based pump performing superior mainly because it eliminates fuel recirculation resulting in an increased thermal margin. This investigation demonstrates the benefit of capturing component level models and thermal concerns in the conceptual design process. Both of these issues are vital to the development of future aircraft designs. Additional research needs to be completed to compare both pumps based on the mass and volume of each system. The second study investigates the implementation of a HEPS device at an air vehicle level. HEPS generate excessive amounts of heat during operation, creating challenges in how to integrate them into an aircraft without overwhelming the vehicle's power and thermal management systems (TMS). In order to evaluate the impact of the HEPS electrical and thermal load on the aircraft's mission, a vehicle level modeling and simulation (M&S) effort must be executed of the power and thermal management systems. To accurately evaluate the
total effect on the aircraft, the HEPS must be integrated into a Tip to Tail (T2T) model of the system that includes the aircraft power and thermal management subsystems. With the HEPS system integrated into the T2T model, not only can its mass and volume effects be analyzed, but also the transient power and thermal loads created by the new system can be evaluated for their effect on other aircraft subsystems. Furthermore, the aircraft subsystems can be optimized to vehicle level metrics instead of subsystem level only. This will result in a more effective and balanced overall aircraft design. Using a T2T model to evaluate the integration of a HEPS system on an aircraft will enable assessment of its overall impact to next generation aircraft. Therefore, the significant impact of highly dynamic power and thermal loads on next generation aircraft is addressed. The third study is the implementation of an air cycle based ECS in a legacy (4th generation) air vehicle. Relatively few attempts have been made to define appropriate validation testing constructs for T2T analysis in a transient mode of operation. Current research addresses the process of validation testing using legacy aircraft systems in order to acquire relevant data that will lead to the validation of existing models, and different modeling methods. The model developed in this work will eventually be utilized in these validation efforts at a later date. To this end, an air vehicle system (AVS), turbine engine, generator, and environmental control system (ECS) have been modeled in a T2T model of the actual legacy system. In particular, this study will focus on the creation and integration of the ECS model. The ECS uses an air cycle machine, which utilizes a Brayton refrigeration cycle to cool the air to the cockpit and avionics. The ECS model will be shown to successfully cool these components while subjected to varying bleed rates from the turbine engine.
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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_p$</td>
<td>Piston cross-sectional area</td>
</tr>
<tr>
<td>$A_{valve}$</td>
<td>Area of control valve</td>
</tr>
<tr>
<td>AFRL</td>
<td>Air Force Research Laboratory</td>
</tr>
<tr>
<td>APTMS</td>
<td>Adaptive power thermal management system</td>
</tr>
<tr>
<td>AVS</td>
<td>Air vehicle system</td>
</tr>
<tr>
<td>$B_m$</td>
<td>Magnetic flux density</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat at constant pressure</td>
</tr>
<tr>
<td>$c_v$</td>
<td>Specific heat at constant volume</td>
</tr>
<tr>
<td>$D$</td>
<td>Shaft diameter</td>
</tr>
<tr>
<td>$D_1$</td>
<td>Unscaled impeller diameter (7&quot;)</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Scaled impeller diameter</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hydraulic diameter of heat exchanger</td>
</tr>
<tr>
<td>$F_{available}$</td>
<td>Maximum available thrust</td>
</tr>
<tr>
<td>$F_{transient}$</td>
<td>Time dependent thrust</td>
</tr>
<tr>
<td>$f_f$</td>
<td>Friction factor</td>
</tr>
<tr>
<td>FTMS</td>
<td>Fuel thermal management system</td>
</tr>
<tr>
<td>H</td>
<td>Shaft clearance</td>
</tr>
<tr>
<td>$h_{in}$</td>
<td>Enthalpy entering component</td>
</tr>
<tr>
<td>$h_{out}$</td>
<td>Enthalpy exiting component</td>
</tr>
<tr>
<td>HEPS</td>
<td>High energy pulsed system</td>
</tr>
<tr>
<td>HPEAS</td>
<td>High power electrical actuation system</td>
</tr>
<tr>
<td>$l_{shaft}$</td>
<td>Shaft moment of inertia</td>
</tr>
<tr>
<td>IPP</td>
<td>Integrated Power Package</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>$m_{1}$</td>
<td>Unscaled pump flow rate</td>
</tr>
<tr>
<td>$m_{2}$</td>
<td>Scaled pump flow rate</td>
</tr>
<tr>
<td>$m_f$</td>
<td>Gear module</td>
</tr>
<tr>
<td>$m_{in}$</td>
<td>Mass flow into component</td>
</tr>
<tr>
<td>$m_{out}$</td>
<td>Mass flow exiting component</td>
</tr>
<tr>
<td>$m_{normalized}$</td>
<td>Normalized mass flow rate</td>
</tr>
<tr>
<td>n</td>
<td>CSD operational speed</td>
</tr>
<tr>
<td>N</td>
<td>Number of pistons</td>
</tr>
<tr>
<td>$N_{design}$</td>
<td>Design shaft speed</td>
</tr>
<tr>
<td>$N_{normalized}$</td>
<td>Normalized shaft speed</td>
</tr>
<tr>
<td>$N_{shaft}$</td>
<td>Component shaft speed</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>OPTIMUS</td>
<td>Optimized integrate multidisciplinary systems</td>
</tr>
<tr>
<td>P</td>
<td>Pressure inside component</td>
</tr>
<tr>
<td>$P_{Cu}$</td>
<td>Copper loss</td>
</tr>
<tr>
<td>$P_h$</td>
<td>Iron loss</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Exit pressure of pump</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Pressure entering component</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Pressure exiting component</td>
</tr>
</tbody>
</table>
\[
P_{\text{r,design}} = \text{Design pressure ratio}
\]
\[
P_r = \text{Prandtl Number}
\]
\[
\Delta P_1 = \text{Unscaled pump pressure}
\]
\[
\Delta P_2 = \text{Scaled pump pressure}
\]
\[
\dot{Q} = \text{Heat load into component}
\]
\[
\dot{Q}_{\text{engine}} = \text{Engine volume flow demand}
\]
\[
\dot{Q}_{\text{recirc}} = \text{Recirculation volume flow rate}
\]
\[
\dot{Q}_s = \text{Variable displacement pump volume flow rate}
\]
\[
R_g = \text{Ideal gas constant}
\]
\[
Re = \text{Reynolds number}
\]
\[
\text{REPS} = \text{Robust electrical power system}
\]
\[
\text{SEP} = \text{Specific excess power}
\]
\[
T_{\text{fuel}} = \text{Final fuel tank temperature}
\]
\[
T_{\text{in}} = \text{Flow temperature into component}
\]
\[
T_{\text{limit}} = \text{Fuel tank temperature limit}
\]
\[
T_{\text{setpoint}} = \text{Setpoint temperature}
\]
\[
\text{TM} = \text{Fuel thermal margin}
\]
\[
\text{T2T} = \text{Tip to tail model}
\]
\[
U = \text{Heat transfer coefficient}
\]
\[
V = \text{Velocity}
\]
\[
V_p = \text{Volume of component}
\]
\[
V_s = \text{Fuel system volume}
\]
\[
V_{\text{valve}} = \text{Volume of control valve}
\]
\[
\text{VCS} = \text{Vapor compression system}
\]
\[
W = \text{Aircraft weight}
\]
\[
W_{\text{CL}} = \text{Turbomachinery work}
\]
\[
W_{\text{pump}} = \text{Pump work}
\]
\[
\beta = \text{Bulk modulus}
\]
\[
\gamma = \text{Specific heat ratio of air}
\]
\[
\eta = \text{Isentropic efficiency of component}
\]
\[
\eta_1 = \text{Unscaled pump efficiency}
\]
\[
\eta_2 = \text{Scaled pump efficiency}
\]
\[
\theta = \text{Swashplate angle}
\]
\[
\omega = \text{Rotational speed of swashplate}
\]
\[
\omega_{\text{shaft}} = \text{Shaft angular velocity}
\]
Acknowledgements

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1. Introduction

1.1. Motivation

Current and modern aircraft are moving to more electric systems, which in turn increases the amount of waste heat rejected by these systems. These electronics often increase the capability and maneuverability of the aircraft. High power electric actuators move control surfaces further, quicker and with more force, which is motivating their application in aircraft over hydraulic controls.\textsuperscript{1,2} In addition, modern electronics monitor each of the aircraft subsystems in order to relay the information to the pilot and ground crew.\textsuperscript{2,3} These electronics cause increased burdens on aircraft thermal management systems (TMS). Alongside the increasing functionality of avionics equipment and more demanding aircraft missions, these increased burdens have required redesigning aircraft TMS at significant cost.\textsuperscript{4} Along with increased electric systems, power systems on aircraft have grown by an order of magnitude. Not only have these systems grown, but normal methods of thermal cooling have become difficult as standard thermal rejection methods cause drag and mass penalties that are no longer acceptable. Composite aircraft skins have made thermal energy rejection methods to the environment not feasible, so the heat has to be removed inside the aircraft.\textsuperscript{5,6} These thermal concerns should result in considering thermal management at the beginning of the conceptual design process, as opposed to the more traditional method of addressing it at later stages of the design process.\textsuperscript{7} A goal of this research is to demonstrate how modeling and simulation of the complete air vehicle in conceptual design can result in tremendous improvements in performance and thermal management.
Aircraft like the F-16 and F-15 have relatively low power requirements, therefore not much waste heat to regulate. This amount of waste heat can use the fuel as a heat sink, which is desirable because the thermal energy stored in the fuel is sent off and burned in the engine. In addition, RAM air heat exchangers could be used to regulate the temperature of the aircraft. Due to increases in drag, the use of RAM air as a heat sink has been discouraged. In addition, as capabilities have increased on aircraft, the power and thermal requirements have increased substantially. In fact, there is a break in the y (power and thermal requirements) scale of Figure 1, which shows that future capabilities are increasing substantially. Modern aircraft are already struggling to manage all the waste heat the electronics produce, and ways of managing thermal loads will need to be developed to handle the increasing thermal demands. A few ideas on how to reject this heat are listed on the plot, such as fuel, oil, engine bypass duct, thermal energy storage materials, or an expendable. The fuel is used as an expendable heat sink. Another possible expendable is a cryogenic fluid, such as liquid nitrogen or liquid natural gas. Recently,
research has been accomplished investigating and assessing the feasibility of using a cryogenic fuel on an aircraft.\textsuperscript{9-11} A typical method used to regulate the waste heat on aircraft is an air cycle machines (ACM) which uses a Brayton refrigeration cycle to move the heat off the aircraft, normally by using the fuel or an engine bypass as the heat sink.

Traditional aircraft-level TMS studies are not conducted until the end of the design process and are focused on a subsystem or component level. In addition, component models are typically based on a worst case steady state operation.\textsuperscript{12} The result of this type of design can be an overdesign due to lack of optimization as an “aircraft system.” This level of optimization needs to consider transient energy management, not just steady-state. In addition, these steady state points might not be the worst case for the system, because transient operations can often cause large increases in temperature due to system interactions. This has motivated the creation of transient, system level models for detailed design, but conceptual design tools for thermal have been lacking until AFRL’s Optimized Integrated Multidisciplinary Systems (OPTIMUS) R&D program started changing the conceptual design paradigm. Another motivation is that running each individual subsystem model can take more simulation time than an integrated model, and including these models in the conceptual design process requires many runs to reach an optimum design.

1.2. Tip-to-Tail (T2T) Modeling

In order to include TMS in the conceptual design process a vehicle level T2T model was created with collaboration of the Air Force Research Laboratory (AFRL). The T2T model is a system level model that was developed in a multidisciplinary modeling and simulation environment in MATLAB/Simulink, Figure 2. It integrates transient interactions between subsystems and helps ensure that the conceptual aircraft design and control system can actually perform the specified
mission within design constraints. These transient interactions can cause over-temperature and time delays in the response of each individual system that would not be shown in a steady-state analysis. In addition, the structure of this model allows for systems and subsystems to be interchanged based on the design. Therefore, different components can be tested to see their benefit on the overall system design. In addition, if the component models are set up based on scalable parameters, optimization studies can be performed based on the size of the components in order to find the optimum size. All of these methods of study are possible depending on the formation of the vehicle model and designing of the component models.

The overall structure of a T2T model has been consistent since the start of this air vehicle research. A typical model consists of a thermal management system, air vehicle system (AVS), propulsion system, robust electrical power system (REPS), high power electrical actuation system (HPEAS), adaptive power and thermal management system (APTMS), and the fuel thermal management system (FTMS). 

![Figure 2. Vehicle level T2T model](image-url)
The AVS consists of an aerodynamic model of the aircraft, which computes a thrust demand based on the mission profile. This can range from a 6 degree of freedom model to a reduced order model that only takes two coordinate directions into account. In the research presented in this thesis, a reduced order model is used to save on computational time without significantly reducing the fidelity for power and thermal management. The propulsion system models the engine of the aircraft. This can be a fully dynamic model with takes into account the time constants associated with the shaft inertia and turbomachinery pressure, or can be based on steady state performance tables. For two of the studies presented in this thesis, performance tables are used to represent a more modern and relevant engine system. For the study that models a traditional aircraft, a fully dynamic engine model was utilized. The REPS and HPEAS are both electrical models, but are not dynamic in the current T2T model. They are modeled as steady state look up values (heat loads) in MATLAB/Simulink that vary over the mission. The thermal management system consists of the FTMS and APTMS, which together regulate the waste heat in the aircraft. The FTMS tracks the temperature of the main fuel line as fuel runs from the tank to the engine. This fuel is used as a heat sink for many of the electronics, as well as for the engine oil, which accounts for the highest heat load. The APTMS models an environmental control system, which has the main function of cooling the avionics and cockpit. Most of the thermal systems in the T2T model include some sort of refrigeration cycle, which is normally either a vapor compression system (VCS) or air cycle machine (ACM). All of these systems are connected through the system controller, which contains the controllers for each of the above subsystems.

Previous work has been completed that demonstrates the capability to optimize this T2T model based on energy efficiency. Efficiency was defined as how much fuel was burned over the mission. This was based on first principle calculations of conservation of energy, and includes the interactions between the increased heat loads and the TMS. However, no method existed to
measure the performance of the vehicle, or how much excess power exists to possibly deviate from the mission. This is significant for a tactical vehicle, which may need to suddenly change direction or accelerate. Therefore, the addition of a performance based parameter, specific excess power (SEP), to the T2T model using a FTMS fuel pump trade study to demonstrate its capability will be developed.

1.3. Laser Operation and Motivation

As air vehicles have advanced in technology, the addition of high energy pulsed systems (HEPS) have been proposed. These systems consist of high energy lasers, and a TMS devoted to managing the temperature of the laser system. HEPS significantly increase the heat load on the aircraft by two to three times the load on a non-HEPS aircraft. Most current laser systems operate at room temperature as they are designed for manufacturing applications. At room temperature, the electrical and thermal efficiencies of different types of solid state lasers are fairly low, and research has been completed showing increased efficiencies for these types of laser systems when operated at significantly lower temperatures more than doubling their efficiencies.\textsuperscript{17–19} Figure 3 gives an example of laser properties versus temperature for one possible HEPS considered.
In particular, a room temperature HEPS system is considered, which yields a 20% thermal efficiency based on the graph in Figure 3. This means that for a 150 kW optical output power system, 750 kW of low quality heat is generated. This is the heat that needs to be removed from the aircraft, in addition to the parasitic aircraft heat loads, such as the avionics, controllers, subsystems and cockpit loads.

Heat loads aboard modern aircraft have been rising and are expected to rise drastically in next generation aircraft. The addition of laser systems will only exacerbate the problem. With the addition of 750 kW of waste heat aboard an already overheating aircraft, conventional TMS will likely not be sufficient. This means that other methods may need to be investigated. One potential option is thermal energy storage (TES). TES includes a phase change material that is designed to go through a solid to liquid phase change while the HEPS is in operation. After the HEPS stops firing, the coolant is still run through the TMS and heat is rejected as the phase change material freezes back into a solid phase. The feasibility of using liquefied natural gas in a separate
laser TMS has been investigated.\textsuperscript{10,21} Part of this thesis will cover a room temperature solution to this thermal management problem, but without the use of a phase change material. A separate fuel loop cools the HEPS at room temperature, using component models already present in the T2T model. The use of fuel as a coolant allows the TMS to be run at room temperature and is a coolant that could be used as a back-up supply of fuel for the aircraft.

1.4. Legacy Aircraft

Part of the motivation of this thesis is to validate the techniques used in these T2T models. Validation of these models means statistically quantifying the uncertainty between the model and actual systems. A laboratory at AFRL is working with a physical legacy aircraft, and has a goal of validating physics-based models like the ones used in T2T models.\textsuperscript{22} A design of experiments procedure is being used to find the parameters in the aircraft models that greatly affect the system and can be influenced by the experiment. This method has been demonstrated for a generator model, which is a physics-based model in MATLAB/Simulink.\textsuperscript{22} This was completed for a generic generator model and was validated for transient performance. In order to complete this same work on a vehicle level, a physics based model is needed for the aircraft. So the third phase of this thesis is creating a T2T model which models the legacy aircraft. This will allow for further component model validation, and hopefully full vehicle model validation in the future.

This T2T model will be set up in the same manner as described previously: with an electrical model (REPS and HPEAS), and a thermal management system. The thermal management system is comprised of a FTMS and APTMS just like the other T2T models. However, the APTMS is focused on modeling the environmental control system (ECS) of the legacy aircraft. The environmental control system of this legacy aircraft both pressurizes the cockpit and regulates the temperature of both the cockpit and avionics. A schematic was provided by AFRL illustrating the architecture
of the ECS, including controller setpoints. The T2T model was modified using the available components, and will be described in detail in the Methodology section. This model eventually will be run through a designed mission for the legacy aircraft, and validation will be performed using experimental data obtained at a later date by the laboratory at AFRL. The research presented in this thesis

1.5. Literature Review

Because of the nature of this work, the literature review will cover a variety of topics, ranging from very high level studies to component modeling. Overall, topics related to T2T and dynamic modeling will be discussed. First, examples of dynamic modeling and simulation will be discussed as they relate to the current work. After this, background into laser systems as it relates to this research will be introduced. Then motivations for including TMS modeling in the conceptual design process will be discussed. Finally, previous research into T2T modeling will be discussed.

Del Valle and Munoz discuss in detail some of the motivations and advantages of including dynamic thermal simulations into system design. As systems become more and more complex on air vehicles, avionics and other electronics have increased their functionality, which in turn has increased the amount of heat dissipated into the air vehicle. Previously, environmental control systems (ECS) were only designed to meet the peak heat load requirements, and thus were not sized appropriately to be efficient in every part of a vehicle's mission. A dynamic thermal model allows designers to analyze a system at a higher level of vehicle integration, which if used early in the design process will lead to a more efficient and correctly sized designs. Many examples are given by Del Valle and Munoz that cover a broad range of applications. Examples include accurate predictions of solar radiation on the aircraft based on the world's position, adjusting the duty cycle of electronics on a vehicle based on the mission, and even adjusting the thermal
management architecture based off mission profiles and power requirement. This article gives a high level perspective of some of the motivation and applications that have led to the current work.

Eastbourn and Roberts presented the modeling and simulation of a dynamic turbofan engine at the 2011 AIAA Joint Propulsion Conference. A motivation of this research was to create a fully dynamic engine model in MATLAB/Simulink that replaces the use of numerical solvers that algebraically loop to solve for a steady state engine solution. This not only decreases the amount of simulation time required, but also gives an idea of the transient behavior of the engine. The model still utilized steady state performance maps for the turbomachinery compressor and turbine. Plenum volume models were added to each turbomachinery component that uses the ideal gas law to calculate the dynamic pressure. In addition, an equation was added to capture the inertia of both the LP and HP shafts of the engine. These two methods add a time delay in the response of both the pressure and shaft speed by means of physics based models. This new dynamic engine model was run alongside the previous T2T engine model for verification purposes. There is a slight difference in performance between the two engines, but overall they followed the same trends with respect to mass flow rate and temperature in each component. The major differences were in the LP and HP inlet temperatures and pressures, which was due to differences between the engine performance maps. Overall this engine model is more computationally efficient and gives more detailed dynamic information than previous models. This engine model has been used in various studies since then, and for the legacy model study included in this thesis, an updated version of the model is included.

At the SAE International Power Systems Conference, McCarthy et al. presented a toolset to model thermal management. The motivation for this work is similar to that of the previous two papers discussed. Aircraft TMS have historically been designed based on the worst case steady state
conditions, and not based on a mission-level analysis. The tools presented in this paper are dynamic in nature, and are preliminary versions of many of the tools used in the current research. A dynamic and complex fuel tank model was included in their toolset for use in an aircraft fuel thermal management system. This model uses convective heat transfer relations to calculate the heat transfer between the fuel and tank walls, and also includes convective and radiative heat transfer between the outer tank and the environment. The tank uses the conservation of energy equation to find the time derivative of the temperature of the tank, which is integrated to find the final tank temperature. The toolset also includes models that can be used in environmental control systems. These include heat loads, heat exchanger, and turbomachinery components for use in an air cycle machine. For the legacy vehicle study that will be discussed in this thesis, the heat load models are similar to those discussed in this paper. Overall, the purpose of the research discussed in this paper is very similar to this thesis. The goal was to create component models in MATLAB/Simulink that could be used to create different thermal management architectures. These different architectures would then be assessed as part of the conceptual design process of a complete air vehicle.

Chen, et al. summarized the efficiency of solid state lasers, and specifically an Er-doped InP diode laser. Two designs were studied experimentally at various temperatures: a control design optimized for room temperature, and a new design aimed at cryogenic temperatures. Both were tested over a wide range of operating temperatures in order to measure the efficiency of each laser. For both laser configurations, efficiencies were given for the output power, threshold loss, slope loss, and voltage loss as a function of temperature. For the new design, a maximum efficiency of approximately 70% was measured at a temperature of 77 K. In the research presented, the reduction of voltage defect at low temperatures was targeted by increasing doping density, reducing the energy band offsets, and changing the p-cladding to reduce ionization
energy. For the new design, this reduced the voltage loss from 30% to 10%. Thermal efficiencies of an Er-doped InP diode laser were presented by these authors. In this thesis, a high energy laser system will be represented as a heat load based on these thermal efficiencies. The graph in Figure 3 was presented by Chen et al and gives the efficiency as a function of temperature. For room temperature, a thermal efficiency of 12.5% was used in this thesis.

Alyanak and Allison presented a paper at AIAA Scitech 2016 which discussed the importance of considering thermal management and fuel thermal management in particular, in the aircraft conceptual design process. The study analyzed four fuel architectures on a system level. The first was a single tank model that runs the fuel through a single heat exchanger, which rejects heat to the fuel, and then runs this hot fuel to the engine. The second system recirculates any excess fuel that the engine does not demand back to the fuel tank, with a second heat exchanger to cool this hot fuel as it recirculates back into the tank. The third system is almost the same, but with a feed tank for the recirculating fuel, so the fuel in the main tank stays at a lower temperature. The last system recirculates fuel back into the main fuel tank, but then still has a feed tank that the fuel runs into before being used as a heat sink for the aircraft and then is sent to burn in the main engine. Each of these configurations used an energy balance to calculate the fuel temperature within the system. In addition, the fuel system was sized in order to meet the thermal requirements of the aircraft, as well as to meet the requirements of the mission. When sizing is completed in this way, the difference in fuel weight shows that the thermal design heavily constrains the size of the aircraft. The architecture also has a very large impact on the aircraft sizing as well. The study showed that running fuel directly to the engine based on the thermal requirements and then throwing the excess fuel off the aircraft actually ended up as a better design than recirculating the fuel without cooling it in the process. This is extremely counterintuitive, but even at the conceptual level, the way that heat is rejected and managed in
the system can have extreme effects on its weight. This is a motivation for one of the studies that will be presented later, where two fuel pump systems will be evaluated on a system level to study their effects on an aircraft as a whole.

Gvozdich, Weise, and von Spakovsky presented a paper at the 2012 AIAA Aerospace Sciences Meeting discussing energy requirements, thermal demands, and thermal management associated with a high powered laser system. This study assumed a 100 kW laser, and utilized a previous version of the INVENT T2T model. The laser system had its own dedicated TMS, and was hooked into the fuel thermal management system and adaptive power thermal management system of the T2T model. The laser model included a battery bank, associated power electronics, the solid-state laser itself, and the optics. The devoted thermal management system to the high power laser system included a thermal energy storage (TES) subsystem. This subsystem utilizes a phase change material to buffer the high heat load that the laser is imposing on the TMS. A coolant flows over the laser system and TES material, then runs through two heat exchangers to reject this heat to the rest of the aircraft so the laser can fire again. The results of this study show that a laser TMS without TES causes a higher spike in cockpit temperature. In addition, the TES system required a lower coolant flow rate by more than half. Even so, this TMS for the laser system, because it requires very high flow rates (on the order of 15.3 kg/s) to cool the laser is not feasible.

The laser system presented by these authors is a high fidelity laser model, which takes into account dynamic optic analysis and heat transfer in the individual diodes. In this thesis, a simplified laser TMS will be presented, based on general thermal efficiency values.

In a paper presented at the 2011 AIAA Joint Propulsion Conference, Roberts and Eastbourn outlined an early version of Wright State University’s T2T model. This is a non-proprietary model, which was designed to investigate the thermal management of a long range strike vehicle. This is a similar, but less developed, version of the model used for the studies presented in this thesis.
The T2T model consisted of a fuel thermal management system, aircraft vehicle system, adaptive power and thermal management system, engine model, and system controller. The paper primarily focused on the development and implementation of four transient models: the IPP, heat exchanger model, fuel and oil pumps, and engine oil heat rejection. The IPP is an air cycle machine that uses a Brayton refrigeration cycle to cool systems on the aircraft. The methods of dynamic analysis are the same as for the engine model described previously. Plenum volume dynamics use the ideal gas equation to calculate the pressure in each turbomachinery component. Shaft inertia dynamics include a time constant for the calculation of the shaft speed. The heat exchanger model is set up as a 1D nodular model, which means that more nodes can be added to calculate the temperature distribution along the length of the heat exchanger. Each node consists of three control volumes, one for the hot fluid, one for the cold fluid, and one for the heat exchanger itself, and uses conservation of energy equations along with Nusselt correlations to find the temperature of each volume. The fuel and oil pumps used in this paper are quasi-steady-state pumps, which do not consider pump inertia. Instead they use generalized centrifugal pump maps to calculate the mass flow rate and efficiency based on pressure ratio and shaft speed. The engine oil heat rejection was added to the FTMS by means of heat loads. The heat was added to the oil through heat load models, then the oil was run through a heat exchanger to reject heat to the main fuel loop.

In a Journal of Dynamic Systems, Measurement, and Control paper, Roberts and Decker ran a control architecture study on an updated version of the WSU T2T model. This model utilized the dynamic models described previously, and in particular focused on the controls of the IPP. They focused on how much bleed extraction is necessary to run the IPP and cool the adaptive power and thermal management system based on two variable speed trade study cases. The baseline case was a fixed shaft speed IPP model. The two variable speed cases controlled the
speed of the IPP based on the desired amount of cooling. This was implemented in the first trade through the use of a control valve on the bleed flow running to the power turbine of the IPP, which controlled the shaft speed. The second trade run was for an electric driven case using an electric motor to power the IPP. The baseline case utilizes four control valves that help regulate the polyalphaolefin (PAO) cooling oil temperatures in the APTMS. The first variable speed case uses a cascade control architecture that simultaneously regulates the liquid cooled avionics temperature and the IPP shaft speed. The electric driven case is controlled by the level of power put into the electric motor. All three were run in the T2T model with fuel burn analyzed. The electric driven case burned the least amount of fuel, with 6.06% less than the baseline (constant speed) case. This was due to the fact that there was no bleed air from the engine. The first variable speed IPP case was also better than the base case, burning 4.75% less fuel. However, the electric driven case has a significant weight and volume increase due to the large electric motor necessary to implement this case. So the natural option to choose is the first variable speed case, because it burns less fuel than the constant speed, but has less mass and volume than the electric driven case.

2. Development of Vehicle Models

In this section, the development of three different vehicle models will be discussed. The first of the vehicle models will be used to address the thermal impact of two different fuel pump systems: a centrifugal pump system and a variable displacement pump system. The second vehicle model consists of the same airframe and engine models, but has a different thermal management architecture to account for the addition of a HEPS. The third vehicle model was designed to model a legacy aircraft system. This is different from the other two studies in that it is modeling a currently existing system, while the other two vehicle models represent a conceptual aircraft. The
airframe, engine, and TMS are all different than those from the other two vehicle models. However, many of the subsystems are similar between the vehicle models.

Much of the work in generating these vehicle-level models consisted of creating and connecting different transient subsystem models. As such, most of these models will be discussed in detail, including equations used to model the component and how they were used in the context of the overall vehicle. This work focuses on aircraft thermal management, so the electrical system models are simplified, and are taken as functions of the aircraft mission. Many of the subsystem models are similar between the three different efforts, such as heat exchanger models, fuel pumps, and heat loads. These models are all designed to be transient in nature, however due to the availability of information some steady state pump maps are evaluated across each time step. This was done for the fuel pump models and turbomachinery models, because steady state data was the only information available for these components.

2.1. Fuel Pump Study

This study addresses the impact of two different fuel pump systems on overall aircraft thermal management. This subsystem was chosen because of the role that the fuel of an aircraft normally plays in its thermal management system. Typically, fuel is used as the primary heat sink of the aircraft because it is an expendable, and is burned and sent off the aircraft taking the rejected heat with it. However, modern aircraft requirements have pushed the allowable temperature limits of fuel. In addition, as Alayanak and Allison showed, the architecture and design of the fuel thermal management system can drastically affect both the range and weight of the aircraft. So, the aircraft level effects of two fuel pump systems will be discussed, along with the vehicle system into which these pumps have been placed.
2.1.1. Tactical Fighter Platform

The air vehicle platform, M85, is a notional tailless tactical air vehicle configuration that has been recently developed as a suitable platform for integrated power and thermal management studies. It has a total weight of 85,000 lbs with a length of 78 feet and a span of 50 feet. It relies partly on lateral thrust vectoring for yaw stabilization. Figure 4 shows a conceptual view of this aircraft model.

![Figure 4. Conceptual View of M85](image)

A drag polar representation of the aircraft aerodynamics is used with the conventional point mass aircraft assumption. The coefficients used in the drag polar model have been obtained thru an inviscid CFD analysis, using CART3D, spanning a range from Mach 0.3 to 0.8 with a least-squares parabolic curve fit. This air vehicle model is a significant improvement to the T2T model, which enables more thermally stressing configurations to be considered.
2.1.2. Engine Model

The engine model is a Simulink steady state tabular based model of a variable cycle engine (VCE). A variable cycle engine uses variable geometry features within the engine to enable a single engine to operate in both high efficiency cruise and high performance modes as required. The model is based on a Numerical Propulsion System Simulation (NPSS) model developed by AFRL. The model includes fan and core bleeds along with shaft loading for power extraction from both the high speed and low speed shafts. Also included in the engine model is the ability to reject thermal energy to the engine bypass. The model accounts for the change in fuel burn and thrust associated with different bleed, extraction and heat addition. This new engine model allows more realistic fighter conceptual design studies especially from a thermal perspective, but the steady state assumption does present some limitations.

2.1.3. Fuel Thermal Management System (FTMS)

The focus of this study is the effect of different fuel pumps on the fuel thermal management system (FTMS). This system manages the fuel temperatures as fuel runs from the main fuel tanks through various heat loads to the engine. Modern aircraft often use fuel as the major heat sink for electronics and various other heat loads, so this FTMS models these heat loads as well as their effect on the fuel temperature. A system level architecture is shown in Figure 5.
Components cooled by the fuel include actuators, engine pumps, engine oil, PAO cooling the APTMS, and the engine controller (FADEC). These all have various temperature limits that can depend on the different part of the mission (taxi, flight idle, cruise, etc.). These together constrain the allowable temperature limits for the FTMS as a whole.

### 2.1.4. Electronics Heat Loads

The electronics are modeled in the FTMS as heat loads into the fuel. Modeling each component as a heat load greatly simplifies the T2T model, and allows for more computationally efficient simulations. Because a goal of this T2T model is to easily compare different system configurations with respect to thermal management, modeling electrical components as heat loads is sufficient.

The temperature increase in the flow caused by this heat load is modeled using the following equation:

$$mC_p \frac{dT}{dt} = Q + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}$$

This equation is then integrated to calculate the temperature of fuel exiting each heat load.
2.1.5. Engine Oil

The FTMS also models the temperature changes in the engine oil throughout the mission. The heat added to the engine oil by the engine is modeled by a heat load block. It uses a similar method as the one discussed for the electronics. Along with the heat load by the engine, heat rejection from the oil into the main fuel loop is modeled using a counter-flow, plate-fin heat exchanger model. The heat load is calculated for the oil based on a simplified heat transfer coefficient and the temperature difference in the oil and the temperatures throughout the engine such as fan exit, compressor exit, low pressure turbine (LPT) and high pressure turbine (HPT) turbine inlet temperatures using Equation 2.

\[ Q_{oil} = U(T_{fluid} - T_{Engine}) \]  

(2)

2.1.6. Fuel Pump Systems

Two fuel pump systems were implemented into the T2T model: a centrifugal pump and a variable displacement pump. The fuel and oil pumps previously used in the T2T model are generalized centrifugal pump models, which use maps designed to scale to the demands required by the engine and AVS. These are replaced with models based on specific systems, which relate the necessary outputs with the geometry of the pump. This way, more studies can be performed later to see the effect of pump geometry on total aircraft performance.

2.1.6.1. Variable Displacement Pump

A variable displacement piston pump was modeled in Simulink to replace the fuel pump in the FTMS. The pump consists of a circular swash plate that can tilt along a range of angles, with pistons following the edge of the circle. The swashplate rotates, and its angle determines the stroke of each piston. In addition, the rotational speed, the area of the piston, and the radius of the
swashplate also affect the flow rate of the pump. All of these components and an overview of a variable displacement pump is shown in Figure 6.

![Figure 6. Variable Displacement Pump](image)

Equation 3 shows the equation derived to calculate the flow rate of this variable displacement pump.

$$\dot{Q}_s = 2R \tan \theta A_p N \frac{\omega}{2\pi}$$

(3)

After this is calculated, the pressure difference across the pump is found using a control volume approach, shown in Equation 4.\textsuperscript{27}

$$\frac{V_s}{\beta} \dot{P}_s = \dot{Q}_s - \dot{Q}_{\text{engine}} - \dot{Q}_{\text{recirc}}$$

(4)

The flow rate to the engine is determined by the look-up tables in the engine subsystem. The recirculation flow rate is only included to maintain the pressure in the system. Equations 3 and 4 show that the volume flow rate of the piston pump is not directly proportional to the pressure head added. However, in order to achieve the necessary pressure difference across the fuel
injectors, a control loop is added that changes the swashplate angle to achieve the desired pressure. Because this can be achieved for a large range of flow rates, there is no need to recirculate flow back to the fuel tank, and $\dot{Q}_{\text{recirc}}$ is zero for the piston pump.

2.1.6.2. Centrifugal Pump

The other case considered for this study is the implementation of a centrifugal pump. Unlike the variable displacement piston pump, there is no dynamic model available for a standard centrifugal pump. Instead, a pump is chosen that meets the necessary flow rate and pressure difference. The selected pump is a Weinman End Suction Back Pull-Out Model 1.5P. The performance curves were found on the manufacturer’s website. Figure 7 gives a drawing of this industrial centrifugal pump.

![Centrifugal Pump](image)

Figure 7. Centrifugal Pump

In order to calculate the pressure of the fuel flow, Equation 4 is used. In this case, recirculation of fuel is required in order to control the pressure. Four stages of pumps were necessary to help maintain a constant pressure. Also, a sizing routine is necessary to scale the pump map to reach
the required pressure rise. The sizing routine is broken into a series of steps. First, the pressure difference is scaled for comparison to the original pump map.

\[ \Delta P_1 = \Delta P_2 \left( \frac{D_1}{D_2} \right)^2 \]  

Equation 5 gives the scaling equation for the pressure difference across the pump, with \( D_1 \) being the 7” impeller diameter on which the maps are based, and \( D_2 \) being the desired scaled impeller diameter. The pressure difference and rotational speed are used to find the mass flow rate and efficiency through look-up tables. The pressure difference is found through a control volume analysis of the entire fuel system, and the rotational speed is assumed to be a fraction of the LP shaft speed of the engine. These outputs then need to be scaled using Equations 6 and 7.

\[ m_2 = m_1 \left( \frac{D_2}{D_1} \right)^3 \]  
\[ \eta_2 = \eta_1 \left( \frac{D_1}{D_2} \right)^2 \]  

These scaled values are used to determine the system performance. The baseline data is for a 7” diameter impeller, which corresponds to \( D_1 \) in the above equations.

2.1.7. Performance Metrics

2.1.7.1. Specific Excess Power

As was stated before, SEP is a measure of a vehicle’s ability to climb, turn, or accelerate at a given flight condition. The SEP value will be calculated at any point along the vehicle’s mission, which varies in altitude and Mach number over a period of time. Various parameters are necessary to calculate SEP, such as maximum thrust available, aircraft drag, aircraft weight, and airspeed. These values are calculated by different subsystems within the T2T model, specifically the engine and air vehicle systems. The SEP is then calculated using Equation 8.

\[ SEP = V \left( \frac{F_{\text{available}} - F_{\text{transient}}}{W} \right) \]
Normally, the aircraft drag is used to calculate SEP, because in a steady state calculation, the aircraft drag equals the thrust. Because this is a transient simulation, the thrust calculated by the model was used.

The units of SEP is velocity. A positive value of SEP signifies that the vehicle has enough thrust available to accelerate or turn at that point in the mission. If the SEP is zero at a point in the mission, it indicates that the plane must decrease its altitude in order to turn or increase its speed. A negative value of SEP signifies that the plane must decrease its altitude to remain at a constant speed.

In order to use SEP as an optimization parameter, a single number is preferable, so that different cases can easily be compared. This was achieved by using the integral of the SEP instead of the SEP itself. A lower value means that there is less SEP margin over the mission as a whole. This integration will be used as a parameter to judge between two different fuel pump designs.

### 2.1.7.2. Fuel Burn

Another important consideration during the design of an aircraft is the amount of fuel burned during its mission. The T2T model calculates the amount of fuel burned in order to complete the desired mission. This is calculated based on the demand required by the engine model. The amount of fuel burned will be compared between the two different pump designs.

### 2.1.7.3. Fuel Thermal Margin

The T2T is intended to predict the thermal impacts of different systems on the aircraft, considering how close various system temperatures are to their limit is important. The thermal margin (TM) was calculated by comparing the fuel tank temperature to a temperature limit. This thermal margin is defined in Equation 9.
\[ TM = T_{\text{fuel}} - T_{\text{limit}} \]  

Based on this equation, a negative thermal margin means more heat can be added to the fuel without exceeding the temperature limit of the fuel tank. A positive TM indicates that the temperature of the fuel exceeds the limit.

3. High Energy Pulsed System Integration

The second study performed for this research was the integration of a HEPS into a vehicle level model. Based on the information provided in the Introduction and Literature Review, a room temperature solid state 150 kW laser was selected. As Figure 1 shows, at room temperature the output efficiency of an Er-doped InP diode laser is only 20%, which means that the 150 kW laser produces 750 kW of excess thermal energy on the aircraft. The next sections will describe the vehicle model in which this HEPS was placed, along with the strategy used to manage the large amount of excess thermal produced by this room temperature HEPS.

3.1. Air Vehicle System (AVS) and Engine Model

The same tactical fighter platform and engine model introduced in the fuel pump study were utilized in this vehicle level model. These were implemented in the same format. The AVS was implemented as a reduced order model that represented an aircraft designed to weight 85 klbf, and uses drag polars based on data produced from CART3D. In addition, the same control system for the aircraft altitude, speed, and heading were used in this model. Similarly, the engine model used in this study is based on the steady state operation of a variable cycle engine. This ties into the overall TMS of the aircraft in a few ways. First, the fuel flow is an input to the table, and the temperature and flow rate of the fuel affect engine performance. Also, necessary bleed is an input to the table, and affects the engine performance. Last, the ability to reject heat to the
engine bypass is included in this tabular model. This is utilized in the aircraft TMS, and affects both engine performance and temperature.

3.2. **Fuel Thermal Management System (FTMS)**

The FTMS models the interaction of the main fuel lines with different aircraft components to provide a liquid cooling heat sink to various subsystems prior to entering the main fuel pumps of the engine. As is typical on modern aircraft, the main fuel of the aircraft is often used to cool many components before it is burned in the combustor of the engine. The FTMS used in this study is very similar to that used in the fuel pump study, but without a separate PAO loop. The maximum fuel temperature is only limited by a maximum pump inlet temperature of about 250°F in order to limit cavitation of the main fuel pump. The FTMS used in this T2T model includes the capability of using fuel as a heat sink. Different components cooled by the fuel to the main engine include: engine oil, generators and controllers, electric actuators, the FADEC, and various oil and fuel pumps and each may have a different allowable operating temperature limit(s). Some operating temperature limits are different depending on the particular phase of the mission (taxi, flight idle, cruise, etc.). These must be satisfied, thus introducing multiple sets of temperature constraints on the fuel system. An overview of the FTMS architecture is shown in Figure 8.

![Figure 8. Fuel Thermal Management System Architecture](image-url)
3.2.1. Fuel and Oil Pumps

Currently, the main engine fuel and oil pumps are modeled based on generic centrifugal pumps. This is similar to the centrifugal pump model presented in the fuel pump study above. However, these pumps use maps that have been generalized to be used over a range of angular speeds (RPM) and pressure ratios. The maps calculate mass flow rate and efficiency as a function of these two parameters.

\[
\dot{m} = f \left( \frac{P_{\text{out}}}{P_{\text{in}}}, N_{\text{shaft}} \right)
\]  \hspace{1cm} (10)

\[
\eta = f \left( \frac{P_{\text{out}}}{P_{\text{in}}}, N_{\text{shaft}} \right)
\]  \hspace{1cm} (11)

The pressure into the pump is known, and is based off the pressure of the fuel leaving the fuel tank (typically there is a boost pump in the tank to lift the fuel pressure to about 50 psi). However, the pressure leaving the fuel pump system is also needed to calculate the pressure ratio necessary for the pump maps, which then calculate the flow rate and pump efficiency. This pressure is based on taking the entire system as a control volume, and using the flow rate across an orifice.

In addition to calculating the flow rate and pump efficiency, the model calculates the exit temperature of the fuel from the pump system based on the efficiency of the pump, mass flow through the pump, specific heat of the fuel, and work done by the pump on the fuel:

\[
W_{\text{pump}} = \dot{m}_{\text{pump}} \frac{(P_{\text{out}} - P_{\text{in}})}{\rho_{\text{fluid}}}
\]  \hspace{1cm} (12)

\[
T_{\text{out}} = \frac{W_{\text{pump}}}{\dot{m}_{\text{pump}} C_v \left( \frac{1}{\eta} - 1 \right)} + T_{\text{in}}
\]  \hspace{1cm} (13)

3.2.2. Electronics and Engine Oil Heat Loads

The electronics and engine oil heat load models are the same in this study as they were for the fuel pump study. Equations 1 and 2 give the two main equations used to model these two heat loads.
loads. The electronics are assumed to be just a simple heat addition into the fuel, while the engine oil heat load is calculated based on a heat exchanger between the engine oil loop and fuel. The electronics heat load profile are different for this system as well, along with the addition of the HEPS electric and thermal load on the aircraft. The engine oil heat load differs in this study based on engine operation.

3.2.3. Recirculating Flow and APTMS Connection

The amount of fuel required by the main engine is set by cascade PI controllers, which converts a thrust demand from the AVS to a required fuel flow rate. The main fuel pump in the FTMS calculates the actual mass flow based on a calculated pressure difference across the pump and a rotational speed set by a ratio of the LP shaft of the engine. A consequence of this is that there is a difference between the supplied and needed flow rate. The remaining flow rate is recirculated back to the main fuel tank. This fuel is at a high temperature, because it is recirculated after running through the electronics, generator, and controller heat loads.

This recirculating flow can cause a large temperature rise, particularly at the end of the mission. This is due to the high temperature and pressure of the recirculating fuel being sent to the fuel tank. In order to mitigate this temperature rise, a fuel-air heat exchanger was placed between the recirculating fuel flow and the air entering the compressor of the Integrated Power Pack (IPP). This air is compressed and the heat is rejected through a fan duct heat exchanger in engine bypass. This functions as a heat sink for the hot recirculating fuel to cool it before it returns to the main fuel tanks.

3.3. Adaptive Power and Thermal Management System (APTMS)

The goal of the APTMS is to cool the main PAO loop of the aircraft, which then cools the Cockpit, Air Cooled Avionics (ACA), Liquid Cooled Avionics (LCA), and the HEPS. The APTMS included in this
vehicle model is significantly different than the one discussed in the first study. This APTMS still uses an IPP to reject heat from the cockpit and avionics, but also utilizes a vapor compression system (VCS). These are set up in a cascade fashion to cool the PAO loop. First, the PAO loop is directly cooled by the evaporator heat exchanger in the VCS. Then the condenser heat exchanger rejects heat to a separate air loop that uses the IPP to reject heat to the engine bypass.

There are three main control systems for the APTMS. The rotational speed of the IPP is controlled based on a set point for the exiting condenser temperature of the VCS. The work input by the VCS compressor is controlled based on the PAO temperature exiting the evaporator of the VCS. Lastly, the flow rate of the PAO loop is also controlled based on the temperature of the PAO exiting the evaporator of the VCS. Therefore, the main function of the IPP is to cool the VCS, so that the VCS can more effectively cool the main PAO loop. The total architecture for this APTMS is shown in Figure 9.

![Figure 9. Adaptive Power Thermal Management System Architecture](image-url)
3.3.1. **Integrated Power Pack**

The integrated power pack is an air cycle machine that cools both the condenser of the VCS and the recirculating fuel in the FTMS using a Brayton gas refrigeration cycle. It consists of a power turbine, closed loop compressor, and closed loop turbine. The IPP uses high pressure bleed air from the compressor of the main engine to power the IPP via the power turbine. The closed loop cycle expands air in the closed loop turbine to cool the condenser of the VCS and the recirculating fuel. Then the air is compressed in the closed loop compressor and sent to a fan duct heat exchanger in the engine bypass where it rejects heat and returns to the closed loop turbine.

Two different approaches are used to model the dynamics of the IPP. The first is through the use of modeling plenum volumes after each turbomachinery model. The turbomachinery models include generic performance maps based on normalized inputs of pressure ratio and shaft speed.

\[
P_{r,\text{normalized}} = \frac{P_{\text{out}}}{P_{\text{in}} P_{r,\text{design}}} \quad (14)
\]

\[
N_{\text{normalized}} = \left( \frac{N_{\text{shaft}}}{\sqrt{T_{\text{in}}}} \right) \left( \frac{T_{\text{in,design}}}{N_{\text{design}}} \right) \quad (15)
\]

This normalized pressure ratio and shaft speed are input into the generalized performance map of each component. The outputs are the normalized mass flow rate and efficiency of the component.\(^{14}\)

\[
\dot{m}_{\text{actual}} = \dot{m}_{\text{normalized}} \left( \frac{\dot{m}_{\text{design}} \sqrt{T_{\text{in,design}}}}{P_{\text{in,design}}} \right) \left( \frac{P_{\text{in}}}{T_{\text{in}}} \right) \quad (16)
\]

The efficiency of the component maps is then used to find the outlet temperature of each component. Example equations for the compressor and turbine outlet temperature are given below:
\[ T_{\text{out,comp}} = T_{\text{in}} \left( 1 + \frac{1}{\eta} \frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\frac{y-1}{y-1}} \]  \hfill (17)

\[ T_{\text{out,turb}} = T_{\text{in}} \left( 1 + \eta \frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\frac{y-1}{y-1}} \]  \hfill (18)

After each of these turbomachinery calculations, a plenum volume is used to calculate the exit pressure for each component. These plenum volumes are assumed to be isentropic ducts with minimum momentum change. Assuming air as a perfect gas, the pressure in the volume is calculated based on the difference in mass flow rates:

\[ P = \int \left( \frac{\dot{m}_{\text{in}} - \dot{m}_{\text{out}}}{V_p} \right) R_g T \, dt \]  \hfill (19)

In addition to volume dynamics, the model of the IPP also considers shaft inertia. Any change in shaft speed is calculated based off the following equation

\[ N = \frac{30}{\pi} \int \frac{W_{\text{power,turb}} + W_{\text{CL,turb}} + W_{\text{CL,comp}}}{I_{\text{shaft}} \omega_{\text{shaft}}} \, dt \]  \hfill (20)

The shaft speed of the IPP is controlled based on the bleed air sent to the power turbine, and the equation above gives the time delay for the response of the IPP to any change in torque.\textsuperscript{14}

3.3.2. Heat Exchanger Model

The heat exchanger used throughout the T2T model has been documented in previous publications.\textsuperscript{14,15} A counter-flow, plate-fin heat exchanger was modeled along with volume and mass estimates to affect the total mass and volume of the aircraft. The model consists of an energy balance solved alongside a heat transfer coefficient calculation. The energy balance is calculated for each of the major components of the heat exchanger: the hot fluid, the cold fluid, and the heat exchanger mass. The energy balance equation and temperature equation for the hot and cold fluids are given in the equations below.
\[
\frac{dE}{dt} = -\dot{Q} + \dot{m}(h_{in} - h_{out})
\]  
\( (21) \)

\[
\frac{dT}{dt} = \frac{1}{\dot{m}C_p} \frac{dE}{dt}
\]  
\( (22) \)

Each of these equations are solved at each time step, and the temperature gradient is integrated to find the temperature at each time step.

\[
T = \int \frac{dT}{dt} \, dt
\]  
\( (23) \)

The \( \dot{Q} \) used in both the cold and hot energy balance is found using a simple convection equation

\[
\dot{Q} = hA_{HX}(T_{fl} - T_{HX})
\]  
\( (24) \)

The heat transfer coefficient is dependent on both the type of fluid and the flow. The fluid properties are included in each heat exchanger block, and can be changed using the block user interface. Based on the selected properties and the flow input, the Reynolds number is calculated for both the hot and cold fluids. Then the Nusselt number is calculated based on the Gnielinski correlations.\(^{32}\)

\[
Nu = \frac{f/2(Re - 1000)Pr}{1 + 12.7(f/2)(Pr^{2/3} - 1)} \left[ 1 + \left( \frac{D_h}{L} \right)^{2/3} \right]
\]

\( Re = [2300,5 \times 10^4] \)  
\( Pr = [0.5,2000] \)  
\( Nu = 0.0214(Re^{0.8} - 100)Pr^{0.4} \left[ 1 + \left( \frac{D_h}{L} \right)^{2/3} \right] \)  
\( Re = [10^4,5 \times 10^6] \)  
\( Pr = [0.5,1.5] \)  
\( Nu = 0.012(Re^{0.87} - 280)Pr^{0.4} \left[ 1 + \left( \frac{D_h}{L} \right)^{2/3} \right] \)  
\( Re = [3 \times 10^3,10^6] \)  
\( Pr = [1.5,500] \)
From these Nusselt number correlations the heat transfer coefficient can be found based on the hydraulic diameter using the following equation:

$$h = Nu \left( \frac{k}{D_h} \right)$$

(28)

Once the heat transfer into each fluid has been calculated, the temperature change in the heat exchanger itself can be found from the heat transferred to the cold fluid and from the hot fluid into the lumped mass of the heat exchanger.

$$\frac{dT_{HX}}{dt} = \frac{1}{m_{HX}c_p} (\dot{Q}_{cold} + \dot{Q}_{hot})$$

(29)

This equation assumes that the heat exchanger can be treated as a lumped mass, which is only appropriate for a Biot number less than 0.1. In order to make this assumption more appropriate, the heat exchanger can be broken into multiple nodes or control volumes.

3.3.3. High Energy Pulsed System (HEPS)

The high energy pulsed system represents a solid state laser as discussed by Nuzum. Therefore, a conservative thermal efficiency of approximately 20% was used for the HEPS, and because the model assumes a 150 kW laser, a total thermal input of 750 kW is modeled. In order to account for this large thermal load, a separate TMS is necessary. There are multiple options for this TMS, including thermal storage either with or without a phase change. For this study, a fuel cooled laser TMS has been selected, in order to represent a more conventional style liquid cooling used to cool lasers currently.

The goal of this research is to investigate the effects of this system with respect to thermal management, therefore the laser system components are only modeled as a heat load into the separate HEPS TMS. The HEPS is cooled by a separate fuel loop in the APTMS. This is a completely separate fuel tank than the one used in the FTMS to run the engine of the aircraft. Thus, it can be
managed separated from the main fuel line for the engine. However, this fuel could potentially be used in the main engine towards the end of a mission. This gives an advantage over other liquids, such as water, which are completely expendable and cannot serve a purpose other than to cool the HEPS. The model discussed in this paper does not currently utilize the capability of using the fuel of the HEPS system in the engine, but instead it is discussed as a motivation of using this fluid rather than water.

The fuel cooled TMS consists of already discussed components, including a fuel pump, fuel tank, and two heat exchangers. The first heat exchanger models the heat flowing from the HEPS fuel loop to the PAO loop of the APTMS. The second heat exchanger models the 750 kW heat load from the HEPS system into the fuel. Both of these heat exchangers are of the same type described in the previous section, but with one major exception. The heat exchanger modeling the HEPS heat load is modeled as a one-sided heat exchanger. This means that the energy balance for the cold side is still calculated, along with the heat transfer into the cold fluid. The heat transfer from the hot side into the heat exchanger is assumed to be the 750 kW heat load, and so the equation for the temperature of the heat exchanger becomes:

$$\frac{dT_{HX}}{dt} = \frac{1}{m_{HX}C_p}(\dot{Q}_{cold} + \dot{Q}_{HEPS})$$

(30)

3.4. High Power Electric Actuation System (HPEAS) and Robust Electrical Power System (REPS)

Because the T2T model is primarily focused on thermal management, the dynamics of the electrical systems are greatly simplified into heat loads that cause an increase in temperature over the course of the mission. The HPEAS includes the actuator heat loads, which are implemented in Simulink as look-up tables that are solely a function of the mission. The REPS includes simple
models of electrical components such as the generator, avionics, controllers, and IPP motor. All of the signals from these models are input into an electrical bus to be used in the rest of the model.

4. Legacy Vehicle Model

The previous vehicle models have attempted to dynamically model current and future aircraft configurations. No effort has been made to create a model of a legacy aircraft configuration, due to the lack of electrical or high power electrical systems on those aircraft. However, recent research has been started to validate modeling and simulation tools utilizing already existing aircraft platforms. This research has concluded that individual component testing and validation is not sufficient for complex integrated systems. Instead, validation is needed for entire vehicle level models, so accurate subsystem interactions can be captured and modeled. Therefore, a vehicle level model is needed for legacy vehicle systems, which is the goal of this study.

An AVS similar to the generic M85 model in the previous two studies was developed to model the aerodynamics of the legacy aircraft. This is a lower order aerodynamics model, which has a reduced simulation time. Higher order models, like a six DOF model, give more information necessary for thermal management when high performance electrical actuation systems (HPEAS) are used on the aircraft. The legacy aircraft of this investigation does not have an HPEAS on board so the lower order aerodynamics model is appropriate. The engine model is a two-stream, dynamic engine model, similar to those used in previous studies. Multiple additions have been made to the model, including an afterburner, to make the engine more applicable to this legacy aircraft. An overall schematic of the thermal management system for the legacy aircraft is given in Figure 10.
The TMS diagram includes both the FTMS and ECS. The upper half of this diagram is the FTMS, which tracks the fuel temperature as it goes from the fuel tank, through various heat loads and into the engine. Because fuel is a primary heat sink in many legacy aircraft, most of the heat loads present in the aircraft use the fuel as a heat sink. An exception to this is present in the ECS. The ECS both pressurizes the cockpit and maintains the temperature of both the cockpit and avionics. This is achieved by bleeding air from the engine and cooling it through the use of an air cycle machine (ACM). The ACM uses a Brayton cycle refrigeration system to cool the bleed air before it goes to the cockpit and avionics.

4.1. Engine Model

In this study, a two-stream turbofan engine was used, in order to utilize previous work completed. The engine model is a transient model that utilizes the same methods of dynamic analysis as the IPP described in the High Energy Pulsed System Integration section above. The engine has both a
high pressure and low pressure shaft. The high pressure shaft spins the high pressure compressor and high pressure turbine, and the loads from each of these components are added to the shaft speed equation, which was shown in Equation 20. This equation is also used for the low pressure shaft, with the loads from the low pressure compressor and low pressure turbine used. Another dynamic characteristic of the model is captured by using of the ideal gas law along with conservation of mass to calculate the pressure of each component (i.e. compressibility effects). Equation 19 shown previously models this effect, where the change in mass flow rate in the component is integrated and then converted to pressure using the ideal gas equation. In addition, the engine model includes a combustor, mixer, and nozzle models. The engine was previously sized for a 29 klbf class engine, which is not the size required for this aircraft.

Multiple steps were performed to update the engine to accurately represent the engine used in this aircraft. The legacy aircraft engine has afterburner capability, so this capability was desired in the engine model as well. However, in order to utilize an afterburner in this model, a variable area nozzle is required. This is a nozzle that implements a control system based on the fan surge margin, and changes the nozzle exit area in order to maintain a specific fan surge margin. For the purposes of this engine and application, the PI controller was set to control the surge margin to 12%. This controller then feeds through a demand nozzle area percent to the nozzle model. Once this was implemented and verified, the afterburner model itself was implemented. The model itself functions as another combustor, with the majority of the functionality of the afterburner dependent on the control logic. This was implemented as two triggered subsystems, one that activates if there is fuel flowing to the afterburner, and then one that activates if no fuel goes to the afterburner. The amount of fuel used depends on the main fuel controller of the engine, and whether the main burner is fully saturated. Verification was completed to ensure that this engine has a maximum dry thrust of 17 klbf, and a maximum wetted thrust of 29 klbf.
4.2. Environmental Control System (ECS)

The ECS model focuses on cooling the various electrical systems and cockpit of the aircraft using air as the main working fluid. Many of the current T2T models use other methods of cooling, including using multiple working fluids to cool the avionics and cockpit. This ECS system uses an air cycle machine (ACM) to cool bleed air from the high pressure compressor of the engine based on a Brayton refrigeration cycle. Before the air enters the compressor of the ACM, it runs through a series of heat exchangers, in order to cool the air before the ACM. The isolated ECS schematic is given in Figure 11.

![ECS Schematic](image)

**Figure 11. ECS Schematic**

4.2.1. Control Structure

As the right hand side of this diagram shows, the ECS utilizes bleed air from the high pressure compressor of the engine to pressurize and regulate the temperature of the cockpit and avionics. The amount of bleed is controlled by the valve labeled 1, and is controlled indirectly based on the cockpit and avionics temperatures. As the heat loads change in the cockpit and avionics, the Simulink block calculated the flow rate necessary to maintain the setpoint temperature. A generic heat load equation is used for this calculation:
\[ \dot{m} = \frac{\dot{Q}}{c_v(T_{in} - T_{setpoint})} \] (31)

This value is calculated for both the cockpit and avionics heat loads, and is used in the PI controller for control valve 1.

The bleed flow is then fed into the ECS. There are two main splits for this bleed flow: the hot bypass at point two, and the warm bypass at point three. The hot bypass controller manages the temperature of the warm bypass and hot bypass merge just after control point three. The overall purpose of this air mixture is to be mixed with the cold air leaving the turbine of the ACM, to manage the temperature of the cockpit, and to ensure that the air cooling the cockpit is above the freezing point of water to prevent icing. The control valve at point three is controlled based on the temperature of the cockpit, mostly to ensure it does not overheat from the hot bypass.

Before the cockpit, the cooling air leaving the ACM merges with the warm air leaving the fourth control valve. The control valve at point four is controlled based on the temperature of this air.

The other major component of this control structure is a feed forward loop implemented in the bleed controller. As previous work with this model showed, variable bleed inputs posed issues for the controllers, and with the bleed controller in particular. In order to address this problem, an equation relating the mass flow demand to a necessary control valve position was added to the PI controller for the engine bleed. The pressure in and out of the valve is required to calculate the Mach number of the flow through the valve. Then the ratio of specific heats, \( k \), is found from a look-up table for air at a given temperature. This equation is based on the density of the air in the valve and the velocity of the air in the valve (Equation 34):

\[ A_{valve} = \frac{\dot{m}}{V_{valve}\rho} \] (32)
where the density and velocity are calculated based on look-up tables for air. This area is then fed into a look-up table that has the relationship between the desired area of the valve and the percent opening of the valve.

4.2.2. Control Valves

In the previous section, the control structure was outlined. As is shown in the system schematic, all of these controllers open the four control valves present in the ECS model. These are ideal gas control valves, and specifically use a V-port ball valve characteristic curve to relate the percent open to the area of the valve. The properties of the flow entering the control valve, including pressure and temperature, are used to calculate the Mach number and then the ratio of specific heats, \( k \). These are then used to calculate the upstream density, throat velocity, and throat density. The calculated values, along with the valve area, use Equation 33 below to solve for the flow exiting the valve, assuming a discharge coefficient of 1:

\[
\dot{m} = V_{\text{valve}} \rho_{\text{throat}} A_{\text{valve}}
\]

4.2.3. Air Cycle Machine (ACM)

The ACM is similar to the IPP described in the High Energy Pulsed System Integration section. Its function is to compress bleed air from the engine, then expand it in the turbine. This operates based on a Brayton refrigeration cycle which cools the air through this cyclic process, and the amount cooled is dependent on the work into the compressor by the bleed air. The ACM is a dynamic model, which utilizes the same major methods of dynamic analysis as the engine. A plenum volume model is attached to both the compressor and turbine models, which calculates the pressure in each volume based on the ideal gas law and difference in mass flows. The shaft model takes the loads from the compressor and turbine and integrates them with respect to time to find the shaft speed. This is input into the compressor and turbine models to be used in the
turbomachinery calculations. The turbomachinery is modeled using performance maps, which calculate the mass flow rate and efficiency of the component. The turbine and compressor maps require inputs of normalized pressure ratio and normalized shaft speed. Equations 14 and 15 give the method used to calculate these required values. These values are input into the performance maps, which calculate the normalized mass flow and efficiency:

\[
\dot{m}_{\text{normalized}} = f(N_{\text{normalized}}, P_{r,\text{normalized}}) \quad (34)
\]

\[
\eta = f(N_{\text{normalized}}, P_{r,\text{normalized}}) \quad (35)
\]

Equation 16 gives the conversion from the normalized flow rate to the actual flow rate out of the turbomachinery component. Then the isentropic efficiency is used to calculate the temperature leaving the compressor and turbine, based on Equations 19 and 20.

### 4.2.4. Avionics and Cockpit Heat Loads

In the Control Structure section, the heat loads for both the cockpit and avionics were briefly discussed, as an inverted heat load calculation was used as an inversion for the main controller in the ECS. The goal of the heat load models is to include the heat load induced into the system by the electronics associated with the avionics and the cockpit. The entire purpose of the ECS is to regulate the temperatures of these two systems. This is performed by controlling the temperature and mass flow rate of the cooling air over these systems, and adjusting the control valves accordingly. The avionics controller setpoint was 160 degrees Fahrenheit to prevent overheating the electronics. The cockpit controller setpoint was 75 degrees Fahrenheit, so that the pilot is kept at a reasonably comfortable temperature. Another convenience of using high pressure bleed air from the compressor of the engine is that it helps to keep the cockpit at a comfortable pressure at higher altitudes.
The heat load models in the ECS are similar to those discussed previously, but deal with conservation of energy entirely with respect to enthalpy. Multiple functions and look-up tables are included in the model that calculate the enthalpy of both the entering and exiting heat load based on the temperature of the flows. The general heat load equation is derived from the conservation of energy, and is given in Equation 36.

\[ \dot{m} h_{in} - \dot{m} h_{out} + \dot{Q}_{in} = m \frac{dh_{out}}{dt} \] (36)

Equation 36 is then solved for the enthalpy gradient, and integrated to calculate the enthalpy of the fluid leaving the heat load. A curve fit for the relationship between enthalpy and temperature of the fluid then solves for the temperature of the exiting fluid based on its enthalpy. Inside the models, Equation 31 estimates the mass flow rate that is required to reach the set temperature given the current heat load. This mass flow rate is fed into the control system to set the bleed control valve.

**4.2.5. Heat Exchanger**

The heat exchanger model has been described in previous studies. This is a counter flow, plate-fin heat exchanger. A one-dimensional heat exchanger model is used that has the capability of calculating using different nodes along the length. Each node is treaded as three control volumes: the cold fluid, the hot fluid, and the heat exchanger mass. The conservation of energy equation is used for both the hot and cold fluids to solve for the temperature gradient in Equations 21 and 22. This is then integrated to find the temperature at each time step of the solution. The heat flow from the hot and cold fluids are then found based on the temperature difference between the fluid and the heat exchanger mass, as well as on the heat transfer coefficient, as is shown in Equation 24. The Gnielinski correlations, given in Equations 25-27, are used to find the Nusselt number for both the cold and hot fluids, based on each fluid’s Reynolds number and
Prandtl number. Then the appropriate heat transfer coefficient is calculated from this Nusselt number.

5. Results and Discussion

The Methodology section above discusses the development and structure of three T2T models created for three separate studies. The first study is a fuel pump trade study, which seeks to evaluate two fuel pump systems inside a tactical fighter T2T model. The two systems, which include a centrifugal and variable displacement pump, are judged based on SEP, fuel temperature margin, and fuel burn. The second study addresses the impact of a high energy HEPS on an aircraft TMS. This system uses a fuel cooled TMS to cool the HEPS separately, which connects to the aircraft TMS through a heat exchanger. The final study addresses the development and capability of a traditional ECS architecture to cool a legacy aircraft’s cockpit and avionics. Results for these studies are given below.

5.1. Fuel Pump Study

Two different cases were simulated to compare the different performance parameters for the same mission. The generic fuel pump in the T2T model is replaced with the Weinman centrifugal pump. This centrifugal pump configuration is then compared with a variable displacement piston pump. The goal in this study is to demonstrate that the model has the capability to analyze the entire aircraft based on aircraft performance, efficiency, and thermal margin. It does not consider reliability, cost or mass and volume estimates. These parameters, which are essential considerations for industry, are the subject of future research.
5.1.1. Variable Displacement Pump

The first case considered is for the integrated variable displacement piston pump. This pump is incorporated into the Fuel Thermal Management System of the T2T model, and replaced the generic pump that was initially implemented in the system. SEP, FTMS temperatures, and the mass and temperature of the fuel tank along the mission are shown in the following figures. These will then be compared with those from the centrifugal pump case to judge the two based on these system performance metrics. Figure 12 shows the fuel temperature results over a 3,000 second mission.

![Figure 12. Fuel Temperatures for the Variable Displacement Pump Case](image)

Because there is no recirculation back into the fuel tank in order to maintain the pressure provided by the fuel pump, there is a minimal increase in temperature inside of the fuel tank. As a result of this, none of the FTMS systems reached their temperature limits.

Another metric used to compare these two fuel pump systems was SEP. The SEP gives a measure of how much excess power is available to the aircraft throughout the mission, and comparing the two systems SEP gives a measure on which system has more potential for maneuverability. However, changing the fuel pump had a minimal impact on the demanded thrust and speed of the aircraft throughout the mission. In fact, when the two plots of SEP are overlaid, there is almost no perceivable difference between the two systems. For this reason, Figure 13 shows the SEP
variation for both fuel pump systems, along with the altitude and Mach values along the 3,000 second mission.

Figure 13. SEP variation with the mission

Over the entire mission, the SEP stays positive, which shows that the engine can actually deliver the thrust necessary to complete the mission. In addition, the plot follows the general trend as described in the Technical Foundation section. As the aircraft increases in altitude, it generally decreases the SEP, and as the aircraft decreases in altitude, the SEP increases. There are sections of the mission where this is not the case, but that is due to the change in the speed of the vehicle. As the velocity of the vehicle increases, both the possible excess thrust and the SEP itself will change accordingly. A comparison of the two systems based on SEP will be summarized later based on the integral of the SEP. This value will show which of the two systems had a total higher SEP.

The final metric used to compare these two systems is fuel burn. This is a measure of how much fuel is used by the aircraft over the mission. This is tracked in the fuel tank model, along with the fuel tank temperature. Like with SEP, the amount of fuel burned is very similar between the two fuel pump systems. Figure 14 shows the change in the fuel mass over the length of the mission.
Nearly all of the fuel leaves the fuel tank over the length of the mission, which relates to the total fuel burned. In addition, the fuel tank temperature stayed fairly constant, because none the fuel heated by the pump is recirculated back into the fuel tank. The total amount of fuel burned during the mission in the piston pump case was 27.10 klbm.

5.1.2. Centrifugal Pump

The centrifugal pump model discussed earlier was implemented in the T2T model and run through the same mission profile, Figure 14, as for the variable displacement pump case. Both were implemented in the same T2T model, but with different control systems to manage the required pressure for the main pump of the engine. The three parameters shown for this system are temperatures of different components in the FTMS, the temperature in the fuel tank, and the mass of fuel in the tank. Figure 15 shows the fuel temperature results of the centrifugal pump case.
As the plots show, the fuel temperatures in the tank exceed the specified limits. Because fuel is recirculated back into the tank to regulate the pressure of the system, the work done by the pump on the fuel causes a large increase in tank temperature. This is not present in the piston pump system because the pressure is controlled by the swashplate angle, which means that no recirculation is necessary.

Like before, the fuel tank mass was tracked throughout the 3000 second mission, in order to compare the fuel burn between the two cases. Figure 16 shows the amount of fuel in the tank and the temperature of the tank over the entire mission.

![Figure 16. Centrifugal Pump Fuel Tank Results](image)

This plot shows that there is a small change in the fuel consumption throughout the mission when compared to the variable displacement pump; however, like the previous plots showed, the final temperature of the fuel tank for the centrifugal pump configuration is much higher than for the variable displacement pump FTMS. There is very little difference in SEP over the mission. The SEP plot over the mission for the centrifugal pump case is not visibly different than that for the piston pump case, so that plot is not shown. This will be shown more in the comparison of the integral of the SEP at the end of the mission, which is 1.26E+05 feet. In addition, the final fuel burn for the centrifugal pump case is 27.20 klbm.
5.1.3. **Summary**

Table 1 gives a summary of the two fuel pump cases with respect to fuel burn, SEP, and fuel thermal margin. There was not a large difference between the two cases with respect to SEP, however, the variable displacement pump case did have a slightly higher integral SEP at the end of the mission. This means that there is a slightly better capability for performance using this pump over the centrifugal. There is more difference in fuel burn between the two cases, with the variable displacement pump burning 96 lbs (0.355%) more fuel than the centrifugal pump.

An overlay plot of the fuel tank mass along the mission is given in Figure 17. Over the majority of the mission, the two plots show the same amount of fuel mass on the aircraft. In the first few minutes the two systems are different, which is to be expected because the two systems are starting up from their initial conditions. The more interesting segment of the mission is near the 35 minute mark. Figure 13 shows that this segment is the thermally constraining part of the mission, with a low altitude and high Mach number. This likely caused a difference in the fuel tank mass over that time segment, based on the transient interactions between the pump system and the engine model. The two systems ended up settling out to the same value overall ending value.
A similar overlay plot was also made for each system’s SEP, and is given in Figure 18. Like the plot for the fuel tank mass, the two lines on the plot of SEP overlap for most of the mission. In fact, the only difference is between the 30 and 35 minute marks. Again, this is the most thermally constraining part of the mission because the aircraft is at low altitude and high speed. The variable displacement pump systems offers more control and possibilities for thrust increase, which explains the increase in SEP at that segment of the mission. In addition, this system causes less of a temperature increase in the system, which could affect the SEP. Further studies would need to be performed to check the influence of the increase in temperature on the thrust demand or engine performance. The likeliest reason for this increase is the difference in fuel mass between the two systems. In Figure 17, the piston pump uses more fuel during that leg of the mission. The total weight of the aircraft figures into the calculation of SEP, and a decrease in total
mass causes an increase in SEP. A combination of all of these reasons is likely the cause of the difference shown in the following plot.

![Figure 18. Plot of SEP comparison between centrifugal pump and variable displacement pump systems](image)

The last metric was the fuel thermal margin. This margin is determined based on the ending temperature of the fuel in the main fuel tank. This margin is the factor that has the greatest difference between the two fuel pump systems. A comparison plot between the two is shown in Figure 19. This plot shows that the variable displacement pump fuel temperature does not vary, let alone increase, over the mission. The centrifugal pump, on the other hand, causes the system temperature to rise slowly at first, and then much more rapidly as the fuel tank nearly empties at the end of the mission. This is due to the amount of recirculation that is present in the centrifugal pump system. The fuel being supplied to the engine is more than is needed, and so the rest of this fuel is sent back into the fuel tank. However, this fuel has been used as a heat sink for different electronics and heat exchangers, so this hot fuel raises the temperature of the fuel tank. As the fuel tank empties, this recirculation causes an even higher temperature rise, until it exceeds
the specified limit. Due to the flow rate being more tightly controlled, the variable displacement pump had no fuel recirculation, which kept the temperature lower.

![Graph of fuel temperature comparison between centrifugal pump and variable displacement pump systems](image)

**Figure 19.** Plot of fuel temperature comparison between centrifugal pump and variable displacement pump systems

A numerical comparison of each system is made in Table 2. This table includes the values of the described evaluation parameters: SEP, fuel burn, and fuel thermal margin. The integral SEP is just what is expected: the SEP is integrated to a final value over the mission. Because the SEP is positive over the aircraft’s mission, the two can be compared, and the higher the SEP at different mission segments, the higher its integral will be. The fuel burn is the amount of fuel each system burned by the end of the 3000 second mission. The fuel thermal margin is a bit more complicated. The temperature of the fuel in the main fuel tank is tracked throughout the mission, and the final temperature is used to calculate the fuel temperature margin. A negative value is desired,
because this means that the system has not gone over the temperature limit. A positive value means that the limit has been exceeded.

### Table 1. Case Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Integral SEP (m)</th>
<th>Fuel Burn (klbm)</th>
<th>Fuel Thermal Margin (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugal Pump</td>
<td>1.26E+05</td>
<td>27.1016</td>
<td>53.6826</td>
</tr>
<tr>
<td>Variable Displacement Pump</td>
<td>1.27E+05</td>
<td>27.1977</td>
<td>-82.3521</td>
</tr>
</tbody>
</table>

The largest difference between the two cases is the fuel thermal margin. The fuel tank in the centrifugal pump system is 136.3°F higher than the temperature in the variable displacement pump case. This means that the variable displacement pump case has more potential to cool other subsystems before reaching its temperature limit. So in summary, the variable displacement pump performed slightly better when the SEPs are compared and has a better fuel thermal margin. Though the fuel burn for the centrifugal pump case is slightly lower, overall the variable displacement pump would be the better choice because of its desirable thermal margin.

**5.2. High Energy Pulsed System Integration**

The T2T model was run for a 3000 second mission, which is shown in Figure 20. The lines refer to the Mach number, altitude, and HEPS fires during the mission. These are the only requirements to run the T2T model, because the aircraft model is a reduced order model, and only requires a speed and altitude to calculate the required thrust. The HEPS is fired at four strategic points in the mission: a low speed, high altitude cruise; a high speed high altitude cruise; a thermally constrainning low altitude, high speed dash; and a low speed, medium altitude point. Each of these firings is a six shot cluster of six seconds on, six seconds off. This was selected in order to give the HEPS a small time to cool down before the next shot is fired, and time is given between each cluster for the same reason. Also, these firing clusters were selected for times where both the
Mach number and altitude are constant during that mission segment. This is to avoid any major transient reactions between the different systems as the engine and AVS models transition the aircraft to the next mission segment.

![Vehicle Mission](image)

**Figure 20. T2T Mission Profile**

A goal of the fuel cooled system is for its results to be compared with a comparable liquefied natural gas (LNG) cooled HEPS system. Therefore, the fuel cooled system was sized based on the same design constraint as the LNG cooled system: that the wavelength of the laser output would not change by more than 1 nm. The temperature of the HEPS system greatly affects the output wavelength of the laser. At room temperature (298K), through figures-of-merit the beam distortion and refractive index are 87 and 31 times greater than for a laser operating at 100 K for same output power.17 Therefore a laser operating at room temperature is much more sensitive to stress-optical effects.

Two fuel cooled systems were designed based on these requirements. The first system, dubbed the large heat exchanger system has a HEPS heat exchanger sized in order to meet the stringent
2K temperature delta requirement during a firing pulse. The second system has a smaller HEPS heat exchanger sized based on other heat exchangers used in the T2T model. The mass and volume estimates of these two systems are shown in Table 2.

**Table 2. Fuel-Cooled HEPS Component Masses**

<table>
<thead>
<tr>
<th></th>
<th>Laser HX Mass (kg)</th>
<th>PAO HX Mass (kg)</th>
<th>Fuel Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small HX</td>
<td>168</td>
<td>110</td>
<td>136</td>
</tr>
<tr>
<td>Large HX</td>
<td>887</td>
<td>110</td>
<td>136</td>
</tr>
</tbody>
</table>

This table includes the masses for each of the components, excluding the fuel pump and tank. These two component models did not include a mass and volume estimate, due to a lack of available information on aviation fuel pumps and tanks.

A major design constraint for the fuel-cooled HEPS is the temperature change during each activation of the HEPS. This means that during each 6 second fire of the laser, the HEPS heat exchanger temperature could not change more than 2K. Therefore, the temperature of the HEPS heat exchanger was tracked throughout the mission. An example of these temperatures is given in Figure 21. The small heat exchanger HEPS model does not hold the 2 K temperature requirement during one activation and has a temperature increase of 10K. The large heat exchanger is able to maintain a 2.4K temperature increase while firing, which almost meets the 2K requirement. Based on the size required to transfer 750kW across the necessary temperature difference, the heat exchanger mass used was the largest possible before reaching unreasonable mass and volume values.
5.2.1. APTMS Results

The HEPS system was implemented in the T2T model as part of the PAO loop in the APTMS. Other components in this cooling loop include the liquid cooled avionics (LCA), the APTMS controller, the PAO pump, and bleed air that cools the cockpit and air cooled avionics (ACA). Three of these components are treated as heat loads that vary along the mission, and the bleed air is cooled using an air-PAO heat exchanger. The T2T model controls the temperature of various systems based on different set point temperatures inside this PAO loop. The primary system temperature controlled is the temperature of the evaporator of the VCS. This is controlled based on the amount of work put into the VCS, which then cools the evaporator using a simple COP method. A plot of the temperature exiting the PAO side of the evaporator heat exchanger is shown in Figure 22.
The plots compare three different systems: a baseline, which does not include the HEPS, the small heat exchanger fuel-cooled system, and the large heat exchanger fuel cooled system. These three systems have a similar performance along the length of the mission, with a few exceptions. At the four points in the mission where the laser system is firing, there is an increase in temperature of nearly 20ºF for the small heat exchanger HEPS, and about 10ºF for the large heat exchanger HEPS, when compared to the baseline architecture.

The evaporator temperature shown in Figure 22 is the temperature of the PAO just after it is cooled by the VCS. The two other systems, besides the HEPS, that are cooled by the PAO loop are the LCA and the cockpit. These temperatures are indirectly controlled through the control of the evaporator of the VCS. The temperature of the liquid cooled avionics for the baseline, small heat exchanger, and large heat exchanger systems is shown in Figure 23. These plots show a similar trend to that shown in Figure 22. During the four parts of the mission where the HEPS is firing, there is a spike in temperature in both fuel cooled systems. Again, because of the large mass of
the HEPS heat exchanger and the large flow rate of fuel, the large heat exchanger system showed a smaller increase in temperature of the liquid cooled avionics. However, both of these temperature increases are within the allowable limits of the LCA, so both systems manage the laser heat load with respect to the aircraft thermal management requirements.

Figure 23. Liquid Cooled Avionics Temperature

Figure 24 shows the cockpit temperature for the three different systems. All three systems manage the temperature of the cockpit within reasonable temperatures. The cockpit follows the same trend as shown for the LCA and evaporator: all three systems follow each other except at the points when the laser system is firing. One section of the mission where all three systems maintain the cockpit at a high temperature is in the first five minutes. This is the part of the mission where all systems are starting up, and trying to cool the systems from their initial temperatures of 298K down to their set points. In addition, this is the section where the AVS and
engine models are working hardest to reach the desired Mach number and altitude from the initial conditions.

![Cockpit Temperature Graph](image)

**Figure 24. Cockpit Temperature**

5.2.2. **Comparison with LNG System**

Another motivation of this system is to compare it to a system that utilizes the phase change of liquefied natural gas. A big difference in these systems is the weight necessary to thermally manage the HEPS system. Whereas the fuel cooled systems require a large fuel pump and laser heat exchanger, utilizing the heat of vaporization of natural gas could allow for a smaller mass and volume than a fuel cooled TMS.

In addition, the LNG cooled system has the ability to cool the rest of the aircraft system, as opposed to the fuel-cooled system whose function is to lower the amount of heat rejected to the rest of the aircraft. Nuzum et al\textsuperscript{21} has completed a similar study that investigated the application of LNG to cooling the HEPS. That system consists of a two-phase fuel tank, HEPS cooling system,
and mixing chamber. In addition to this, the size of the major TMS components were changed based on how the system performed. The maximum work possible by the VCS was reduced to 100kW, as opposed to a maximum work of 150kW for the fuel-cooled system. Also, the IPP was sized at 60% smaller than the one used in the fuel-cooled case. Figure 26 gives a comparison graph between the fuel-cooled and LNG-cooled HEPS.

![Liquid Cooled Avionics Temperature](image)

**Figure 25. Liquid Cooled Avionics Temperature for Fuel Cooled and LNG Systems**

The plots show that despite the smaller TMS components, the LNG cooled system outperforms both of the fuel cooled HEPS systems. During the segments of the mission where the laser is firing, the LNG used to cool the HEPS also cools the PAO loop through an LNG-PAO heat exchanger. This extra cooling led to a difference of approximately 20 K during most of the mission. In addition, the LNG system is able to maintain a lower temperature during the first few minutes of the mission, when each system in the T2T model is reaching its initial set point temperature.
As these comparisons have shown, the LNG system has consistently outperformed the fuel cooled system in the same T2T model configuration. In fact, the LNG system has outperformed both the fuel cooled systems with a significantly smaller IPP and VCS. The comparisons showed that unlike the fuel-cooled systems, the LNG system actually cooled the APTMS because of the flow of cold natural gas. If the additional cooling of the gaseous LNG could be utilized as well, the APTMS could be downsized even more, or potentially removed completely. This is the next study, because the massive size and worse performance of the fuel cooled HEPS systems limit its usefulness.

5.3. Legacy Vehicle Model

The desired outcome of this work is to model the transient interactions between different subsystems of the legacy aircraft. In particular, the environmental control system was investigated and built to model the actual aircraft. The ECS model described in the Development of Vehicle Models section was implemented in the T2T model, which was designed to model a legacy air vehicle. A general mission was selected to demonstrate the capabilities of this vehicle, as well as to demonstrate the capabilities of the ECS model. This mission is shown in Figure 26.
Figure 26. Vehicle mission run for the T2T model

The mission has a maximum altitude of 25,000 feet, and a maximum Mach number of 0.8. A higher Mach number was not selected because the current engine model does not include a supersonic inlet, and so any results at a supersonic speed will not be accurate. The vehicle model was able to successfully complete this mission, but with a slight variation due to available thrust. At approximately 5.5 min as shown in Figure 26, there was a slight dip in velocity. This shows another capability of the AVS utilized in the legacy T2T model. If there is not enough thrust to available to achieve the desired mission, the aircraft controller allows for a temporary adjustment. Then as more thrust is available, the controller corrects and gets the aircraft back on course.

The main result of this work was an ECS model that is able to maintain the cockpit and avionics temperatures based on a variable bleed input. This way, the ECS model can be implemented in the T2T model. Due to the variation of speeds and altitudes, the bleed from the engine changes, and so this ECS model needs to be able to handle a wide variety of bleed air properties. The bleed air temperature and pressure at each point along the mission are given in Figure 27.
Figure 27 shows the large variation in temperature in pressure as the engine changes its operating point throughout the mission. The control architecture was designed in order to accept this variable input and utilize the ACM and heat exchangers to maintain the setpoint temperatures. Based on these inputs, the control valves and control gains were updated to manage the varying heat loads in the avionics and cockpit. These heat loads are inputs into the system, and can be changed to reflect different mission types. The heat loads for both the cockpit and avionics are given in Figure 28.
The avionics heat load is set at a constant 6 kW for the entire mission. This is the largest heat load and dominates the cooling flow stream. However, the controller sets the bleed control valve based on the necessary flow rate for both the cockpit and avionics heat loads. The necessary flow rate is determined based on a predictor equation, which bases the flow rate necessary on the heat load and working fluid. This is an effective way to control the cooling flow based on the architecture shown previously.
Figure 29 shows that the ECS controlled the avionics temperature closely throughout the mission. The variation shown is due to the varying bleed input, because the head load input is constant for the avionics. However, the ECS is still able to maintain the setpoint temperature within a few degrees. The control valves adjust the temperature as the heat load is applied to the cooling flow. The temperature of the avionics after the initial state are maintained very well by the ECS; however, this is a constant heat input throughout the mission. The cockpit has a varying heat input throughout the mission. The controlled temperature of the cockpit based on this varying input and the cooling flow of the ECS is given in Figure 30.
Figure 30 shows that the ECS controlled the cockpit temperature as well as the avionics. As the scale of this plot shows, the ECS manages to maintain the cockpit temperature within 3ºF. This is for the varying heat load that is given in Figure 28. This proves that the ECS can maintain this temperature despite the varying heat load and the large variation in bleed input from the engine.

6. Conclusion

For the first study, a tactical fighter platform and three stream engine model have been added and used in a T2T model. This is a conceptual design trade study, which was completed for the fuel thermal management system. Two different fuel pumps have been analyzed: a variable displacement piston pump and a centrifugal pump. These fuel pumps were implemented as the main fuel pump in the FTMS of the T2T model. In addition, the T2T model has been modified to include the analysis of specific excess power, which is based on the performance of the air vehicle. Three parameters were used to analyze the two different fuel pump architectures in the FTMS:
SEP, fuel burn, and fuel thermal margin. There was not a large difference between the two cases with respect to SEP, however, the variable displacement pump case did have a slightly higher integral SEP at the end of the mission. This means that there is a slightly better capability for performance using this pump over the centrifugal pump. There is more difference in fuel burn between the two cases, with the variable displacement pump burning 96 lbs (0.355%) more fuel than the centrifugal pump. The fuel tank in the centrifugal pump system is 136.3°F higher than the temperature in the variable displacement pump case, which means that the variable displacement pump is far superior than the centrifugal pump system with respect to fuel temperature margin.

The results of the fuel pump study give very important conclusions. First, the selection of fuel pumps and other FTMS components have a significant impact on the performance of the aircraft. The two pump systems had minimal impact on the amount of fuel burnt or the SEP of the aircraft, but had a very significant impact on the temperature of the fuel in the aircraft. In reality, this has a very important implication. An actual aircraft uses the fuel as the main heat sink. If the fuel temperature rises too high, it cannot be burned, so the aircraft will either have to be grounded or go to more thermally favorable conditions. In addition, as the temperature increases, it becomes a less useful heat sink, and so the rest of the aircraft temperatures will likely rise as well. The second conclusion is that the control system and the controllability of the system is vital to maintaining temperature. The variable displacement pump system was able to more directly control the output mass flow rate of the pump because the swashplate angle was directly controlled. This means that for a given pressure and shaft speed, the flow rate could be controlled based on the swashplate angle. This was not true for the centrifugal pump system. For a given pressure and shaft speed, there was a set mass flow rate the centrifugal pump could provide. This extra control allowed the variable displacement pump system to control the flow rate more
tightly, and prevented recirculation. Little to no recirculating fuel meant less of a temperature rise. So the two takeaways from this study are as follows: subsystem selection has a major impact on aircraft capabilities, and different control structures can greatly impact the temperature rises on an aircraft.

The second study investigated the effects of adding a HEPS on the thermal management system of the entire aircraft. The addition of a laser system on an aircraft greatly increased the thermal load to be removed by the aircraft TMS. In order to manage this increased thermal load, a separate fuel cooled TMS was created using previously existing component models. These consist of a fuel tank, fuel pump(s), PAO-fuel heat exchanger, and a one sided heat exchanger representing the HEPS heat load into the fuel. This represents a TMS that does not utilize a phase change, and that uses fuel that could be used in the engine towards the end of the mission. Overall, this system left much to be desired. The mass of this fuel-cooled system was very large, exceeding 1000 kg for the system that regulated the temperature rise of the HEPS, and this estimate did not include the large fuel pump that would be required for this system. In addition, this “large HX” system also did not fully meet the temperature change requirement, and allowed a 2.4 K change as opposed to the 2 K change desired. The one benefit of this system, however, was the buffer it gave the rest of the aircraft TMS. There was minimal temperature rise due to the laser firing throughout the mission, because the flowing fuel gave the system a buffer, allowing the temperature of the fuel to rise rather than the rest of the system. This allowed the heat to be rejected to the aircraft TMS over time. When compared with a LNG cooled HEPS system, the LNG system was shown to greatly outperform the fuel cooled systems. It had a much lower weight, and cooled the aircraft much more effectively.

Future work based on this study will investigate more ways to thermally manage a HEPS system. This could include some sort of thermal energy storage (TES). Technically, the fuel cooled HEPS
includes TES in the form of a temperature increase, but more typical TES systems use a phase change to store energy. One such system was explained earlier, a system that uses the phase change of LNG to cool the HEPS. Another option is the use of a phase change material (PCM). A PCM utilizes a phase change from solid to liquid. This material would melt as the laser fires, then solidifies afterwards, slowly rejecting the heat to the aircraft TMS. Future work will likely be focused on LNG however, and specifically will focus on other ways to use it to cool the aircraft or other high heat loads. Specific projects that have been completed since this work include the creation of a palletized HEPS model that is cooled by LNG, and a model created to be entirely cooled by LNG. These models are based on the T2T model developed and described earlier, and use a similar TMS as for the HEPS implementation study.

The third study supported the creation of a legacy vehicle power and thermal management model. This model includes an AVS that is based on data from the actual legacy system, and is similar in structure to those used in the other two models. The legacy T2T model also includes an updated engine model. This model is dynamic in nature, and includes a working afterburner model. An ECS model was created to be utilized in this model as well. This was designed to model that of the legacy aircraft, which uses engine bleed air to pressurize the cockpit and cool the cockpit and avionics. This model consists of a control system that regulates multiple control valves in the ECS to run bleed air from the engine through the ACM. The ACM cools the hot bleed air, and is then split to cool both the avionics and cockpit. The ECS model was shown to successfully maintain the cockpit and avionics temperatures at their associated setpoints while subjected to the variable bleed input from the engine.

Other work was completed alongside the development of the ECS model to add fidelity to a legacy T2T model.
Now that these models have been created, work will be completed to validate them with data from the actual legacy system. The physical subsystems will be run for different missions based on their typical operation. Then this data will be used to validate many of the models described in this work, including the ECS, generator model, heat exchangers, fuel pumps, etc. Eventually, full system level transient validation will be completed, which will validate the subsystems and interactions between systems. This should first be completed on a component level. The current T2T model effort has been devoted to modeling the overall thermal management architecture, not modeling accurate components or validating the physics based models. The next step towards validating this transient vehicle level model will be to update component models, such as heat exchangers, fuel pumps, and control valves, which more accurately represent the geometries and configurations used in the legacy vehicle. Once these are updated, the components should be validated with respect to data taken from operating the actual physical component. Transient validation would be preferred, though this is a new area of research. Once each component is validated on its own, interactions between larger subsystems, such as the FTMS or ECS described in this research, need to be validated as well. The final goal should be to validate the overall system interactions between these larger subsystems, which would require a very detailed experimental setup and new statistical techniques to quantify the uncertainty of such a complicated model.
References


