University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

REcuperating Advanced Propulsion Engine Redesign (REAPER) Conceptual Design Document

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I. Information

Project Customers

Ryan Starkey AES, University of Colorado Boulder, CO 80309 (303) 492-0871 rstarkey@colorado.edu	Captain Joshua Rittenhouse WPAFB, Bldg. 18-D, Room D026 (937) 255-3178 joshua.rittenhouse@us.af.mil

Team Members

Kevin Bieri Kevin.Bieri@colorado.edu (303) 804-1611	David Bright David.Bright@colorado.edu (970) 596-7236	Kevin Gomez Kevin.Gomez@colorado.edu (303) 968-9906
Kevin Horn Kevin.F.Horn@colrado.edu (303) 960-1833	Becca Lidvall Rebecca.Lidvall@colorado.edu (303) 416-0366	Andrew Marshall Andrew.Marshall-1@colorado.edu (952) 715-2562
Carolyn Mason carolynmason3@gmail.com (214) 675-6302	Peter Merrick petermerrick6@gmail.com (720) 987-4101	Jacob Nickless Jacob.Nickless@gmail.com (303) 842-8709

II. Project Description

A. Project Purpose

The purpose of REAPER is to model, build, implement, and verify a recuperative system integrated into a JetCat P90-RXi miniature turbojet engine for increased efficiency from its stock configuration. The JetCat P90-RXi is part of a class of miniature turbojet engines that are used in small unmanned air vehicles (UAV). UAV's have broad mission applications within both military and civilian markets. With increasing demand for performance, more powerful and efficient engines are required. Traditionally, small UAV's have utilized electric or piston propeller propulsion systems due to their high efficiency and low specific fuel consumption. Turbojets improve speed and altitude flight envelopes, but inherently have high specific fuel consumption. Recuperators for turbine engines traditionally are applied to large ground-based electrical power generation systems. These engines provide shaft work opposed to providing flow work like aircraft propulsion systems. A successfully recuperating turbojet engine would provide decreased specific fuel consumption while maintaining the benefits of turbojet propulsion. The recuperating turbojet engine designed for aviation would increase range, altitude, and speed performance for small UAV's, which would expand mission capabilities for military and civilian applications alike. For previous work related this system, refer to the Project Definition Document for the REAPER project.

B. Specific Objectives

In order to generate a goal for the effectiveness of the recuperator, the team examined the previously mentioned 3 kW UAV micro-turbine design to determine appropriate values for average heat-transfer coefficients then applied the NTU heat exchanger sizing method.[1–4] The effectiveness of a heat exchanger is defined as the ratio of the temperature rise of the cold flow divided by the maximum temperature difference of the hot and cold flow. Based on the analysis, the team found that a viable range of heat exchanger effectiveness was between 11% and 14% depending on the configuration of the exchanger. Ultimately, the team choose a design goal of 13% effectiveness for the recuperator. Using engine performance values found by previous projects, a value of 13% effectiveness will correspond to a 10% decrease in thrust specific fuel consumption.

To reach level two success, the engine must run for 120 seconds. Sixty seconds is needed for the engine to stabilize, so 120 seconds allows a period of time to measure the recuperator performance with the engine operating at steady-state conditions. To reach level three success, the engine must be brought up and run at full throttle with the recuperator integrated. Based on tests from previous years, a full test at full throttle requires 4 minutes, so this level will be successful when full throttle is reached with the recuperator integrated.

To attain these goals, the REAPER team will create a computerized thermal model of a recuperator and use this model to guide the design and fabrication of the physical recuperator. There are three levels of increasing success for the REAPER project, as defined in Table 1. Level 1 addresses minimum success, while Level 3 defines full success. The increasing levels of success are designed as steps along the process to achieving a fully functional recuperation engine that meets all requirements (success level 3).

Various tests will be performed during the academic year to determine functionality, compliance to requirements, and success level, with full engine tests occurring at Boulder Municipal Airport. After the class and academic year are over, the project will finish by testing the recuperator-engine design at the Wright-Patterson Air Force Base with the Air Force Research Labs.

Success Level	Project Description	
	Simulation	Recuperator/Engine
Level 1	• First order, one-dimensional, steady state engine thermal modeled with recuperator design integrated • Predicted efficiency and thrust from model meets recuperator effectiveness (13%), thrust specific fuel consumption reduction (10%), and thrust reduction (10%) requirements	• Recuperator designed and manufactured • Recuperator tested with engine analog at dimensionally scaled steady-state, full-throttle operating conditions without a critical failure
Level 2	• Thermal model includes transient performance • Predicted recuperator effectiveness, specific fuel consumption, and thrust from model continue to meet requirements	• Recuperator integrated to reroute engine exhaust heat • Engine starts and runs at at full throttle for 120 seconds with the integrated recuperator, with recuperator effectiveness at or above 13%
Level 3	• CFD model of the recuperator developed with effectiveness matching actual recuperator test data within 25%	• Engine with integrated recuperator runs continuously for full throttle range • Engine with integrated recuperator meets effectiveness (13%), thrust reduction (10%), thrust specific fuel consumption reduction (10%), mass increase (50%) and volume increase (100%) requirements • Engine runs at full throttle, with recuperator integrated, for at least 4 minutes • Engine throttle time from 50% to 100% throttle is within 100% of stock throttle response time

Table 1: REAPER Success Levels

C. Concept of Operations

The concept of operations (ConOps) within the modified jet engine is shown in Figure 1. Starting at the point labeled 1, the engine will perform nominal start up procedures to reach idle. Then the throttle control will be increased (point 2) to full throttle, where the recuperator will achieve maximum effectiveness (see engine blow-out). The recuperator takes waste heat from the turbine exhaust gases and transfers it to the incoming combustion chamber air, decreasing the amount of fuel needed to heat the air. At maximum throttle, temperature, RPM, and TSFC data will be gathered by the ECU (point 3). Once the test is complete, the engine is shut down and the data will be transferred to a computer for analysis (point 4).

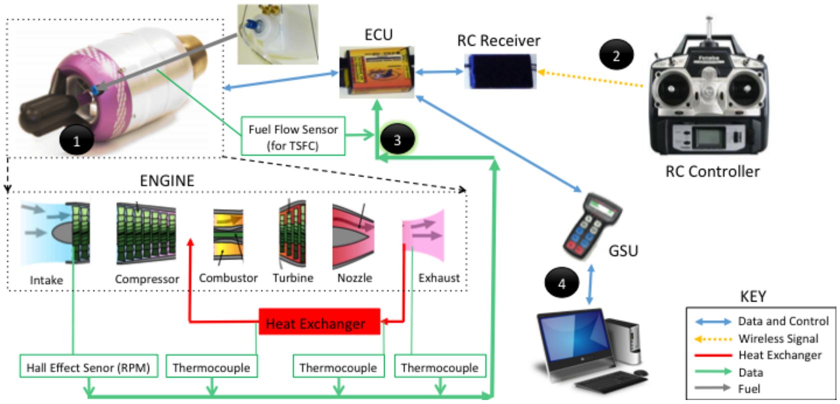


Figure 1: Concept of Operation

D. Functional Block Diagram

The functional block diagram (Figure 2) goes into more detail about the system interactions. Items that existed prior to project REAPER are boxed in black; green boxes indicate items that will be purchased to ensure system functionality; yellow boxes are components that will need to be modified or created to achieve system success.

Beginning with the engine, exhaust heat will be diverted to pre-heat air entering the combustor via a heat exchanger. Moving clockwise (to gold blocks), the fuel flow rate sensor will be integral to measuring thrust specific fuel consumption (TSFC) for engine efficiency. In order to control the fuel flow rate to keep exhaust temperature below 750°C, the ECU will need to be modified. On the peripherals, the RC Controller will send throttle commands to the receiver while the engine sensor package and data handling systems gather data on the engine performance during a test.

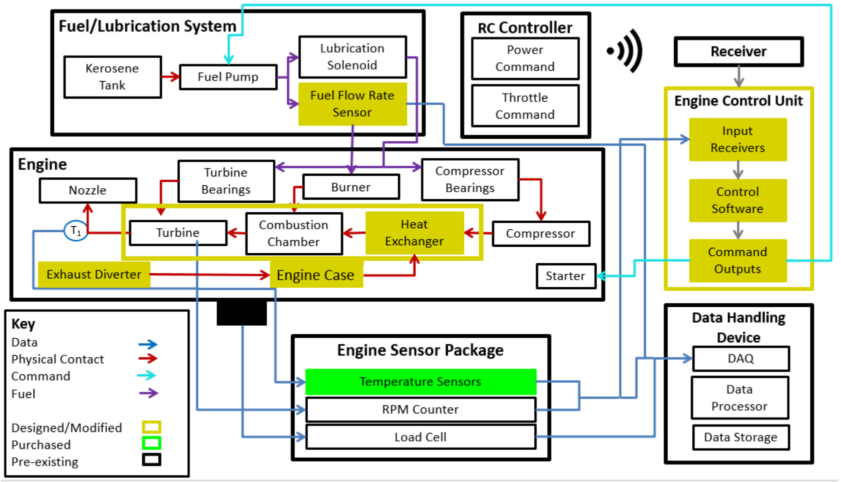


Figure 2: Functional Block Diagram (FBD)

E. Functional Requirements

The functional requirements outline how the final REAPER system will operate. These requirements will guide the team through the design process and lead to design requirements and specifications. The following functional requirements blanket the major systems that will be necessary for full system operation.

FR 1 The engine shall operate with the heat exchanger system integrated.

FR 2 The thrust specific fuel consumption (TSFC) of the engine with the heat exchanger system integrated shall decrease by 10%.

FR 3 The simulation shall model the thrust and efficiency of the engine with the integrated heat exchanger system.

III. Design Requirements

FR 1 The engine shall operate with the heat exchanger system integrated.

DR 1.1 The Engine Control Unit (ECU) shall interface with the Ground Station Unit (GSU).
Motivation: In order to properly control the engine during tests, the ECU needs to communicate with the GSU. Thus, whatever ECU the REAPER team decides to use needs to properly interface with the GSU.
Verification/Validation: Successful verification of **DR 1.1.1** and **DR 1.1.2**.

DR 1.1.1 The Engine Control Unit (ECU) shall send engine status data to the GSU via an established protocol.
Motivation: In order to monitor the health and performance of the engine, data from the Hall effect sensor, thermocouples, and fuel pump must be transferred to the GSU.
Verification/Validation: Inspection - If stock unit is used, the team will only need to verify that the signals between the ECU and GSU are uncompromised; Test - If a team designed ECU is used, a hardware emulator will verify correct data transmissions.

DR 1.1.2 The Engine Control Unit (ECU) connector shall electrically interface to the GSU.
Motivation: In order to monitor the health and performance of the engine, data from the Hall effect sensor, thermocouples, and fuel pump must be transferred to the GSU via an electronic cable.
Verification/Validation: Inspection - The cable connecting the ECU and the GSU must be able to connect to both devices without hindering the performance of either component.

DR 1.2 The ECU shall interface with the receiver.
Motivation: The receiver relays commands from the remote controller to the engine. To be able to control the engine from a safe distance with the remote, the receiver must communicate with the ECU.
Verification/Validation: Successful verification of **DR 1.2.1** and **DR 1.2.2**.

DR 1.2.1 The Engine Control Unit (ECU) shall process commands packaged with the protocol used by the AR7610 RC receiver (45.45 Hz square wave with a varying duty cycle between 6.2% and 8.7%)[1] 1.
Motivation: The team already has possession of an AR7610 RC receiver and RC transmitter to control the engine. If the ECU is modified, it will need to continue to function with the same receiver in order to prevent needing to acquire another RC receiver and transmitter.
Verification/Validation: Inspection - If stock unit is used the team will only need to verify that the signals between the ECU and receiver are uncompromised; Test - If a team designed ECU is used, a hardware emulator will verify correct data transmissions.

DR 1.2.2 The Engine Control Unit (ECU) connector shall mechanically interface to the AR7610 receiver.
Motivation: The team already has possession of an AR7610 RC receiver and RC transmitter to control the engine. If the ECU is modified it will need to continue to function with the same receiver in order to prevent needing to acquire another RC receiver and transmitter with .
Verification/Validation: Inspection - The cable connecting the ECU and the AR7610 receiver must be able to connect to both devices without hindering the performance of the component.

DR 1.3 The ECU shall interface with the Engine Sensor Board (ESB).
Motivation: The ESB reads RPM and temperature data from the engine and sends that information to the ECU. Based on this data, the ECU makes changes to the fuel flow to control the engine. If these communications are not received correctly, the engine could shut down, overheat, or over-rev. Either of the last two problems could create a very dangerous situation.
Verification/Validation: Successful verification of **DR 1.3.1** and **DR 1.3.2**

DR 1.3.1 The Engine Control Unit (ECU) shall use the same data package protocol as the sensor board.
Motivation: The ESB provides the ECU with real time information regarding the status and performance of the engine. Proper functioning of the engine requires that the ECU firmware be able to interpret the temperature and RPM data provided to it from the ESB.
Verification/Validation: Inspection - If stock unit is used the team will only need to verify that the signals between the ECU and ESB are uncompromised; Test - If a team designed ECU/ESB is used, a hardware emulator will verify correct data transmissions between the ESB and ECU.

DR 1.3.2 The Engine Control Unit (ECU) connector shall electrically interface to the ESB.
Motivation: The ESB provides the ECU with real time information regarding the status and performance of the engine. Proper functioning of the engine requires that the cable between the ECU and ESB transmits data across a standardized connector.
Verification/Validation: Inspection - The cable connecting the ECU and the ESB must be able to connect to both devices without hindering the performance of the component.

FR 2 The thrust specific fuel consumption (TSFC) of the engine with the heat exchanger system integrated shall decrease by 10% at maximum thrust.

DR 2.1 The heat exchanger shall have an effectiveness of at least 13% at maximum thrust. Based on the cycle given in Figures 4 and 5 on page 8, heat exchanger effectiveness is defined as:

$$\epsilon_x = \frac{T_{03} - T_{02}}{T_{05} - T_{02}}$$

Motivation: In order to achieve a drop in specific fuel consumption of 10%, the overall thermal efficiency of the engine must increase by approximately 10% which requires the heat exchanger to achieve an effectiveness of 13%.
Verification/Validation: Test - Temperature readings of the compressed air before (T_{02}) and after the heat exchanger (T_{03}) as well as the exhaust temperature (T_{05}) must be taken then compared to the relation defined in the requirement.

DR 2.2 The heat exchanger system shall survive, and maintain its effectiveness, in steady-state, full-throttle engine operating conditions.
Motivation: The heat exchanger system will be useless if it melts or is otherwise damaged under normal engine operating conditions. Therefore, the heat exchanger should be able to survive and operate correctly under nominal conditions.
Verification/Validation: Test - The heat exchanger system will be tested with the engine operating at maximum thrust for 4 minutes, and the total temperature readings shall meet **DR 2.1**. Post run, the engine will be inspected to ensure that the material did not crack or deform.

DR 2.3 The heat exchanger system shall mechanically integrate with the engine.
Motivation: The heat exchanger system's purpose is to move heat from the engine's exhaust to the air flowing into the combustor. The heat exchanger will have to be securely integrated into the engine to perform this operation.
Verification/Validation: Inspection - The team will inspect the heat exchanger's attachment to the engine to ensure that it remains affixed to the engine before and after 4 minutes engine run time, while also not impeding the rotation of the turbo-machinery within the engine during engine operation at all engine rotation speeds.

DR 2.4 Engine throttle time from 50% to 100% throttle shall be characterized for both the stock and recuperating engine configurations.
Motivation: The customer desires that the impact to the throttle response of the engine by adding a heat exchanger be determined and compared to the stock configuration, without requiring a specific envelop of change.

Verification/Validation: Test - The team will run the engine both unmodified and modified across the entire throttle range of the engine in 10% of the throttle increments, and then directly changed from 50% to 100%. The time to accelerate the engine between the increments will be compared to determine the additional time (if any) required to move between the throttle settings.

DR 2.5 The heat exchanger system shall not reduce the maximum thrust produced by the engine by more than 10% from the stock configuration.
Motivation: The customer desires that the impact to the total thrust produced by the engine not be heavily impacted by adding a heat exchanger to increase efficiency.
Verification/Validation: Test - The team will run the engine both unmodified and modified at the maximum throttle setting on the thrust test stand; the percent change in maximum thrust must remain less than or equal to 10%.

DR 2.6 The heat exchanger system shall not increase the volume of the engine excluding peripheral electronics by more than 100% from the stock configuration.
Motivation: The customer desires that the modified engine does not unduly reduce the compactness of the P90-RXi engine. If the engine volume is increased the modified engine will be less suitable for the small air vehicles for which it is designed.
Verification/Validation: Analysis - The CAD models of the unmodified and modified engines will be measured in the CAD program to determine the total volume of the engine without including peripherals such as the ECU, system battery, and fuel pump.

DR 2.7 The heat exchanger system shall not increase the mass of the engine by more than 50% from the stock configuration.
Motivation: The customer desires that the modified engine does not unduly increase the mass of the P90-RXi engine. Any increase in the total mass of the engine will negatively impact the integrated performance of the engine in particular reducing both the thrust to weight ratio and overall endurance.
Verification/Validation: Analysis - The CAD models of the unmodified and modified engines will be measured in the CAD program to determine the total mass of the engine without including peripherals such as the ECU, system battery, and reciever.

FR 3 The simulation shall model the thrust and efficiency of the engine with the integrated heat exchanger system.

DR 3.1 The simulation shall model the thermo-fluid dynamics of the heat exchanger system.
Motivation: Before modeling the engine/heat exchanger system as a whole, the team will ensure the model of the heat exchanger itself is accurate.
Verification/Validation: Demonstration - The team will internally verify that the heat exchanger simulation utilizes thermodynamic, heat transfer, and fluid mechanics principles to predict the temperature change of the compressed air before and after the heat exchanger.

DR 3.2 The simulation shall model the thermo-fluid dynamics of the engine.
Motivation: Before integrating the heat exchanger and engine models, the team will ensure that the model of the engine alone is accurate.
Verification/Validation: Test - The team will compare test data of a stock engine run to results output by the model.

DR 3.3 The simulation shall integrate the thermo-fluid dynamic models of the engine and heat exchanger.
Motivation: After ensuring that the model of the engine and heat exchangers alone are accurate, they will need to be integrated together to get a complete system model.
Verification/Validation: Test - The team will compare test data of a integrated recuperating engine run to results output by the model.

IV. Key Design Options Considered

Once the key design areas have been identified, different design methods and systems are considered to define the whole design space. This ensures all possibilities are considered. REAPER can be divided into two major categories of design: heat exchanger and electronics. The heat exchanger encompasses all the hardware necessary to move the waste heat from the exhaust and transfer it to the internal flow of the engine before fuel combustion. The electronics encompass the engine control unit (ECU) and the engine sensor board (ESB). The ECU will enable power, command, control, and data storage for the engine. The ESB will handle data measurement from the various sensors on-board. These categories are broken down into finer components and systems. Both components are combined into one category for trade study because the choice of ECU will drive the choice of ESB. The components must be designed with any combination of mechanical, electrical, and software features. The design tree below (Figure 3) shows the break down of these components. The features are color coded: green for mechanical, blue for electrical, and red for software.

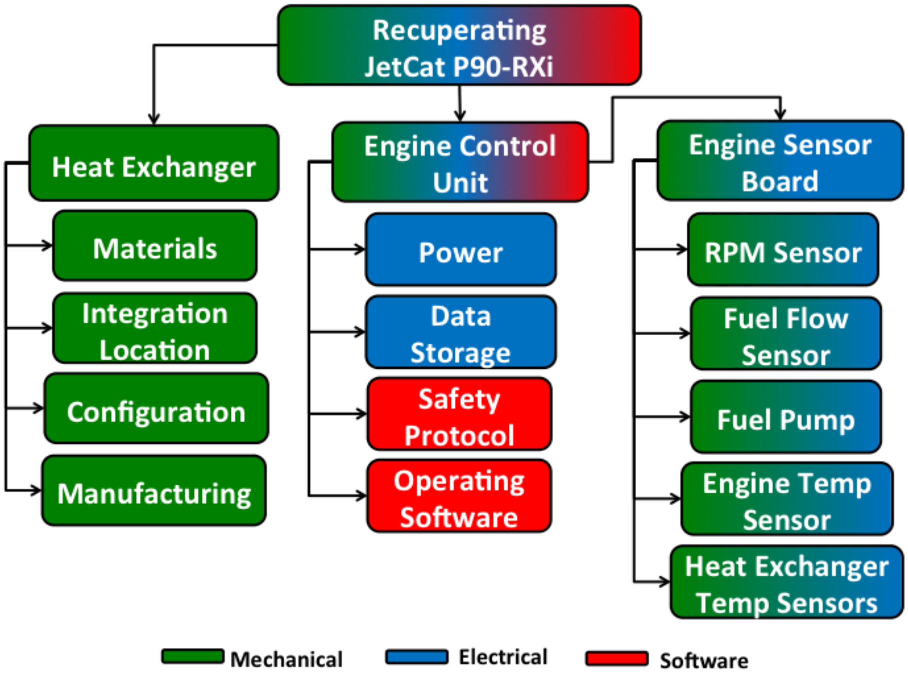


Figure 3: Design Tree

A. Heat Exchanger

Broadly, the goal of REAPER is to increase the fuel efficiency of the P90-RXi jet engine by adding a heat exchanger that uses heat from the exhaust to preheat air after the compressor to reduce the required fuel burn in the combustor (embodied in **F.R. 2**). In order to accomplish the preheating, four main heat exchanger designs were considered. Gas-gas heat exchangers consist of one or more separate passages of hot and cold gas flowing past each other. Heat pipes use a working fluid trapped inside a sealed tube to transfer heat between the hot and cold flows. Flue gas return systems mix hot exhaust gases directly with the post-compressor air inside the engine to heat the flow prior to combustion. Rotary regenerators use a porous matrix which rotates into the alternate hot and cold flows; the heat transfer from the matrix itself heats or cools each flow.

The critical feature of the heat exchanger designs is their ability to obtain the necessary heat transfer rate between the exhaust gas and compressed intake air. As such, an accurate comparison of the different heat exchanger design concepts entails a firm understanding of the heat transfer rate necessary to satisfy requirements **FR 2** and **DR 2.1**.

In order to determine the baseline and modified performance, a sufficiently accurate model of the engine performance is required. Figures 4 and 5 show a thermodynamic schematic and T-s diagram for an open Brayton cycle with a recuperative heat exchanger, the idealized version of the recuperated jet engine cycle. In an open Brayton cycle, the gas is first isentropically compressed from static conditions (0 to 2). Next, waste heat from the exhaust isobarically heats the compressed intake air (2 to 3). After the heat exchanger preheats the air, fuel combustion in the burner isobarically adds more heat to the flow (3 to 4). Next, a turbine after the combustor isentropically expands the flow in order to extract work to power the compressor (4 to 5). Finally, a nozzle isentropically expands the flow to match the pressure of the surroundings and accelerate the flow (5 to 6).

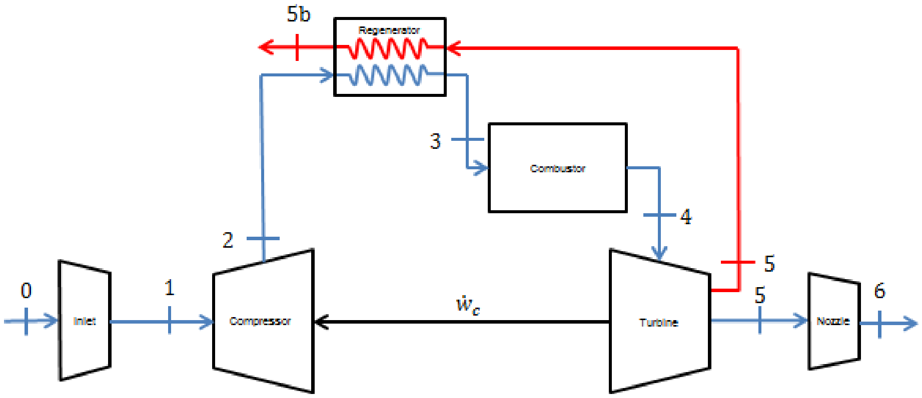


Figure 4: Brayton Cycle Thermodynamic Schematic

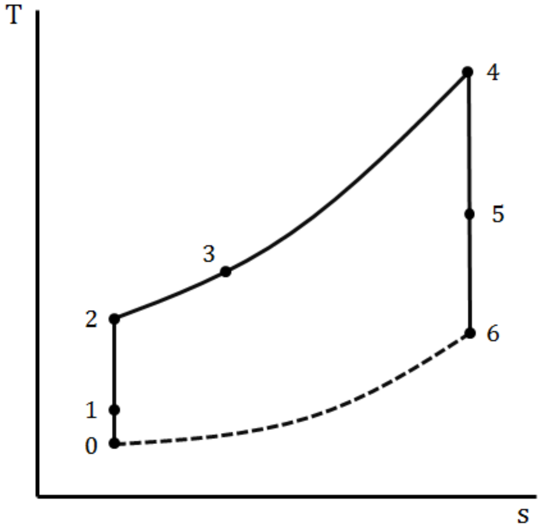


Figure 5: Brayton Cycle T-s Diagram

In order to estimate the required performance of the heat exchanger, an ideal Brayton cycle analysis of the engine was performed. From the Brayton cycle assumption, the performance of the engine is assessed only with a knowledge of the total enthalpies before and after each component. By finding the required enthalpy change across the heat exchanger to achieve the desired heat exchanger effectiveness, the total heat addition provided by the heat exchanger was calculated. In order to determine the enthalpies a calorically perfect gas assumption was applied to the intake air and exhaust gas so that the enthalpy at each station would just be the product of the specific heat and the total temperature of the gas at the point.[2]

Using previously obtained data from past projects, values for mass flow rate of the exhaust, total temperature out of the compressor, and total temperature out of the turbine are known ($\dot{m} = 0.26\frac{kJ}{kgK}$, $T_{0,2} = 318K$, $T_{0,5} = 918K$).[10] Additionally, the calorically perfect gas assumption leads to the value for specific heat capacity ($C_p = 1.005\frac{kJ}{kgK}$). Equations 1 to 3 give the derivation of Equation 4 which provides a relation for the total heat addition required from from the heat exchanger to meet the heat exchanger ϵ_x effectiveness goal of 13%.

$$\epsilon_x = \frac{h_3 - h_2}{h_5 - h_2} \tag{1}$$

$$q_x = \dot{m}(h_3 - h_2) \tag{2}$$

$$h_3 = h_2 + \epsilon_x(h_5 - h_2) \tag{3}$$

The final step is to combined Equation 2 and Equation 3 and insert h = Cp $\triangle T$ for both h5 and h2.

$$q_x = \dot{m}\epsilon_x C_p(T_{0,5} - T_{0,2}) \tag{4}$$

Using Equation 4, the value for the required heat transfer was found to be $22.5\frac{kJ}{s}$.

1. Gas-Gas

Gas to gas heat exchangers are devices that work to transfer thermal energy between two or more fluids flowing by each other at different temperatures. Gas to gas heat exchangers are the most widely used type of exchanger and have flexible design parameters that can be adjusted based on need. Parameters that can varied include the specific type of gas to gas heat exchanger, the flow arrangement, and the heat transfer mechanism. The two types of gas to gas heat exchangers that are considered in this study are tubular heat exchangers and plate heat exchangers. Both the tubular and plate heat exchangers are similar in how they transfer heat, but vary with how they fit into the overall system they are being used in. For gas to gas heat exchangers, the heat transfer is through convection with indirect contact. The three types of flow arrangements for gas to gas heat exchangers consist of parallel flow, counter flow, and cross flow.

The tubular heat exchanger design is based around the implementation of circular tubes transferring heat between fluids flowing through them. Tubular heat exchangers are the most widely used type of heat exchanger with more than 90% of heat exchangers in industry being the shell and tube design.[5] Other types of tubular heat exchanger designs include the double pipe and spiral tube type. The main reason tubular heat exchangers are the most widely used type of heat exchanger is due to their design flexibility. Some of the parameters that can be changed include the tube diameter, tube length, pitch of tubes and tube arrangement.[6] In addition to their flexible design space, tubular heat exchangers have many documented methods for construction, as they are used in industry heavily. There are sources that can be found for material selection, heat transfer calculations, and manufacturing. Tubular heat exchangers also have a high surface area to volume ratio which translates into more effective heat transfer. The last main advantage with tubular heat exchangers is that they can have a very low flow impedance because the flows can be largely directed in a single direction without being forced through narrow passages. One of the main disadvantages with tubular heat exchangers is that calculating efficiency can be difficult due to the flexibility of the design. The many different configurations leads to highly variable efficiency calculations. Lastly, the flow impedance increases with an increase of surface area due to additional tubing being needed. The basic design structure of the shell and tube heat exchanger can be seen in Figure 6.

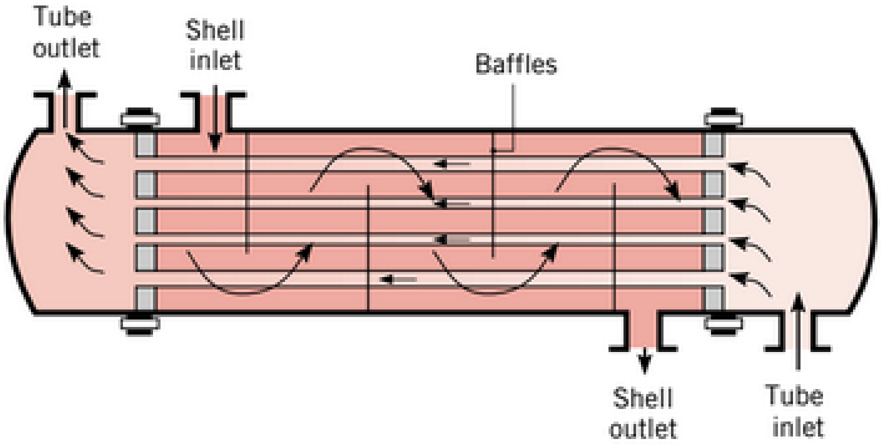


Figure 6: Shell and Tube Heat Exchanger.[2]

The plate heat exchanger design consists of stacking thin plates in order to create a larger heat transfer area as fluid flows through the exchanger. The main types of plate heat exchanger designs are the gasketed-plate, spiral plate, and lamella heat exchangers. One of the advantages of the plate heat exchanger is that they provide a high surface area to volume and mass ratio. The thin plates provide large surface area with low mass depending on material. Another advantage is that they have a very flexible design space because plate dimensions and number of plates can be adjusted. Although they have a more complex design than tubular heat exchangers, there are still documented methods available for design selection and construction. One of the main disadvantages with the plate heat exchangers is that unlike the simple flow path of tubular heat exchangers where the flow is just through tubing, the flow paths through a plate heat exchanger are more complex. Because the flow paths through the plate heat exchanger are shifted more often, there would be more flow impedance through the exchanger. Additionally, stacked plate heat exchangers are most space efficient when the plates are close together creating narrow passages that constrict the flow. The exchanger would also be heavier than a tubular design because more material is used for the plates and overall structure. An example of a plate heat exchanger can be seen in Figure 7.

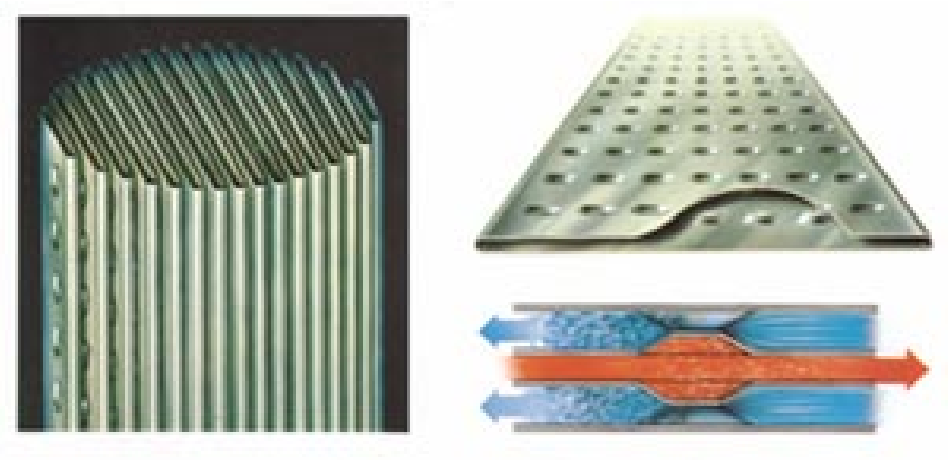


Figure 7: Lamella Heat exchanger.[7]

An additional design option for both tubular and plate heat exchangers is an extended surface or fin. These extended surface heat exchangers work to increase the overall heat transfer area. The main application of plate-fin heat exchangers is with gas to gas heat transfer while tube-fin heat exchangers are more for liquid to air. With plate-fin heat exchangers, there are four types of fin types. These include the plain fin, perforated fin, serrated fin, and herringbone fin. Plate-fin heat exchangers have a more complex design than a plate heat exchanger, but the additional surface area can help with creating a compact structure. Plate-fin heat exchangers are also established for use in gas-turbines, which is similar in some ways to a miniature turbojet. A summary of the pros and cons of the gas-gas type heat exchanger is seen in Table 2.

Pros	Cons
• Design flexibility • Large surface area to volume and mass ratio • Low-Medium flow impedance • Many sources for design selection, fabrication and verification	• Efficiency is variable due to flexibility in design options • Potentially difficult to construct, depending on design type

Table 2: Gas-Gas Pro-Con List

2. *Heat Pipe*

A heat pipe is a passive device used to transfer heat. The system has two main components: a closed pipe and a working fluid. One end of the pipe, called the evaporator, will be exposed to the heat source and the other end, the condenser, will dissipate the heat to a new location. The working fluid starts in the evaporator, where it will heat up and vaporize. The resulting pressure pushes the vapor along the pipe until it reaches the other end (the condenser). The difference in pressure between the liquid pressure gradient and vapor pressure gradient is called capillary pressure.

Once the vapor condenses, capillary pressure will pump the condensed fluid back to the evaporator. The working fluid will often follow a wick that is inside the pipe. The fluid will continue to flow back and forth like this until the heat source is removed. An illustration of a heat pipe is shown in Figure 8.

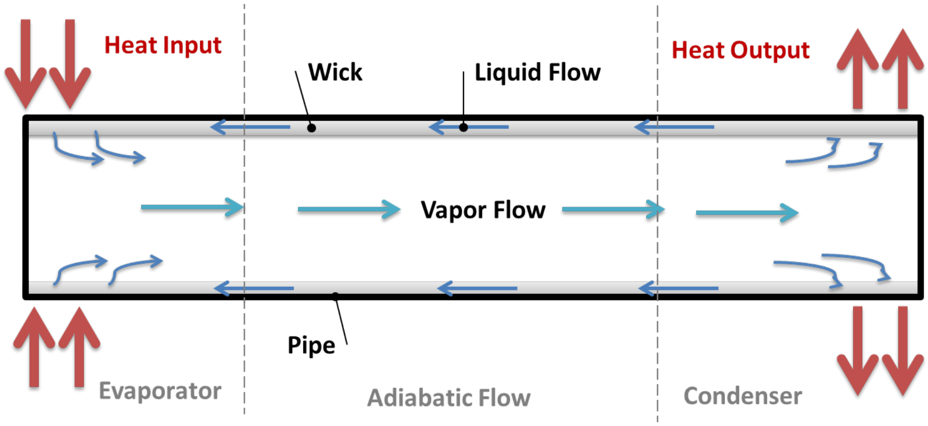


Figure 8: Heat Pipe Heat Exchanger.[6]

There are several key advantages of using a heat pipe as a heat exchanger. The main advantage is that heat pipes are time tested and well researched. There are thousands of papers written on heat pipes, with many specifically on high temperature applications. Heat pipes are also advantageous because they relatively simple to build. The most basic heat pipes can be made out of a copper pipe, two copper caps, water, and a copper weld. There are no moving parts and no external pumps. This can make the heat pipe solution light weight with very little volume. Since the materials are simple the heat pipe system is also flexible in size and length. Heat pipes are considered isothermal and can transfer heat at a high rate over a long distance with little heat drop. Additionally, a heat pipe design could have extremely low flow impedance by only extending narrow fins into the flow which would require no flow diversion or constriction and only minimal drag loses.

The main disadvantages of heat pipes are the start complications and possible complexity making the pipe evacuated. There is a good amount of research regarding start up that leads to failure. Failure is likely when the vapor pressure of the working fluid in the pipe and the interface thermal resistance at the condenser are low. This will eventually cause choked flow and a large temperature gradient that result in the wick drying out. If the wick dries out the pipe will not operate. There can still be a successful start up of a heat pipe with a low vapor pressure as long as there is a high thermal resistance in the pipe material. Optimally there would be both high pressure and high thermal resistance; however, high pressure may not be feasible without special equipment.[8] Further research and testing would need to be conducted to learn how to avoid start up failure. Another key unknown issue is start up time. Some research indicates that if the pressure is too low, the time to heat up the pipe can take many minutes, which would most likely lead to a failed recuperating test. The last issue is operating temperature. Some material and working fluid combinations may not work as well at lower temperatures and result in higher temperature gradients. These same combinations may work very well at full throttle, but much less well at half throttle.[9] The reliability of the system will need to be well characterized with testing. A summary of the advantages and disadvantages for heat pipe exchangers is found in Table 3.

For the application in a jet engine, the heat pipe needs to be built to withstand the temperature at the exhaust. Based on tests from COMET[10] (2013-2014 CU Boulder Aerospace senior design group working with a JetCat engine), the average exhaust temperature of the engine at full throttle is 981K. Possible materials for the pipe are stainless steel, carbon steel, and nickel. Possible materials for the working fluid are liquid sodium, potassium, and water. The cost of these materials would be low and allow for a good amount of experimentation and improvement of the system. Experimentation could be conducted on different wicks and different materials.

Moving forward, there are several key factors to keep in mind. Often heat pipes, which reclaim heat energy from exhaust, have fins on the outside to transfer the hot exhaust air to the evaporator. The heat is then transferred along the pipe to the condenser where there are more fins to transfer the heat out. The fin numbers and placement would need to be considered further. There are many types and variations on heat pipes to consider as well. These include loop heat pipes, pressure controlled heat pipes, annular heat pipes, and monogroove heat pipes. Loop heat pipes can transfer heat over longer distances and are less susceptible to pressure drops because the fluid only flows in one direction instead of counter-current flow. Pressure controlled heat pipes have a piston to push additional gas into the condenser, which helps keep the pipe at a constant temperature. Annular heat pipes have an annular cross section that allows for more capillary action (in the same volume), which also helps to keep a more constant temperature in the pipe. The monogroove heat pipe has an artery below the pipe that helps reduce blockage due to vapor bubbles [12]. Other important factors in regards to materials are: large surface tensions correspond to large capillary pumping capabilities, large latent heat of vaporization means more efficient heat transport, and large thermal conductivity leads to small temperature drops. [8]

Pros	Cons
• High efficiency • Low cost • Low mass and volume addition • Extremely low flow impedance • Well researched and documented	• Possibly difficult to construct (material dependent) • Possible start-up issues (failure and time)

Table 3: Heat Pipe Pro-Con List

3. Rotary Regenerator

Rotary regenerators are slowly rotating disks that contain a highly packed heating surface matrix that transfers heat between two fluids or gases. The disk matrix consists of thin, flat strips of metal or high heat ceramics, coiled and crisscrossed around a central point in the disk while still letting gases flow through. The hot and cold gases continuously flow into the rotating matrix while some portions of the disk are in the path of the hot air and the other portions are in the cold air path. As the disk rotates around, the portions of the matrix heated by the exhaust come in contact with the cold air resulting in heat transfer between the heated matrix and the cold air, increasing the temperature of the air and decreasing the temperature of the matrix. Then as the now cooled sections of the regenerator rotate in the hot flow, heat is again transferred into and stored in the matrix.

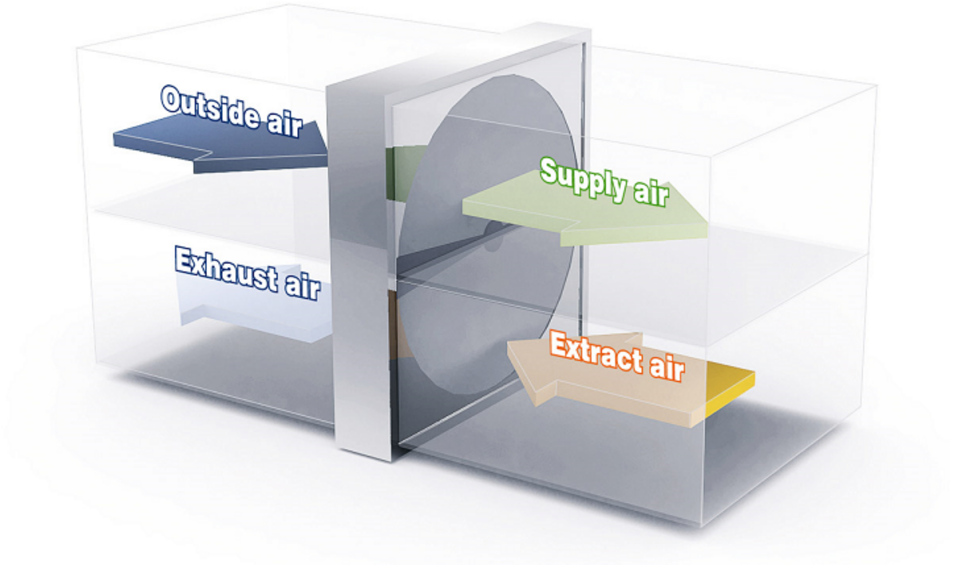


Figure 9: Rotary Regenerator

Some advantages of these regenerators are high heat transfer effectiveness due to high average temperature differences between the matrix and the gases, relative compactness due to the shared usage of heat exchange area, and considerable literature regarding industrial use. However, most rotary regenerators are employed in power plants in sizes up 10 meters in diameter for maximum mass flow.

Rotary regenerators also have distinct disadvantages. They are a complicated method of heat transfer that will require an additional external power source to run the rotor motor or a gear-box to use work off the compressor shaft. Optimal speeds for the disk range between 3-20 RPM with standard temperature range of -20C to 60C. There will also be partial exhaust contamination as the two gases pass through the heating matrix, potentially decreasing efficiency.

One of the largest drawbacks of the rotary regenerator is the flow impedance. Rotary regenerators by necessity need to force the hot and cold flows by through a tight matrix. Even at low rotation and flow speeds, a pressure drop of 250 Pa or more is common through the matrix.[3] The only way to effectively reduce the pressure drop is to increase the pore size of the regenerator matrix which directly reduces the effectiveness of the heat exchanger.

If a rotary regenerator were to be implemented on the JetCat engine, an external power source turning the disk at a maximum of 20 RPM would be needed as the shaft speed is 40,000 RPM at idle. Or a series of gears to bring the shaft speed down to run the rotor at an appropriate speed. The exhaust speed and heat of the jet engine is extremely high for any reasonable rotary regenerator. Steps would need to be taken in order to slow down the mass flow of exhaust, which adds a major complexity to this design solution.

In addition to the issues with rotation speed, rotary regenerators by necessity directly impede the hot and cold flows by forcing them through a matrix. Even at low rotation and flow speeds, a pressure drop of 250 Pa or more is common through the matrix.[3] The only way to effectively reduce the pressure drop is to increase the pore size of the regenerator matrix which directly reduces the effectiveness of the heat exchanger.

Table 4 provides a summary of the pro and cons of a rotary regenerator type heat exchanger.

Pros	Cons
• Provides excellent efficiency	• Requires external power source • High flow impedance • Purchasing a rotor will be costly • Manufacturing a rotor in house may be nearly impossible • High mass

Table 4: Rotary Regenerator Pro-Con List

4. Flue Gas Return

Flue gas return is the process of injecting the some of the engine's exhaust directly back into the air flowing into the combustor. Thermodynamically, this is a highly efficient way to recuperate heat. All of the heat contained in the harvested exhaust is injected directly into the compressed air flowing into the combustor. Looking beyond thermodynamics reveals some complications with this method. First, the gas in the exhaust flow will be around 1 atmosphere of pressure, whereas the air flowing into the combustor has been compressed to 2.6 atmospheres. To avoid flow in the wrong direction through the recuperator, the harvested exhaust would have to be pressurized to 2.6 atmospheres or higher before being injected back into the engine. To repressurize the exhaust, some sort of fan or compressor would be needed. Powering this compression device would present another challenge. The shaft of the P90-RXi engine spins at a nominal top speed of 130,000 rpm. To avoid destroying the compression mechanism by spinning it at excessive speeds, the power for the compressor will have to be geared down substantially from the engine's shaft or come from an external source. The basic operation of the flue gas return system, with the two power options for the compression device, are shown below.

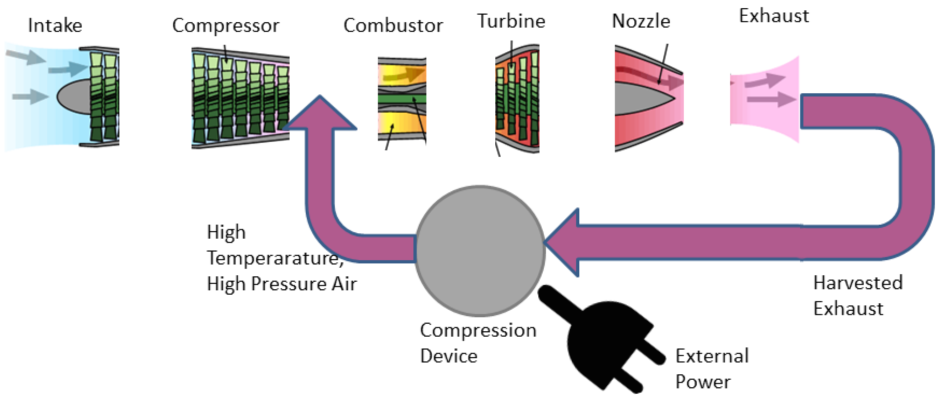


Figure 10: Flue Gas Return with External Power

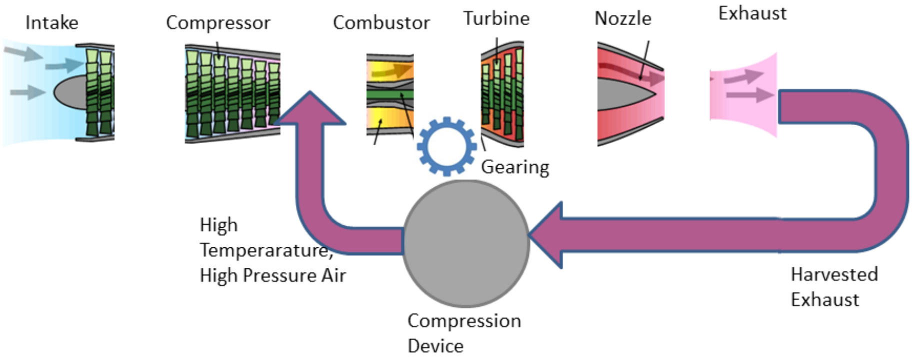


Figure 11: Flue Gas Return with Shaft Gearing

The second major drawback of the flue gas return is the drop in chemical efficiency of the combustor. The exhaust has already had the majority of its oxygen consumed when it was burned in the combustor. So, when it is injected back into the engine, the oxygen concentration of the air flowing into the combustor effectively drops. This reduction of efficiency is compounded by the presence of combustion byproducts (mostly carbon dioxide and water). Both of these affects reduce the amount of kerosene that burns and thus reduces power gained from the combustion process and the efficiency of the engine. Thus, to have any positive effect on the overall efficiency of the engine, the efficiency gained from the recuperated heat will have to exceed the efficiency lost due to the reintroduced combustion products.

Besides the compression device, the flue gas return would be relatively simple to build: a scoop to collect exhaust and a pipe to carry it to the point where it will be injected. To withstand the temperature of the exhaust gas, all components will have to be made of a high-temperature metal like stainless steel. These components will be easy to obtain or create, and wont be very costly monetarily. However, depending on the size of the compression device, the flue gas return could add a significant amount of mass and volume to the engine.

As stated above, in order to hit the 13% effectiveness goal, this heat exchanger will have to transfer 22.5 kJ/s of heat into the air flowing into the combustor. A very low fidelity calculation can be made to estimate the amount of exhaust needed to achieve this heat transfer goal. Assuming the re-pressurization is isentropic and the exhaust gas retains its temperature until it is injected into the engine, the following calculation reveals that around 9% of the exhaust will need to be harvested.

At the full throttle exhaust temperature of 980 K^{10}, the enthalpy of air is h = 1023.25 $\frac{kJ}{kg}$[7]. Dividing the needed heat transfer by the energy contained in the exhaust air gives

$$\frac{22.5\frac{kJ}{s}}{1023.25\frac{kJ}{kg}} = .022\frac{kJ}{s} \tag{5}$$

At full throttle, the engine has a mass flow of .26 $\frac{kg}{s}$. Dividing the total mass flow by the needed mass flow diversion gives an 8.5% diversion.

$$\frac{.022\frac{kg}{s}}{.26\frac{kg}{s}} = .085 = 8.5\% \tag{6}$$

This flow diversion can then be used to get a very rough estimate of the flow diversion and drop in chemical efficiency. Assuming that the mixture of kerosene and oxygen is almost stoichiometric, the exhaust air will have essentially no oxygen left (all will have been consumed in the reaction with kerosene). Thus, injecting 8.5% of the exhaust gas will result in a reduction in concentration of the oxygen flowing into the combustor. If the air flowing through the engine is assumed to be 21% oxygen and the flue gas is 0% oxygen, this reduction will be on the order of 2%.

$$\frac{21_{gO2}}{100_{gAir}} + \frac{0_{g02}}{8.5_{gAir}} = \frac{21_{gO2}}{108.5_{gAir}} = 19.35\%_{O2} \tag{7}$$

Assuming a linear correlation between burner efficiency and oxygen concentration, injecting the flue gas could reduce the efficiency of the burner by 2%.

Additionally, there will need to be some structure (scoops, tubes, etc.) in the exhaust flow in order to harvest this heat flow. This redirection of the flow will reduce the thrust provided by the engine. Intuitively, collecting 10% of the exhaust flow will reduce the thrust of the engine by about 10%. Between the decrease in chemical efficiency and redirection of exhaust, this type of heat exchanger has the potential to reduce the thrust by 12% or more. The advantages and disadvantages of the flue gas return are shown in Table 5

Pros	Cons
• Highest possible Thermodynamic efficiency • Relatively simple construction	• Reduction of chemical/burner efficiency • Necessitates compression device • Potential for large mass and volume additions

Table 5: Flue Gas Return Pro-Con List

B. Electronic Engine Control

Three main design options were considered for the electronics and software of the engine, which includes the Engine Control Unit (ECU) and Engine Sensor Board (ESB) of the engine. The goal of both of these components is safe and proper operation of the engine. The ECU must provide the main power and control logic of the engine (including a default of shut down for errors encountered to provide safe operation), while the ESB primarily controls the engine components and sensors.

The stock ECU and ESB incorporate these items, and are discussed below as a design option. However there are limitations to the stock controller, so custom printed circuit boards (PCBs) (section 2) and third party reprogrammable ECUs (section 3) were considered as alternatives to the stock electronics. Each option was addressed as it would apply to the engine with the recuperator attached. A pros and cons list is included with the description for each, and the trade study to determine the most viable solution is discussed in Section V of this report.

1. Stock

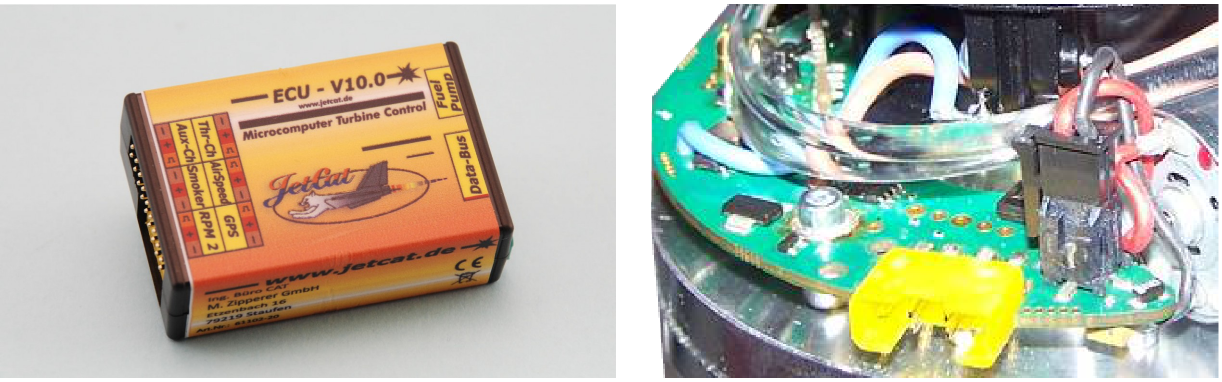
The first option available to control the engine and sensors is to use the stock ECU and ESB that come standard with the JetCat engines (shown in Figure 12). This option would be the easiest, if it would work. The stock components have already been proven to function and can obtain data relatively easily. They are pre-built and programmed, and all components are already in house at CU due to previous engine projects. The ECU and ESB record the exhaust gas temperature (EGT), engine RPM, and voltage provided to the fuel pump at a rate of one sample per second, over a maximum length of 17 minutes. This data can supposedly be downloaded to a computer for later analysis, but all attempts to find the software to do this or contact the company for more information has been unsuccessful thus far.

However, the main disadvantage is that it is unknown whether the engine would function after recuperator modifications. Built-in safeties programmed into the ECU cause the engine to shut down if the EGT is above 700°C for over 5 seconds. Integration of a recuperator on the engine will increase the EGT if the fuel flow is kept at the same level. The electronics/software of the stock engine components are a “black box” because it is very difficult to figure out the software or internal electronics. The manufacturer is known to be difficult and is not willing to share specifications on their products. Since the stock ECU is a black box, it is currently unknown if the ECU would adjust the fuel pump voltage to reduce fuel flow, or if it would just shut down the engine due to over temperature of the EGT. This would mean it is a very high risk to assume all would be fine without pursuing a secondary option.

If it were discovered that the stock electronics could control the engine as desired, testing and development would require minimal effort. Should a heat exchanger design option with extra power and control be incorporated though, the stock components alone would not be enough. Also the stock controller does not incorporate a fuel flow sensor to characterize TSFC or load cell to measure thrust, so there will need to be external components regardless of the design option chosen. The summary of the pros and cons of using the JetCat provided electronics is shown in Table 6.

Pros	Cons
• Already built • Proven functional in stock engine configuration • Proven Safe	• Not customizable • Potentially won’t work once engine is modified • Requires external components and data acquisition for non-stock sensors

Table 6: Stock ECU/ESB Pro-Con List



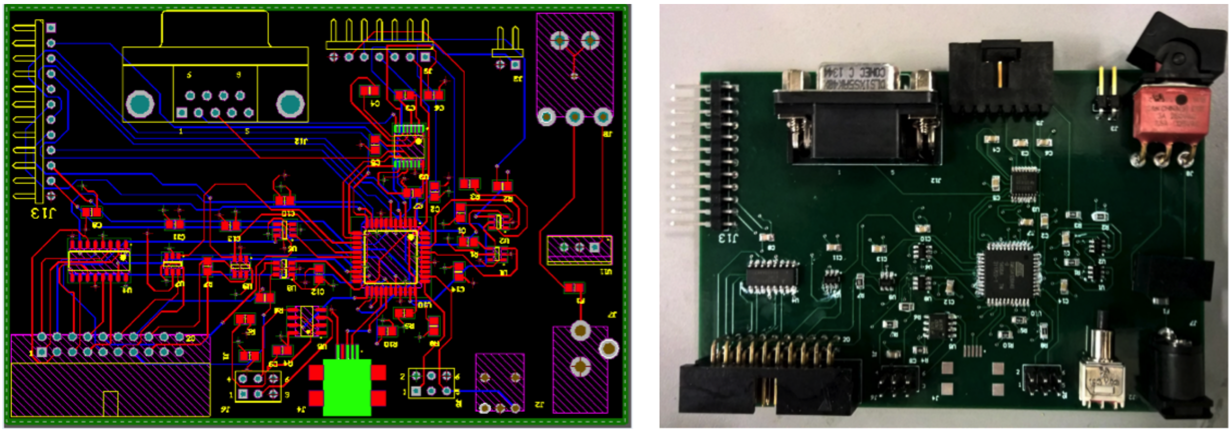
(a) Stock ECU

(b) Stock ESB

Figure 12: Stock Engine Electronics

2. *Custom PCB*

The control of the engine and sensors can also be achieved through the use of a custom PCB. During the 2014-2015 school year, the aerospace senior design team MEDUSA created custom PCBs for both the ECU and ESB. Figures 13 and 14 show the Altium design and printed boards they created. One option considered for the engine electronics was directly using the already printed MEDUSA boards. However, after review of these boards, they were determined unsafe to use due to trace width and layout. They also were designed for the use of methane as the engine fuel, so a few components may need to be changed for use with kerosene. Therefore modifications are needed and a revision of the MEDUSA boards would have to be printed prior to use. In addition, the MEDUSA software was determined to potentially inadequate and would be too difficult to understand in a timely manner, so the software will need to be built up from scratch.



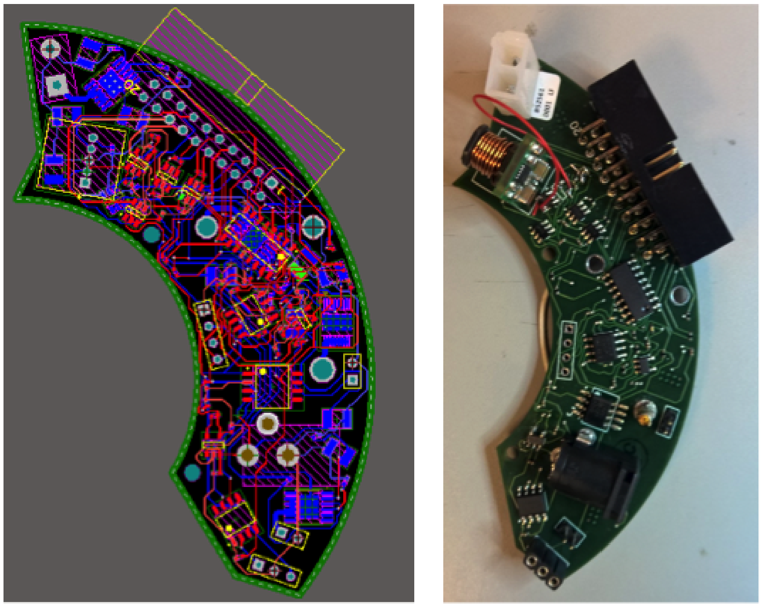
(a) PCB Design in Altium Software

(b) Manufactured PCB

Figure 13: MEDUSA Custom ECU.[11]

REAPER also considered starting from scratch on new PCBs, rather than working from the MEDUSA baseline. This too was determined to be impractical; MEDUSA spent a year researching and developing a replacement for the ECU and ESB that would allow them to control the engine, so the parts they picked out and the protocols used were well chosen. The custom PCB option researched then by the REAPER team is a combination of new parts and design and those created by the MEDUSA team.

A custom PCB means much more controllablity of the engine based on the design chosen for the ECU and ESB. Any heat exchanger design option (and associated power/control needs) could be incorporated into a PCB. However, this advantage comes at a cost of both time and money. Development of a PCB, even when working from a baseline like the MEDUSA part selections and schematics, takes about a month to layout. The boards then have to be ordered



(a) PCB Design in Altium Software (b) Manufactured PCB

Figure 14: MEDUSA Custom ESB.[11]

and populated, which can be up to another month. Most boards also require revisions to fix any unforeseen design issues, which takes less time to implement but still has lead time and requires population again. Despite all of these drawbacks, the PCB offers something that the other options do not: direct control of the fuel pump flow with integrated sensors and data storage. Code can be created that uses feedback to control the fuel pump voltage based on the EGT temperature and fuel flow rate, and is able to save all the data to an easily accessible system (like an SD card or flash memory). For a full list of the pros and cons, see Table 7.

Safety is also a paramount consideration when using a custom PCB. Because it is not the stock electronics that have been tested by manufacturer, there could be more risk with running the engine. However, team members have experience with creating custom PCBs and code for satellites that have safeties and redundancies for full functionality in orbit so REAPER has confidence that proper safety and control will be implemented on the custom PCB. Designing the board directly also means the team is more more familiar with the parts and the functionality, so there would be more confidence about how the engine will behave when a recuperator is integrated.

Pros	Cons
• Previous research available to build off • MEDUSA parts well research and chosen • Customizable for specific functionality • MEDUSA team available for questions • More familiarity with electronic system • Data recorded and available as desired • Team has experience with PCB design & code creation	• Requires substantial time commitment • Multiple revisions may be costly • Requires complete coding redesign • Unproven with P90-RXi engine

Table 7: Custom PCB Pro-Con List

3. *Third Party Reprogrammable ECU*

The third and final option for controlling the engine is using a third party ECU which is programmable. An example of this is shown in Figure 15. This is the least understood of the options due to lack of readily available information. There are many questions that would need to be answered before fulling investing in this design path, which may be impractical given the rapid schedule required in this course. The main thing known is that this option would eliminate the need to build a custom ECU and would allow custom software. However programmable ESBs are not available for purchase, so the ESB which would either need to be stock or custom built. If building an ESB is required, it could be easier and cheaper to build the ECU to ensure that it will interface correctly with the ECU.

Although the programmable ECUs offer more customization than the stock ECUs, there are may disadvantages. Software to control the engine will most likely need to be built from scratch, and intensive research will be needed to make sure the ECU can handle the control needed. Information about the electronics in the third party ECUs may also be as proprietary as the JetCat ECU, making it very difficult or impossible to modify or fix. This also limits the addition of non-stock sensors or required components for running a heat exchanger (if applicable). Therefore the development work will be much greater than stock ECU, and potentially on par with the custom PCB, for possibly less functionality and control.

This option is also highly expensive as some ECUs have been quoted around 00-$2500 and without knowing exactly how things would work out, it is a very large cost risk. A full list of the pros and cons can be found in Figure 8.

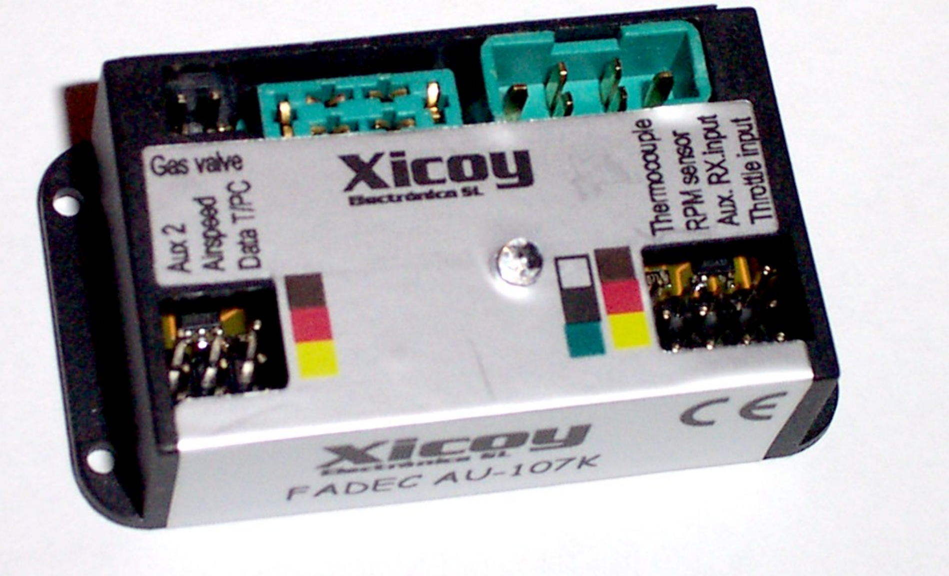


Figure 15: Example Programmable ECU

Pros	Cons
• Already built and readily available • Software customizable	• Hardware not customizable • Expensive • Many unknowns • Requires custom ESB or special work to interface to stock ESB

Table 8: Programmable ECU Pro-Con List

V. Trade Study Process and Results

Two trade studies were considered critical for project REAPER: the heat exchanger, and electronic engine control. Both trade studies used a weighting system of -9,-3,0,3, and 9, which provided differentiation between solutions.A score of zero corresponds to a design that meets the design requirements with minimal risk. Scores of 3 or 9 indicate the design will slightly exceed or greatly exceed the required performance respectively. Conversely, a score of -3 indicates the design will struggle to meet requirements while a score of -9 indicates the design will not meet the requirement. The categories with weightings are described below, with the results given in Tables 10 and 12.

A. Heat Exchanger

1. Trade elements

Six different categories were considered for the heat exchanger trade study: efficiency, volume, mass, flow, feasibility and cost. The descriptions below will provide more detail for each category. Heat transfer capacity and feasibility were each given the highest weight values at 30%, as they are major factors in choosing and implementing a heat exchanger. Cost was considered as an individual element in the trade study as opposed to integrating it into each trade element. Budget will be large factor in any design and it is important to understand the budgetary restraints placed on this project.

a. Efficiency

Efficiency, specifically the total impact of the heat exchanger to the overall engine efficiency, is considered as a trade element because it provides a direct correlation to achieving the desired heat exchanger effectiveness. Efficiency of a heat exchanger is a measure of the amount of heat extracted from the hot gas to the amount of heat eventually transfered to the cold gas. An exchanger with a low efficiency will require more of the exhaust gas to be diverted to obtain the same heat transfer rate as a more efficient exchanger. Consequently, a less efficient heat exchanger will provide less engine level efficiency gain or even result in a loss in engine performance by needing more fuel burn to obtain the same thrust. To accommodate the unique natures of the rotary regenerator and flue gas return concepts diluting the air in the combustor with combustion products, efficiency will also contain any impacts to burner efficiency from the heat exchanger. Burner efficiency is a measure of how much of the energy in the fuel injected into the combustor is actually used to heat the gas in the engine.

If a system design option presents an efficiency that will not meet the required heat transfer rate of 22.5 kW without diverting excessive amounts of the exhaust flow, then a low score results. If a design options provides excellent efficiency that design will be given a high score to show its potential benefit to REAPER. Efficiency was given a weight of 30% as reducing fuel burn by preheating the intake air with excess heat from the exhaust is the main goal of the REAPER project.

Values for the different heat exchangers were assigned based on their ability to increase the overall efficiency of the engine. Gas to gas heat exchangers have the capability to easily exceed the required efficiency due to their large heat transfer rates and minimal impact to the efficiency of the other engine components. Rotary regenerators can also easily exceed the required efficiency due to their characteristic of slowing down the flow to increase the amount of time to transfer heat. Heat pipes in theory can obtain high efficiencies in steady-state heat transfer; however, the literature indicates that heat pipes can have poor transient performance. A flue gas return will give the maximum possible heat addition per exhaust gas extraction indicating it should receive a high efficiency score. However, a flue gas return also pollutes the combustion chamber lowering burner efficiency; hence the flue gas return can not receive highest marks for efficiency.

b. Volume

In order to successfully test the incorporated heat exchanger, the engine will need to fit on a pre-built test stand. The test stand has a maximum width of 20 centimeters between the engine bracket risers that needs to be considered when evaluating design options. Additionally, the customer wants to limit any volume increase in order to continue to allow the engine to be used in small UAVs. As such, volume was given a weight of 7.5%. A high score will correspond with a design option minimizing any volume additions to the engine and still fitting on the test stand provided.

The amount of volume added by each heat exchanger system varied substantially. Heat pipes are generally very compact and would add only a small amount of volume to the system, likely only increasing the footprint of the engine by around 10-20%. This led the team to assign the a fairly high value to the heat pipe. On the other hand, flue gas return adds some kind of compression device as well as scoops and tubing to the engine, possibly increasing the total volume by over 100%. Thus, the flue gas return received the lowest possible score. Gas to gas heat exchanger require a high amount of surface area to be effective which in turn results in a large volume addition to the engine. Likewise, the addition of a rotary regenerator is likely to require additional ducting and gearing or a drive motor that will result in significant volume addition if not carefully controlled.

c. Mass

Limiting mass additions to the engine is considered in the trade study as a trade element because it is one of the few requirement set out by the customer. As with volume the customer wants to keep mass additions to a minimum. Any design option with low mass will be given a high weighted score and a design option will high mass will be given a low score. Mass, similar to volume, was given a weight of 7.5%. As stated above, the mass addition of the heat exchanger system is supposed to be minimized, and the regenerator receives the lowest possible score. The rotary regenerator would have high mass because it would require gearing to be powered by the shaft or an external power source to rotate the regenrator. Additionally, by nature, rotary regenrators have a high density matrix. Flue gas wouldn't have the high density matrix, but would be similar in mass requirement to the rotary regenerator, so it was given a -3 score. The heat pipe does well in the mass category due to its small size, and was rated highly. The gas-gas heat exchanger was given neutral score due to its need to be constructed of a high temperature metal. It wasn't given a negative score because the amount of metal would be regulated to fit the volume requirement.

d. Flow Impedance

Flow of the engine exhaust is a key feature of heat exchangers. The thrust produced by a turbojet engine is directly proportional to the difference in the flow velocity before and after the engine. The key to minimizing thrust degradations will be minimizing flow impedance, i.e. drops in the exhaust velocity. Additionally, any friction or drag effects inside the engine will decrease the overall efficiency of the engine by converting total pressure (which ultimately is transformed into exhaust velocity) into excess temperature. By examining data from previous years, a total pressure drop of just 0.01 bar inside the results in slightly less than a 1% drop in total thrust.[10] Due to the importance of maintaining an unobstructed flow, a 15% weight was assigned, the second highest in the study.

As in the mass metric, the regenerator receives awful marks for flow impedance and receives the lowest score once again. In the regenerator, both the air being taken from the exhaust and the compressed intake air must pass through an extremely flow restrictive porous wall in order for heat transfer to occur. Flue gas scores fairly well in the flow impedance, as it needs to harvest the least amount of exhaust due to its excellent heat transfer characteristics. Additionally, a flue gas system does not require a heat exchanger to be in contact with the interior flow reducing drag and friction effects on the internal flow. However, if the pressure in the flue gas return is not perfectly matched to the pressure at the injection point, the compressed internal flow will either leak out (if the flue gas pressure is too low) or the flue gas will impart a negative pressure gradient on the internal flow reducing its total pressure. Despite these drawbacks, the team assigned a slightly positive score to the flue gas return due to its low exhaust diversion and lack of internal flow resistance in matched system. Due to their high heat transfer capacity, gas to gas heat exchanger would not require large exhaust flow diversion; however, their large surfaces areas and narrow passages will constrict the internal flow. As a result, gas to gas heat exchangers are of middling performance in terms of flow impedance. Heat pipe type heat exchangers in theory do not require any flow diversion but do have fins that stick into both flows producing drag and reducing flow velocity and total pressure. Still, heat pipe heat exchangers will impede the flow less than the other physical heat exchanger devices.

e. Feasibility

Feasibility is responsible for 30% of the weighted scale. Feasibility is further broken down in ability to manufacture, complexity of the final product and integration with the engine. When a design option presents an ease to integrate into the engine and minimal external components it will receive a higher score. But if a design option needs external power, gearing or machinery, it will be marked lower. Feasibility is a key to a successful project and that is reflected in it high weighed percentage.

Feasibility is a highly dichotomous section: either the solution is relatively easy to implement or it is incredibly difficult. The flue gas return and rotary regenerator, due to their moving parts, are difficult to build and keep operational. The gas-gas and heat pipe exchangers have no moving parts, and thus are significantly easier to build and maintain.

f. Cost

As with any project, cost will certainly factor into the design of the heat exchanger. However, the budget for this project is not overly restrictive and there are sections of this project that will have a much greater effect on the choice of design. With these factors in mind, cost was weighted at 10%.

None of the design choices received high marks for cost. The gas-gas and heat pipe exchangers, due to their simple manufacturing and inexpensive components, were given a neutral score for cost. The gas-gas heat exchangers would most likely be made of a high temperature steel, which can be found at relatively reasonable prices due to its abundance in engineering application. Heat pipes can be bought from various vendors in different sizes and are common in industry. The flue gas return and rotary regenerator receive negative marks, due once again to their complex components. These components will either have to be store bought or custom manufactured by an outside entity, incurring significant cost.

2. Trade Study

The result of the heat exchanger trade study is given in Table 10 for the four options as described in Section IV. Six categories were considered, and a weighting system of -9,-3,0,3, and 9 was used to provide differentiation between solutions. A score of zero corresponds to a design that meets the design requirements with minimal risk. Scores of 3 or 9 indicate the design will slightly exceed or greatly exceed the required performance respectively. Conversely, a score of -3 indicates the design will struggle to meet requirements while a score of -9 indicates the design will not meet the requirement. Weightings were applied as described in the previous sections to give the final weighted total. Table 9 quantitatively describes what the weighting for each category corresponds to.

	9	3	0	-3	-9
Feasibility	Very High	High	Good	Poor	None
Efficiency	95-100%	65-95%	35-65%	5-35%	5-0%
Flow Impedance	None	Very Low	Low	Significant	No Flow
Cost	<$100	$100-750	$750-1500	$1500-2500	>$2500
Volume	<10%	10-35%	35-65%	65-100%	>100%
Mass	<10% (0.14kg)	10-20% (0.14-0.28kg)	20-35% (0.28-0.50kg)	35-50% (0.50-.72kg)	>50% (0.72kg)

Table 9: Breakdown for Trade Study for the Heat Exchanger

	Weighting	Gas to Gas	Flue Gas	Heat Pipe	Rotary Regenerator
Feasibility	30%	3	-9	3	-9
Efficiency	30%	3	3	0	3
Flow Impedance	15%	0	3	3	-9
Cost	10%	0	-3	3	-9
Volume	7.5%	-3	-3	3	-3
Mass	7.5%	0	-3	3	-9
Weighted Total		1.575	-2.100	2.100	-4.950

Table 10: Trade Study for the Heat Exchanger

B. Electronic Engine Control

1. Trade elements

The electrical trade study considers three design solutions across six weighted categories. The major factors in the study are safety and feasibility. They make up 25 and 30 percent respectively. Other factors include development time, cost, accuracy of the data produced, and the ability to retrieve the data. There were some additional considerations that were left out of the trade study because they were common across all solutions or did not play heavily into a design choice. An example of this would be form factor. The given solutions span the myriad from COTS (consumer off the shelf) components to custom made solutions. The numbers given for each category were derived from extensive research or the experience of several team members.

a. Feasibility

Feasibility is responsible for 30% of the weighting. It was selected to be the largest portion because the ability for the engine to run in a modified configuration is key to the overall success of the electrical system. Feasibility encompasses familiarity with the hardware, ease of use, past experiences and functionality. Also considered in this category was how the engine and control unit would react to the increased temperature caused by the preheating of air in the combustor: the fuel flow will need to be directly controlled to provide desired RPM, EGT, and throttle response.

Based on past experience the stock ECU and ESB work fairly reliably in stock configuration, but have significant problems with even the smallest modifications. To get the stock electronics working in with a modified engine may take significant effort. Based on research (due to lack of availability for a stock engine test at the time of this report), the stock ECU offers the option to control the fuel pump voltage from the ground support unit (GSU). However, that would be manual changes and maybe not be adjustable enough or have a quick enough reaction time to prevent the EGT from going to high and causing an engine shut down. Lack of modifications to the ECU and ESB limit the functionality that can be achieved from the stock electronics when the recuperator is attached.

A custom solution allows much more flexibility with the operating conditions. Because of this it is the most likely to function in a modified configuration. Customizing the electronics also allows for smoother software architecture and integration and therefore has a better chance of success.

A third party reprogrammable solution is slightly more feasible to use in a modified configuration. Depending on the exact unit different safeties can be set that will allow the engine to run in a modified configuration. However, there would be substantial development of software involved. Readily available information on programmable ECUs is minimal though, so this solution could not be rated very high on feasibility unless extensive research is performed.

b. Safety

Safety is responsible for 25% of the weighting. The safety is to be consider from the stand point of a integrated recuperator-engine system. This encompasses both safety of the engine and the safety of the personal operating the engine. Safety is weighted so heavily because no unsafe system will be used in any test.

The stock electronics are considered to be extremely safe with the engine running in stock configuration. However, there is some uncertainty of the performance in a modified scenario. While the manufacturer safeties will still be in place, the very slight unknown caused by the integration of the recuperator means the safety can not be rated at 100%. The ECU also are very fragile and break often, and could also cause damage to other components if it was to short.

A custom solution allows the addition of extensive safety mechanisms. The limiting factor on the custom solution is that it will lack the heritage and thorough validation that the stock electronics have. However, simulations during electronics bench testing can provide validation that safeties have been implemented correctly and will react in a timely manner. The team members also have previous experience implementing safeties and watchdogs on custom PCBs, so there is confidence that the safeties will be as good as the stock engine.

A third party solution does not have the built in safeties that the stock configuration has, nor does it have the ability for custom electronic solutions to be added in. It is a fairly unsafe solution and will take significant work before it can be used in a system.

c. Data

Data is responsible for 15% of the weighting. This represents the recording length and retrievability of the test data. Access to the data post-test is a key element of the electronic system. If the data cannot be retrieved or is incomplete due to lack of storage space, the project will not succeed.

The stock ECU has very difficult data retreivabilty. Based on information from previous projects, the software is outdated and drivers provided from the manufacture have high potential to fail. These possible problems give the stock a negative but could be worked out if needed. A custom solution would allow for purposefully design data recovery which could include using an SD card for easy access. This gives it a positive rating. A third party ECU has large unknowns for how easy it is to retrieve data from the tests and depends heavily on how expensive of an ECU is purchased. This unknown factor is a negative for the design solution.

d. Development Time

Development time is responsible for 15 percent of the weighting. It represents the total time it will take for the electronics to be brought to working and safe condition. This will very significantly from solution to solution and could require a huge amount of time investment.

The stock solutions is off-the-shelf ready with only a hand full modifications that need to be made. Additional sensors for model validation and verification would need to be developed externally though. The key addition to this configuration is the addition of a fuel flow sensor and heat exchanger thermocouples, and corresponding data collection hardware. The third party solutions will still require a complete sensor board redesign due to lack of information available about the communications protocol on the JetCat stock ESB. In addition there is still major software creation and safeties that need to be integrated into the reprogrammable solutions. The custom solutions will require a build of two PCBs. However, the MEDUSA designs from the previous year are available for a baseline, so a majority of the part selection and schematic creation will not be required. The PCB design itself will need to be redone for the ESB, and modified (at least) for the ECU. Often PCBs will also require a revision to get a working board as well, and the software will need to be developed from scratch so the workload is the highest for this design option but still manageable.

e. Cost

Cost is responsible for 10% of the weighting. Cost is always a factor in any design solution. The cost of electronics should not take up a major fraction of the budget. This will include reoccurring costs.

While the stock ECU and ESB are available in the lab now, if either breaks it will cost around \$200 to \$500 depending on the damage. The ECUs are highly known to stop working, and a part of the budget has already been spent on repairs. Building an ECU and ESB will have a higher initial cost as it currently does not exist but if anything breaks, it will be cheaper to replace than any other solution. Also the MEDUSA boards are currently available; while the ESB cannot be used as is due to incorrect trace widths, the available ECU will be tested for functionality. The third party option has variable cost but will probably not be cheaper than \$700 and could be up to \$2000. However it would potentially be less prone to breaking and therefore replacement costs may not be as high.

f. Accuracy

Sensor accuracy is responsible for 5% of the weighting. The accuracy and precision of the measurements is important in verifying our requirements and success levels. Some solutions allow for more customizable options for sensor arrangement.

The stock ECU and ESB have non-customizable options and a gather rate of only 1 sample per second. This is less then desirable if upon examine failure modes or more precise system performance. The programmable third party options allow for more sensor customizability, depending on the specific component chosen. In addition the sample rate can be increased, but may be limited due to hardware with specs that might not be readily available. The custom PCB will allow for a much greater selection of sensor and acquisition rate. This also allows additional non-standard sensors to be incorporated into the same system, with accuracy as needed to confirm requirements. Limitations would be due to the sensors themselves, and the cost that may be associated with high precision equipment.

2. Trade study

Table 12 gives the result of the trade study performed between the three options for the electronic engine control. Six categories were considered, and a weighting system of -9,-3,0,3, and 9 was used to provide differentiation between solutions.A score of zero corresponds to a design that meets the design requirements with minimal risk. Scores of 3 or 9 indicate the design will slightly exceed or greatly exceed the required performance respectively. Conversely, a score of -3 indicates the design will struggle to meet requirements while a score of -9 indicates the design will not meet the requirement. Weightings were applied as described in the previous sections to give the final weighted total. Table 11 quantitatively describes what the weighting for each category corresponds to.

	9	3	0	-3	-9
Feasibility	Very High	High	Good	Poor	None
Safety	Excellent	Very Good	Good	Poor	Dangerous
Development Time	<1month	1-2months	2-4months	4-6months	>6 Months
Data	Streamed Directly	Easily Accessible and all Data Saved	Accessible but not easy/cutoff	Very difficult to access/little data	None
Cost	<$100	$100-500	$500-1000	$1000-1500	>$1500
Accuracy	Very High	High	Good	Poor	None

Table 11: Breakdown for Trade Study for the Electronic Engine Control

	Weighting	Stock	PCB	Reprogrammable
Feasibility	30%	-9	3	0
Safety	25%	3	0	-3
Development Time	15%	3	-3	-3
Data	15%	0	3	0
Cost	10%	-3	0	-3
Accuracy	5%	-3	3	3
Weighted Total		-1.95	1.8	-1.35

Table 12: Trade Study for the Electronic Engine Control

VI. Selection of Baseline Design

A. Heat Exchanger

The results of the heat exchanger trade study in Table 10 revealed that the gas to gas and heat pipe were the two best design options. Both the rotary regenerator and flue gas design possibilities were weighted at -4.95 and -2.55 respectively, much lower than gas to gas or heat pipe heat exchangers. Moving forward the REAPER team will carry forward the gas to gas and heat pipe designs.

The rotary regenerator design concept is clearly the inferior design based on the trade study conducted, with a score of -4.55. The only positive element of the rotary regenerator is its potential thermal efficiency rating; in the other five categories the rotary is found to be unfavorable. The trade gave the worst score to the rotary regenerator in feasibility, flow, cost and mass categories. Regarding the feasibility, the shear complexity of integrating a rotary regenerator with an external power source is insurmountable with the schedule and budgetary restraints.

The second lowest scoring design option is the flue gas return heat exchanger with a score of -2.55. The flue gas received the worst possible score in both the feasibility and volume category. These low scores are due to the necessity of the compression device. The low feasibility score stems from the issue of powering the device, as well as the difficulty of finding a compression device with the appropriate characteristics for this application (high temperature, high pressure, and adaptable to the conditions inside the engine). Depending on the device chosen, a huge amount of volume could be added to the system, resulting in the low score in the volume category.

The two best options both did well in the feasibility and efficiency categories. Neither will be overly difficult to construct or integrate with the engine, and neither have any moving parts. The lack of moving parts reduces the complexity of the solutions and makes a break-down less likely. Additionally, both have the capability to meet the required heat transfer goal; however, the transient performance of the heat pipe requires further consideration. The gas-gas heat exchanger suffers most in the volume category. In order to meet the efficiency requirement, the gas-gas heat exchanger needs a lot of surface area through which to transfer the heat. Depending on the configuration of the exchanger, this surface area could add significant volume to the system. The heat pipe doesn't suffer drastically in any area, but does receive a good mark in the volume category. It is the smallest option that was identified through the trade study process. Additionally, the heat pipe design would have very low flow impedance which has the dual benefit of preserving engine thrust and reducing pressure losses in the engine. As both of these options present highly valid solutions to the heat exchanger design both will be carried into the next stage of system design. As both methods are similar enough and must be further researched before deciding which is more viable, the REAPER team is comfortable moving forward to PDR with two possible solutions.

B. Electronic Engine Control

The electronics trade study considered three possible options: stock components, custom PCBs, or third party reprogrammable ECUs. Based on the trade study in Table 12, creating custom PCBs is the most viable design solution. At a weighted total of 1.8, it beats the second place option (programmable ECU) by 3.15. This is enough margin to consider it as the single design solution to move forward with. However, since the stock engine electronics are already in house, initial engine tests in an unmodified configuration will be performed with the stock ECU and ESB. The next steps will be to confirm the lower level requirements of the ECU and ESB, and then to make part selections based on those needs. Two PCBs will be designed and created that meet the needs of the engine control for project REAPER. The research and part selection of the MEDUSA project will prove invaluable, but the software for the boards will be built from scratch to ensure proper and safe functionality of the engine.

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