FINAL REPORT

Environmental Advantages of an Additively Manufactured Micro-turbine Engine

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14. ABSTRACT

This project focused on demonstrating the advantages of a newly developed low cost additively manufactured (AM) micro-turbine engine as compared to a similar-sized traditionally designed engine. Environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods. The AM engine was tested to characterize its performance and to compare its operational specifications to similar traditionally manufactured engines. This benchmarking effort, collectively with an environmental and cost study, served to demonstrate how such an engine could be utilized in various DoD applications. The development of the engine was led by the Air Force Life Cycle Command Center (AFLCMC) with support from the University of Dayton Research Institute (UDRI).

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AFLCMC	Air Force Life Cycle Management Center
AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
ATTC	Advanced Technology and Training Center
CFD	Computational Fluid Dynamics
DMLM	Direct Metal Laser Melting
DoD	Department of Defense
RPM	Revolutions per Minute
SLA	Stereolithography
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Aerial Vehicle
UDRI	University of Dayton Research Institute

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Abstract

Introduction and Objectives: There is a need across the Department of Defense (DoD) for power plants that yield a reduced environmental impact. In addition, micro-turbine engines, which have both air and ground power applications, are in growing demand. Objectives of the project were to demonstrate the advantages of a newly developed low cost additively manufactured (AM) micro-turbine engine as compared to a similar sized traditionally designed engine. Environmental advantages, related to manufacturing energy consumption and emissions, can be realized while also demonstrating engine efficiency advantages.

Technology Description: The Air Force Life Cycle Management Center (AFLCMC) Product Support Engineering Division and University of Dayton Research Institute (UDRI) Sustainment Technologies Transition Division (STT) team utilized a commercially available EOS M290 AM machine to build a newly designed micro-turbine, employing a powder bed fusion, direct metal laser melting (DMLM) technology that uses lasers to melt ultra-thin layers of metal powder to build a three-dimensional part. DMLM makes possible an iterative design-driven process with significant manufacturing and engine operational improvements. AM technologies offer the capability to rapidly prototype and manufacture the micro-turbine with the following expected benefits: manufacturing cost effectiveness; reduced carbon footprint through less CO_2 emissions during the production process; improved efficiency via optimized engine geometry made possible by the AM process.

Performance and Cost Assessment: Improvements in engine efficiency were identified via use of computational fluid dynamics (CFD) modeling and simulation to determine optimized engine geometry that is also well suited for the AM process. Optimizations of the engine compressor, combustor, and turbine stages were performed. The performance of each stage was demonstrated via printing and testing of the AM engine. The AM engine was successfully tested at its idle condition and up to roughly 50% of its anticipated max speed. The engines performance at these conditions was shown to correlate well to values predicted by the CFD work previously mentioned. Testing at these conditions has also been shown to be stable and the engine's startup procedure is repeatable. Manufacturing cost benefits were demonstrated through use of cost benefit analysis tools and comparison to costs of similar commercially available engines. Likewise, environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods.

Implementation Issues: Higher speed testing and full performance mapping of the engine has not yet been completed due to delays caused by complications with manufacturing of the engine test articles and maintenance of the mobile engine test stand. There is still much to be learned regarding the performance of this AM micro-turbine engine and additional testing is needed.

Publications: ESTCP Symposiums (2020-2022), Additive Manufacturers Users Group Conference (AMUG) Technical Competition Winner 2023

Executive Summary

Introduction: There is a need across the Department of Defense (DoD) for power plants that yield a reduced environmental impact. In addition, micro-turbine engines, which have both air and ground power applications, are in growing demand. However, these types of engines are complex pieces of machinery making them costly and difficult to manufacture. Also, traditional engine manufacturing methods can have a significant environmental footprint. This project focused on demonstrating the advantages of a newly developed low cost additively manufactured (AM) micro-turbine engine as compared to a similarly sized traditionally designed engine.

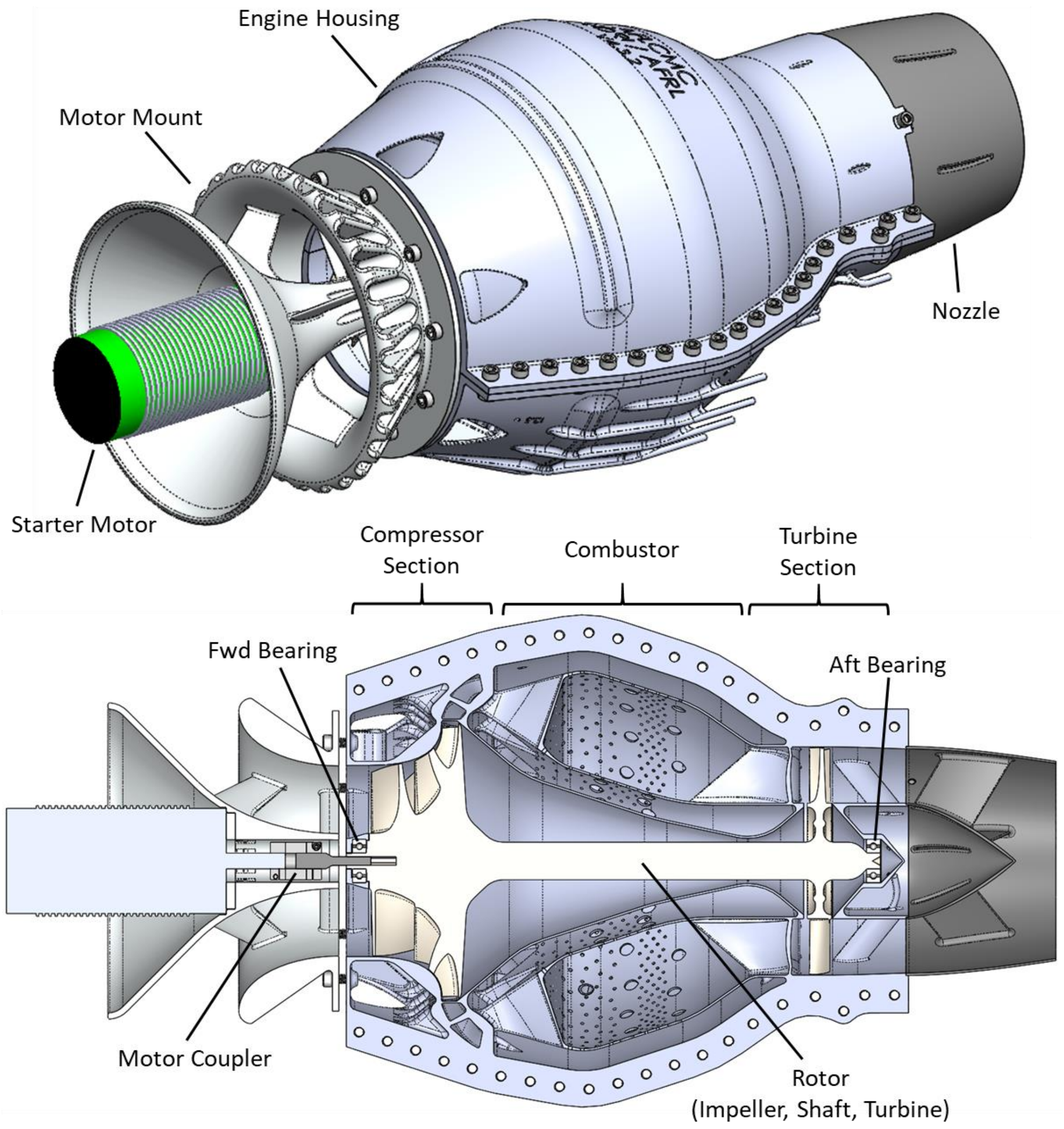
Objectives: The project supported efforts to develop a novel micro-turbine engine that could be manufactured via AM. The program aimed to demonstrate the advantages of an AM engine as compared to a similarly sized traditionally manufactured engine. Environmental advantages, related to manufacturing energy consumption and emissions, can be realized while also demonstrating engine performance advantages. Hence, the following program objectives were developed:

1) Demonstrate an AM micro-turbine for multiple applications, ensuring cost effectiveness and manufacturing sustainability of the newly developed AM turbine engine for DoD services;
2) Demonstrate the potential for improved performance in thrust specific fuel consumption and noise emissions of AM micro-turbine engine by establishing baseline performance criteria and then recommending opportunities for optimization (as required);
3) Validate reduced thrust specific fuel consumption and noise emissions of AM micro-turbine and provide recommendations for implementation at DoD installations.

Technology Description: The Air Force Life Cycle Management Center (AFLCMC) Product Support Engineering Division and the University of Dayton Research Institute (UDRI) Sustainment Technologies Transition Division (STT) team utilized a commercially available EOS M290 AM machine to build a newly designed micro-turbine, employing a powder bed fusion, direct metal laser melting (DMLM) technology that uses lasers to melt ultra-thin layers of metal powder to build a three-dimensional part. DMLM makes possible an iterative design-driven process with significant manufacturing and engine operational improvements. AM technologies offer the capability to rapidly prototype and manufacture the micro-turbine with the following expected benefits: manufacturing cost effectiveness; reduced carbon footprint through less CO_2 emissions during the production process; improved efficiency via optimized engine geometry made possible by the AM process.

Micro-turbine engines are small turbine engines that rely on the same principles as larger jet turbines. These smaller turbines typically consist of a single stage compressor, a combustion chamber, and a single stage turbine that utilize a Brayton cycle to operate. The chosen design for the AM engine consisted of four main printed components including the engine housing, rotor, nozzle, and starter motor mount. The engine housing is manufactured as one component but cut in half to form a clamshell style design enabling assembly of other components to the internals of the housing. In addition to the printed hardware, the engine consists of two ceramic ball bearings that support the rotor, an electric motor to support startup, and miscellaneous hardware for assembly of the components. An outside view along with a centerline section view of the engine model are provided below.

Engine Assembly Model Views

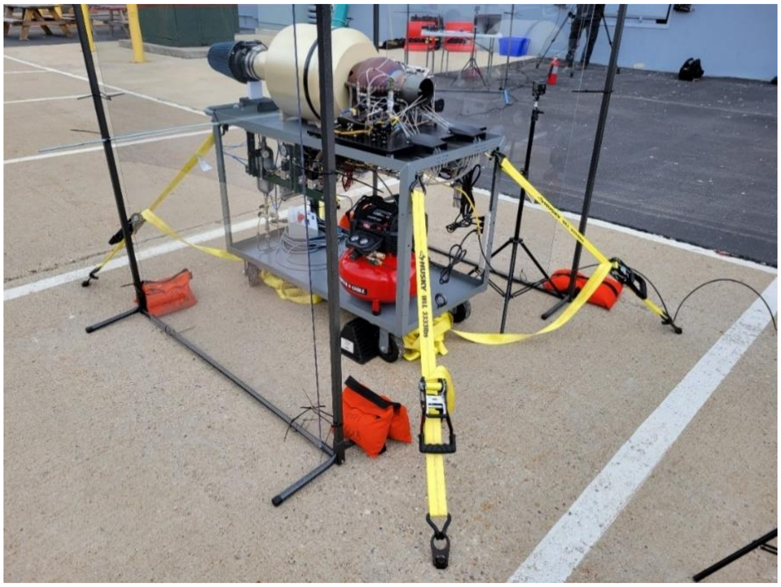


Improvements in engine efficiency were identified via use of computational fluid dynamics (CFD) modeling and simulation to determine optimized engine geometry that is also well suited for the AM process. Optimizations of the engine compressor, combustor, and turbine stages were performed. The performance of each stage was demonstrated via printing and testing of the AM engine. Efficiency of these areas of the engine was then compared to performance of traditionally manufactured micro-turbines. Through this analysis process, a design for the AM engine was revised that allowed the engine to perform favorably compared to traditional micro-turbines. The printed engine assembly is shown below.

AM Micro-turbine Engine

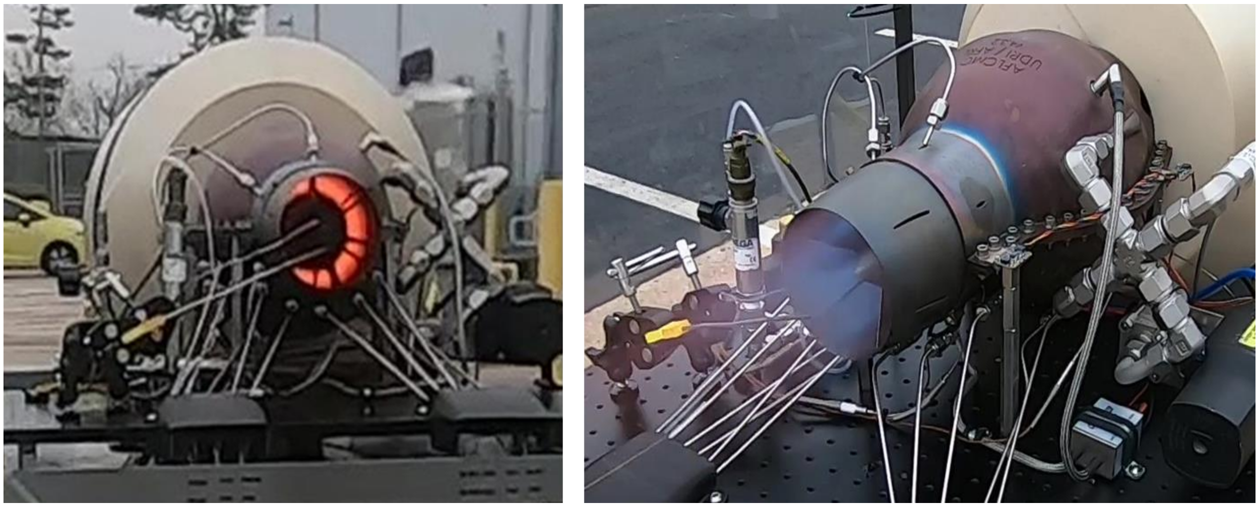
To support testing of the AM engine, a customized mobile test cart with incorporated fuel delivery system and thrust measurement capability was developed by the UDRI engineering team. The cart could easily be relocated in-between tests to allow for inspections and efficient testing modifications if needed. Testing of the AM engine was conducted outdoors at the Advanced Technology and Training Center (ATTC) in Dayton Ohio. The mobile test stand is shown below.

Mobile Engine Test Stand Setup



Performance Assessment: Testing at the idle condition and up to 43,000 RPM has been completed. A repeatable ignition and start-up sequence for the engine has been established. The engine was shown to stably operate at an idle condition of roughly 31,000 RPM as expected. Performance characteristics of the printed engine, such as temperatures, pressures, fuel consumption, and gas flow through the engine, were in line with CFD predicted values. Using a fuel feed rate schedule developed via CFD modeling the engine was also stably operated up to speeds of 43,000 RPM. Within this operating range, engine speed has responded (accelerated) smoothly to fuel feed adjustments, whilst engine temperatures and vibrations have remained safely stable. Unfortunately, due to an error in the fuel feed controls, the engine was overheated during attempted testing at higher operational points and damage to the engine was sustained. Replacement engine components had to be manufactured and the test stand fuel feed controls reworked, which delayed and ultimately prevented testing the engine up to its max speed of 76,000 RPM. This prevented the full characterization of the AM engine's performance as it relates to fuel consumption, thrust generation, and noise emissions. Further testing of the engine is recommnded to collect this performance data.

Engine During Operation



Cost Assessment: Manufacturing cost benefits were demonstrated through use of cost benefit analysis tools and comparison to costs of similar commercially available engines. The analysis performed by UDRI engineering team compares the environmental impact of prototyping a micro-turbine engine using a traditional casting process versus an additive manufacturing process.

Traditional casting process was selected for analysis baseline. The Pratt & Whitney TJ-150 turbojet engine was used in this comparison. For AM micro-turbine engine the UDRI developed AM engine was used in this comparison.

A summary comparison of the environmental impacts from the baseline investment casting process to additive manufacturing for eight design and development iterations is shown below. The analysis shows that investment casting process requires 95,780.52 more kilowatt-hours (kWh) than the additive manufacturing process. Additionally, CO_2 emissions are 96,609.52 pounds higher for the investment casting process.

Manufacturing Cost Analysis

Process	kWh	Cost	Co_2 (lbs)	Cost	Total Cost
Investment Casting	126,943.8	7,616.63	127,411.3	6,370.57	13,987.19
Additive Manufacturing	31,163.3	1,869.80	30,801.8	1,540.09	3,409.89
Difference		**5,746.83**		**4,830.48**	**10,577.31**

Likewise, environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods.

Manufacturing Environmental Study

Process	Total Particulate (lbs)	Sox (lbs)	Nox (lbs)	VOC (lbs)	One (1) Engine		Eight (8) Engines	
					kWh	CO_2 (lbs)	kWh	CO_2 (lbs)
Investment Casting Process								
Investment casting emissions	0.26	0.92	0.472	0.067		22.83		182.66
SLA mold making					2,646.61	2,615.91	21,172.85	20,927.25
Investment casting					8,794.61	8,692.60	70,356.90	69,540.76
Post processing					4,426.76	4,375.40	35,414.04	35,003.24
Transportation (5-ton truck/castings)	6.20		11.20	1.60		219.68		1,757.40
Total — Investment Casting					**15,867.97**	**15,926.41**	**126,943.79**	**127,411.31**
Additive Manufacturing Process								
Gas atomized powder					1,453.92	1,437.06	11,631.38	11,496.46
Additive manufacturing					1,625.60	1,606.74	13,004.80	12,853.94
Post processing					815.89	806.42	6,527.10	6,451.38
Total — Additive Manufacturing					**3,895.41**	**3,850.22**	**31,163.28**	**30,801.78**

Implementation Issues: Despite being unable to complete the full scope of testing during this effort, much has been learned about the feasibility of the use of AM to design an operational microturbine engine. The full extent of the performance mapping testing of the engine along with field testing of the engine on specific applicable platforms is still needed and recommended. These further efforts could allow for the maturation of this engine design to a point where implementation for both ground and air applications would be possible.

Due to the testing setbacks, no current plans for transition of the technology currently exist. However, the engine articles and test facilities developed under this project are readily available for further development work. In addition, the engine could easily be transferred to other existing DoD engine test facilities for further development work. Also, the engine design can be printed at most metal AM service providers should additional engine articles be needed. And while they were unable to be realized during this effort, opportunities do exist to further optimize the AM engine design and performance. And further advancement could be made in the manufacturability of the engine by exploration of newer, more cutting-edge printing technologies. There is still much to be learned regarding this AM micro-turbine engine.

1.0 INTRODUCTION

1.1. BACKGROUND

There is a need across the Department of Defense (DoD) for power plants that yield a reduced environmental impact. In addition, micro-turbine engines, which have both air and ground power applications, are in growing demand. Micro-turbines are essentially scaled down jet engines that can be used to power unmanned aerial vehicles (UAVs) and munitions or to generate electric power. However, these types of engines are complex pieces of machinery making them costly and difficult to manufacture. Also, traditional engine manufacturing methods can have a significant environmental footprint. This project focused on demonstrating the advantages of a newly developed low cost additively manufactured (AM) micro-turbine engine as compared to a similarly sized traditionally designed engine. Environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods. The AM engine was tested to characterize its performance and to compare its operational specifications to similar traditionally manufactured engines. This benchmarking effort, collectively with an environmental and cost study, served to demonstrate how such an engine could be utilized in various DoD applications. The development of the engine was led by the Air Force Life Cycle Command Center (AFLCMC) with support from the University of Dayton Research Institute (UDRI).

1.2. OBJECTIVES OF THE DEMONSTRATION

The overall program technical objectives were stated as:

1) Demonstrate an AM micro-turbine for multiple applications, ensuring cost effectiveness and manufacturing sustainability of the newly developed AM turbine engine for DoD services;
2) Demonstrate the potential for improved performance in thrust specific fuel consumption and noise emissions of AM micro-turbine engine by establishing baseline performance criteria and then recommending opportunities for optimization (as required);
3) Validate reduced thrust specific fuel consumption and noise emissions of AM micro-turbine and provide recommendations for implementation at DoD installations.

Due to the complex nature of the engine development and some setbacks experienced during manufacturing and testing, the project team has been unable to complete objective #3. The demonstration effort for the project was limited to demonstration of the capabilities of the baseline AM engine design at idle and 50% power conditions.

1.3. REGULATORY DRIVERS

Environmental as well as health and safety regulations are the main drivers of this project. From an environmental standpoint, cleaner and less wasteful manufacturing methods are needed to produce future power sources. Traditional engine manufacturing techniques are energy intensive upfront and result in significant amounts of both waste products and emissions. With environmental regulations becoming ever stricter, improved means of providing these critical pieces of machinery to the DoD are extremely important. In addition, the efficiency at which these power sources operate is important. Opportunities exist to improve critical operating characteristics of engines, such as thrust specific fuel consumption. Thus, improved performance factors were also a driver of this program.

The health and safety of maintainers and operators of these pieces of equipment is just as important. Historically, noise emissions pose a significant risk to those in proximity to the engines. Much work is done on commercial aircraft engines to reduce engine noise and improve the safety of these individuals, but the same design techniques have not made their way to the class of engine explored in this effort. Hence another driver for this program was the investigation of noise reduction technologies for micro-turbine engines.

2.0 DEMONSTRATION TECHNOLOGY

2.1. TECHNOLOGY DESCRIPTION

Micro-turbine engines are small turbine engines that rely on the same principles as larger jet turbines. These smaller turbines typically consist of a single stage compressor, a combustion chamber, and a single stage turbine that utilize a Brayton cycle to operate. Within this cycle, fuel and air are mixed and ignited in the combustion chamber producing exhaust gases that are directed through the turbine section at the rear of the engine. The exhaust gas spinning the turbine generates work which powers a driveshaft to spin a compressor at the front of the engine. The rotation of the compressor draws air into the engine which then sustains the combustor thus creating a self-sustaining cycle. The exhaust gases can be directed through a nozzle downstream of the turbine section to generate thrust for aircraft power applications. In non-flight applications, a generator can be coupled to the engine driveshaft to generate power making these engines good candidates for ground power applications in areas where it is difficult to access established power grids.

Direct Metal Laser Melting (DMLM) is an AM technology that uses lasers to melt ultra-thin layers of metal powder to build a three-dimensional part. DMLM makes possible an iterative design-driven process with significant manufacturing and engine operational improvements. The DMLM process supports the use of materials appropriate for application on engine components. A nickel alloy 718 (NA718) material was used for components subjected to high temperatures and rotational forces, while an aluminum F357 alloy (AL F357) was used for ancillary components. Micro-turbines are sized appropriately such that all components could be printed on a commercially available EOS M290 DMLM printer. AM technologies offer the capability to rapidly prototype and manufacture a micro-turbine engine with the following expected benefits: manufacturing cost effectiveness; reduced carbon footprint through less CO_2 emissions during the production process; improved efficiency via optimized engine geometry made possible by the AM process.

The chosen design for the AM engine consisted of four main printed components including the engine housing, rotor, nozzle, and starter motor mount. The engine housing is manufactured as one component but cut in half to form a clamshell style design enabling assembly of other components to the internals of the housing. Bolted flanges on the side of the engine housing allow for reassembly of the two halves. There are three main sections of the engine that support the engine cycle: the compression section, the combustor, and the turbine section. In addition to the printed hardware, the engine consists of two ceramic ball bearings that support the rotor, an electric motor to support startup, and miscellaneous hardware for assembly of the components. An outside view along with a centerline section view of the engine model are provided in Figure 1. The various components and sections of the engine are called out in these images. The flow path of air and exhaust gas through the engine is also visualized below in Figure 2.

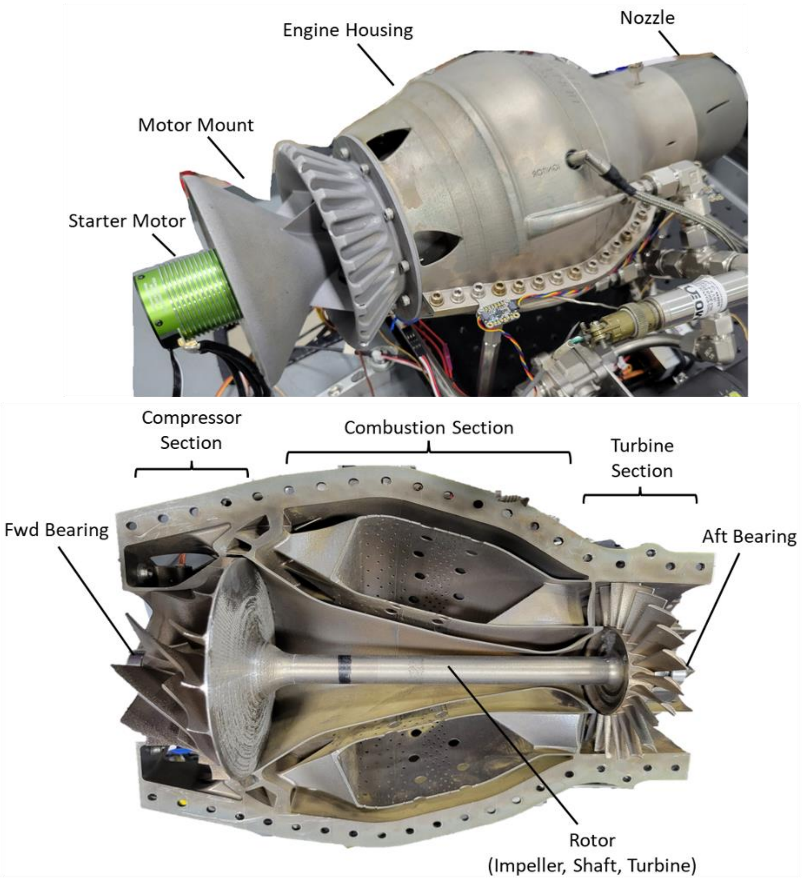


Figure 1. Engine Assembly Model Views

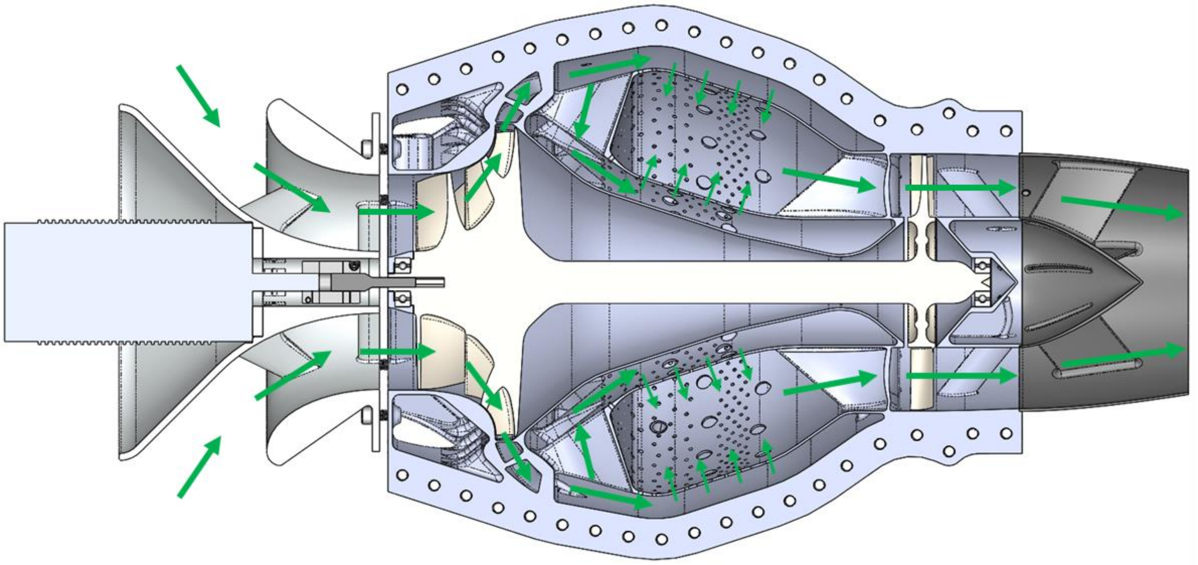


Figure 2. Flow Path of Air & Exhaust Gas through Engine

2.2. TECHNOLOGY DEVELOPMENT

Prior to the onset of this effort, work had been done by AFLCMC and UDRI to prove the validity of 3D printing the complex geometry required of a micro-turbine engine. After validating AM as a manufacturing method for engine hardware, a commercially available micro-turbine was investigated to help the project team learn more about the operation of this type of engine machinery, but also to use as a point of reference in refining the AM engine design concept. The JetCat P400-Pro engine, an engine popular with remote control aircraft enthusiasts and capable of 425 N of thrust force, was selected due to its availability and because its size was appropriate for adapting to AM. The arrangement of the AM engine was very similar to the JetCat engine layout, with the exception that significant part consolidation was possible within the AM engine and certain aspects of the AM engine geometry had to be adapted to the limitations of the AM process.

To ensure the functionality of the AM engine while also attempting to optimize the operational efficiencies of the design, computational fluid dynamics (CFD) analysis was used to further refine the engine design. Primarily, CFD was used to model the airflow and combustion cycle within the engine. An analytical understanding of the engine's performance characteristics drove an iterative design process. The three main stages of the engine, the compressor, combustor, and turbine, were analyzed separately initially to verify the individual performance of each and then later modeled as a system to ensure cohesive operation of the full engine. The analytical models are also how operational procedures for the AM engine were determined and they allowed for points of comparison when analyzing real world test data from the engine.

In addition, environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods. Cost modeling of the AM process compared to investment casting and machining manufacturing methods was also performed.

2.3. ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The main advantages related to the use of AM for producing micro-turbine engines have been alluded to but include a major reduction in waste & cost of manufacturing, a significant simplification of the engine design via part consolidation, and the potential for optimization of engine performance characteristics that would not be possible via designs produced by traditional means. These performance improvements might include improvements in the operational efficiency of the engines and reductions in environmental health & safety risks such as noise emissions.

However, there are some limitations related to the current state of available AM technology. One such limitation relates to materials available for use in the AM process. Within traditionally manufactured engines, specialized alloys developed to withstand the specific forces and high temperatures can be casted to form the parts that require these material characteristics. In the case of AM, some specialized materials are available, but are not as common as in traditional manufacturing. In addition, the same part consolidation that benefits the simplification of the engine design can be detrimental from a materials perspective as part consolidation leads to a one material fits all type of approach. A second current limitation of AM relates to the rough surface finish inherent to parts produced by the DMLS process. In traditional engines, a smooth surface finish is considered critical so as not to disturb the flow of air or exhaust gas in various areas of the engine. Rough surface finishes in areas of the AM engine could be detrimental to the efficiencies of the engine, but the full effect is still being investigated. And one final limitation relating to both the previously mentioned materials and surface roughness issues, is the lack of understanding of how well-suited additive materials are for high-speed rotational applications. The AM engine was specifically sized to maintain a max operating speed of well under 100,000 revolutions per minute (RPM), but many smaller micro-turbines do spin well above that speed. Fatigue failure is the most common type of failure for rotating engine hardware due to the exceptionally high rotational forces experienced and because the parts must operate at extreme temperatures. Higher surface roughness is also known to be significantly detrimental to the fatigue life of components. So, in the case of additive being used for such parts, the lack of specialized alloys combined with that of the surface finish issues inherent to the process becomes a serious concern for the longevity of the rotating components. Other limitations do exist, but these are the main ones that had to be overcome for this program to be successful.

3.0 PERFORMANCE OBJECTIVES

The following performance objectives were identified as the key to the demonstration of the AM micro-turbine for use in future DoD applications:

1. Demonstrate the operability of the AM micro-turbine engine. Test the engine throughout its full operating range to show the applicability of the engine for various applications.
2. Demonstrate the cost & environmental benefits associated with the use of AM to produce a micro-turbine engine.

The first objective was demonstrated by quantitative measurement of key engine operational characteristics and achievement of other qualitative objectives as outlined in Table 1. Due to setbacks experienced during the demonstration effort, multiple performance objectives have not been verified to date and further testing efforts are needed before results can be reported. Details regarding the demonstration setbacks are described in the performance assessment section of this document. The second objective was achieved via completion of a study on the cost and environmental impacts of producing the AM engine. The goal of this study was to understand the ability of the engine to meet the objectives outlined in Table 2.

Table 1. Engine Operation Performance Objectives

Performance Objective	Data Requirements/Test Methods	Success Criteria	Results
Quantitative Performance Objectives			
Thrust (N)	• Measured at max power (~76k RPM) • Via Loadstar® RAS1 S-type Load Cell on custom built thrust stand	Comparable to CFD prediction*	Further testing required
Thrust Specific Fuel Consumption (TSFC) (kg / N hr)	• Measured at idle (~30k RPM) and max power (~76k RPM) • Via AliCat MCR-2000 Mass Flow Controller	Comparable to CFD prediction* and commercially available micro-turbine**	Further testing required
Sound Pressure Level (dB)	• Measured at idle (~30k RPM) and max power (~76k RPM) • Via Rode VideoMic high quality directional microphone	Comparable to commercially available micro-turbine*	Further testing required
Qualitative Performance Objectives			
Engine start-up procedure established	• Procedure to reach idle speed (~30k RPM)	Fuel feed rate and ignition RPM shown to be repeatable	Successful
Stable engine operation achieved	• Stable operation shown at idle (~30k RPM), 50% power (~38k RPM), and max power (~76k RPM)	Engine speed maintained for at least 5s at each point without fuel feed rate adjustment	Successful for idle and 50% power conditions. Max power result - further testing required
* CFD analytical predictions developed by Belcan ** JetCat P400-Pro used as comparable commercially available engine for performance specs			

Table 2. Engine Manufacturing Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Reduction of hazardous waste generated	Analysis of hazardous waste generated during manufacturing	Show reduction from traditional engine process*	Successful
Reduction of manufacturing costs	Analysis of cost of manufacturing methods	Show reduction from traditional engine process*	Successful
Reduction of manufacturing lead time	Lead time for manufacturing engine	Show reduction from traditional engine process*	Successful
Qualitative Performance Objectives			
Reduction in manufacturing complexity	Reduction in manufacturing sites and number of processes	Show reduction from traditional engine process*	Successful
Ease of assembly	Demonstrate reduction in assembly steps	Show simplification over traditional engine*	Successful
* Pratt & Whitney TJ-150 engine used for manufacturing comparison			

4.0 SITES / PLATFORM DESCRIPTION

4.1. TEST PLATFORMS / FACILITIES

Early testing of the AM micro-turbine took place at the Air Force Research Laboratory (AFRL) Small Engine Research Lab located at the Aerospace Systems Directorate at Wright-Patterson Air Force Base, OH. However, due to construction at this facility the testing had to move to an alternative test location. The remainder of testing was conducted at the Air Force Advanced Technology Training Center (ATTC) located on East River Road in Dayton, OH. In order to test at this location, a custom mobile test stand was developed. The mobile test stand included fully self-contained operational controls and data collection capabilities. The mobility of the cart allows for broad collaboration and flexibility in test and demonstration locations. The engine and mobile test stand can be seen in Figure 3.

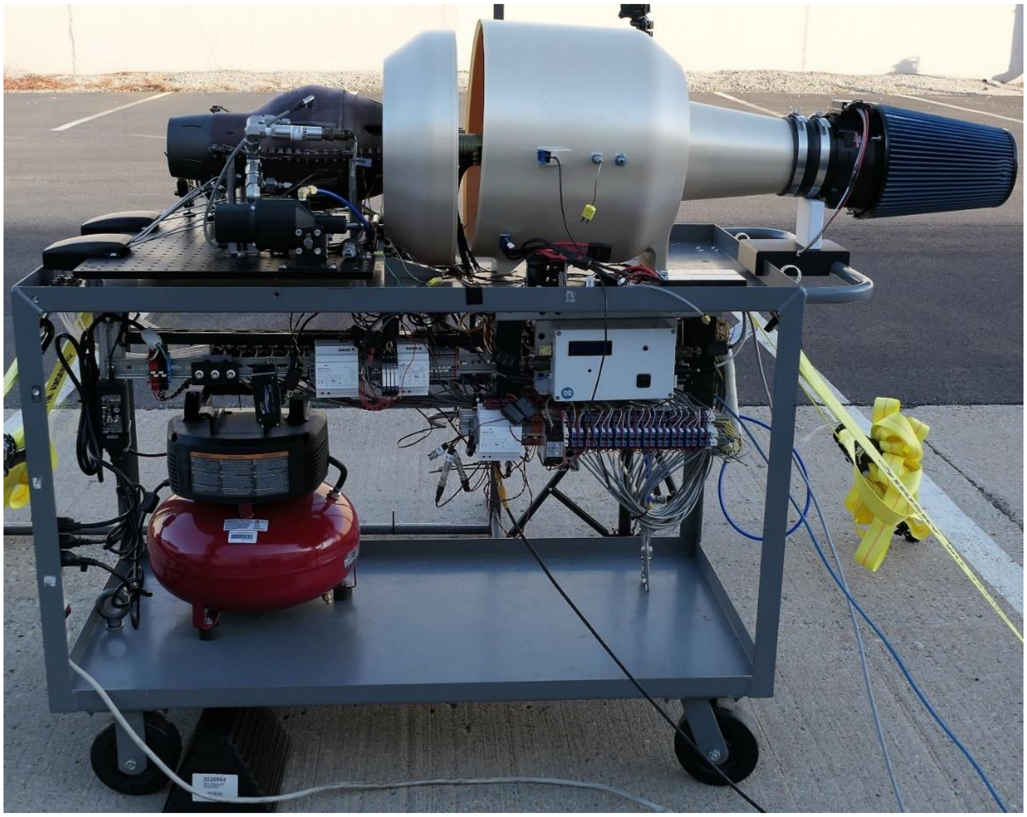


Figure 3. Mobile Engine Test and Demonstration Stand

While it has been discussed that micro-turbines have both air and land power applications, for the purposes of this effort the decision was made to demonstrate the AM micro-turbine for aircraft power applications only. Thus, the demonstration effort focused on validation of the engine's thrust generation ability. While testing of the engine for ground power applications was not completed, it is possible to infer how the AM micro-turbine might perform in these applications given engine performance data collected from this demonstration configuration.

A full test plan was developed to characterize the performance of the AM engine. The steps required to demonstrate the capabilities of the engine can be summarized as such:

1. Dry running (no combustion) the engine to verify the ability of the compression section to draw in and compress air for the combustor.
2. Start procedure testing to establish a stable and repeatable ignition sequence for the engine.
3. Acceleration testing to define the fuel feed rate schedule for the engine at various operating speeds.
4. Performance mapping of the engine to characterize engine performance characteristics throughout its entire operating range.
5. Steady state testing of the engine to demonstrate stable operation of the engine for extended run times.

Completion of these milestones is an important step in being able to compare the AM engine to existing engines and also in determining appropriate applications for this technology. Steps #1-3 had been completed and are reported on in this document. Steps #4-5 were unable to be completed during this demonstration effort. Difficulties were experienced due to damage to certain components caused by overheating the engine when running at higher speeds (and higher fuel feed rates). Replacement test articles had to be manufactured and adjustments made to the test facility controls which led to a delay and ultimately prevented completion of the full test plan prior to issuing this report. While unfortunate, this was not surprising given the novel nature of this engine and the learning curve associated with operating it at its upper limits. Further efforts are required to complete the full test plan.

4.2. PRESENT OPERATIONS

From a manufacturing standpoint, AM is meant to replace several different traditional manufacturing methods that are currently in use to produce jet turbine components. Engine manufacturers employ both investment casting and sheet metal forming processes to create many of the engine components. These components then also typically require significant post-processing operations such as machining of critical features. Finalized components are then assembled into the full engine assembly and tested for functionality. All of these production steps are typically done at different facilities and often by different entities, so shipping is required between each stage. A flowchart of the traditional engine manufacturing process is shown in Figure 4. In comparison, the use of AM for producing micro-turbines presents the opportunity for printing, post-processing, and assembly of components to all be done in one location. Thus, AM could significantly reduce supply chain complexity, environmental emissions, engine cost, and the lead time to produce engines.

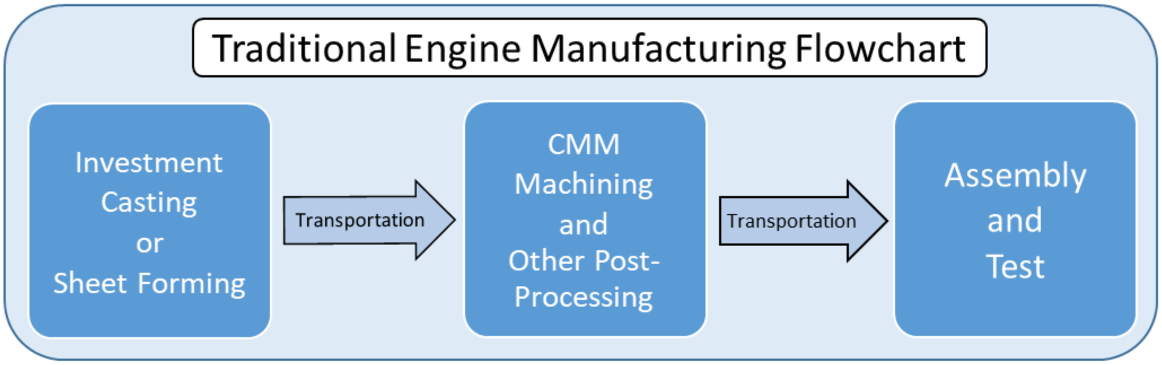


Figure 4. Traditional Engine Manufacturing Flowchart

In terms of application of the engine itself, similar engines, such as the Pratt & Whitney TJ-150, are used for expendable, short life operation vehicles such as missiles and UAVs. The TJ-150, seen in Figure 5, is a small turbojet engine that utilizes a single stage compressor, combustor, and single stage turbine to produce a max thrust of just over 667 N. It has an expected engine runtime life of up to 2 hours and can produce up to 2.0 kW of energy when paired with generator.[1] The design of the AM micro-turbine is similar in that it also utilizes a single stage compressor and single stage turbine to produce roughly 632 N at max power. Given some of the technology limitations discussed in earlier sections of this document, it is believed that the AM engine components may suffer from durability issues and thus would also be appropriate for short runtime life applications. And based on the similar thrust rating of the AM micro-turbine, it's assumed that when paired with a generator the AM engine could produce similar energy levels as that of the TJ-150 engine.

Figure 5. Pratt & Whitney TJ-150 Turbojet[1]

Miniature Air-Launched Decoy, or MALD, missiles are one of the most popular applications of these miniature turbojets. Signal jammer and decoy variations of these missiles exist, but payload carrying versions of this missile type are also in development and would utilize a common power source. The Selective Precision Effects At Range, or SPEAR, tactile strike missile system is another current application for engines of this type. USAF demand for these missiles and thus small turbojet engines is expected to grow significantly in the coming years. Interest from the US Navy and from foreign militaries is expected to add to the demand. With an AM engine offering a simplified supply source and similar or even improved performance characteristics, it could help meet this growing demand.

Figure 6. MALD Decoy Missiles[2]

4.3. SITE-RELATED PERMITS AND REGULATIONS

None required.

5.0 TEST DESIGN

5.1. CONCEPTUAL EXPERIMENTAL DESIGN

Due to the complex nature of engine technology development and the difficulty of testing the technology on a real-world application platform, only laboratory level testing was conducted for this project. However, as previously alluded to, performance of the engine in the laboratory environment will provide sufficient data to judge how well the AM micro-turbine might perform in an applicable system level environment.

As discussed in Section 4.1, the engine needed to be tested throughout its full operating range to characterize its performance. This included testing from low-speed idle conditions up to its high-speed max power. To judge the engine's performance against the objectives defined in Section 2, systems were designed to measure engine thrust, fuel consumption, and noise emissions during operation. In addition to these characteristics, systems were developed to measure mass airflow through the engine, temperatures and pressures throughout the engine, and vibration of the engine. These data monitoring and collection systems were built into the mobile test stand previously shown and are what allowed for a larger understanding of the engines performance.

The methodology for characterizing the engine operation was detailed in Section 4.1, but it is also outlined below in Figure 7.

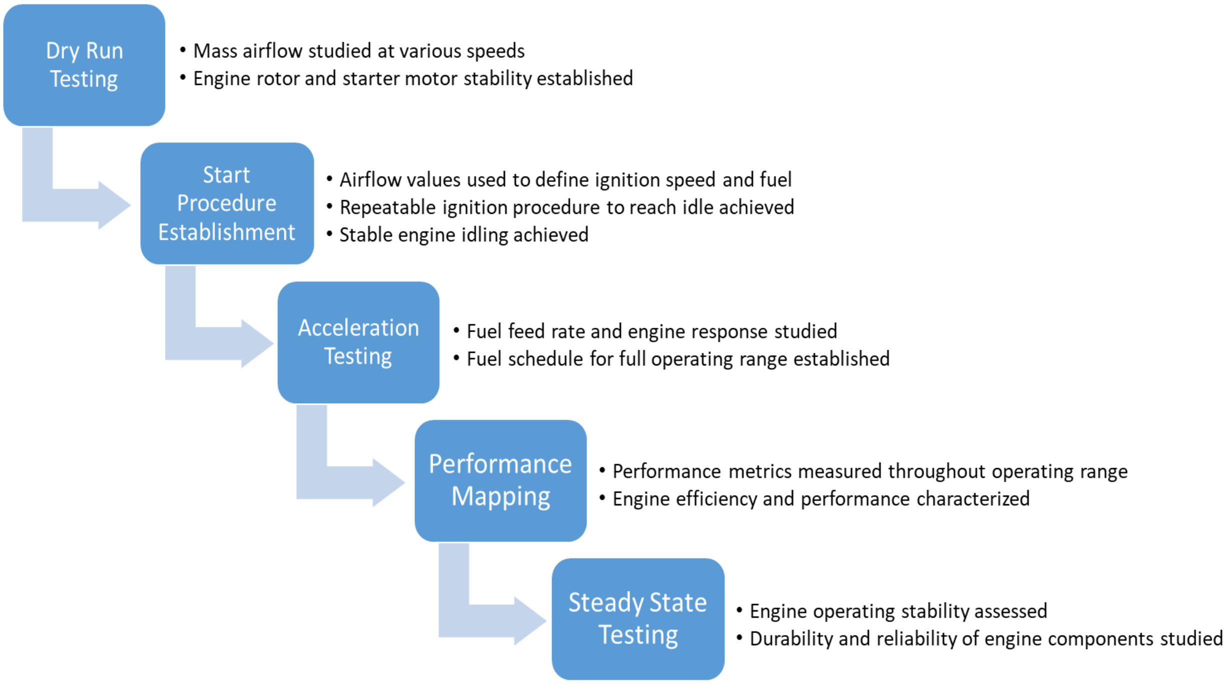


Figure 7. AM Micro-turbine Test Methodology

The test methodology included a step-by-step approach that began with establishing how to operate the engine in a safe and repeatable manner followed by pushing the engine to its operating limits to collect performance data at its extremes. The first step included dry (no fuel) spinning of the engine rotor to study airflow through the engine. This led to the discovery of the proper fuel feed rate to establish a repeatable ignition sequence and the successful idling of the engine. After this acceleration testing was done to establish fuel feed rates for the full operating range of the engine. With this performance mapping of the engine could begin which would include data collection of the various operating characteristics previously mentioned throughout the engines operating range. Collection of this data would allow for understanding how well the engine was meeting its quantitative performance objectives. Steady state testing is to be done after the performance mapping testing to qualitatively assess the engine stability and durability. Performance mapping and steady state testing was unfortunately unable to be completed during this effort due to delays experienced during testing.

5.2. PRE-DEMONSTRATION TESTING AND ANALYSES

Prior to testing of the AM micro-turbine, testing of a commercially available JetCat P400-Pro micro-turbine engine was completed. The JetCat engine was tested on the test stand developed for the AM micro-turbine and in the same environment that the AM engine was to be tested. Via these pre-demonstration efforts, the project team was able to validate several aspects of the test setup design including thrust measurement and engine noise measurement. The JetCat engine on the test stand is shown in Figure 8.

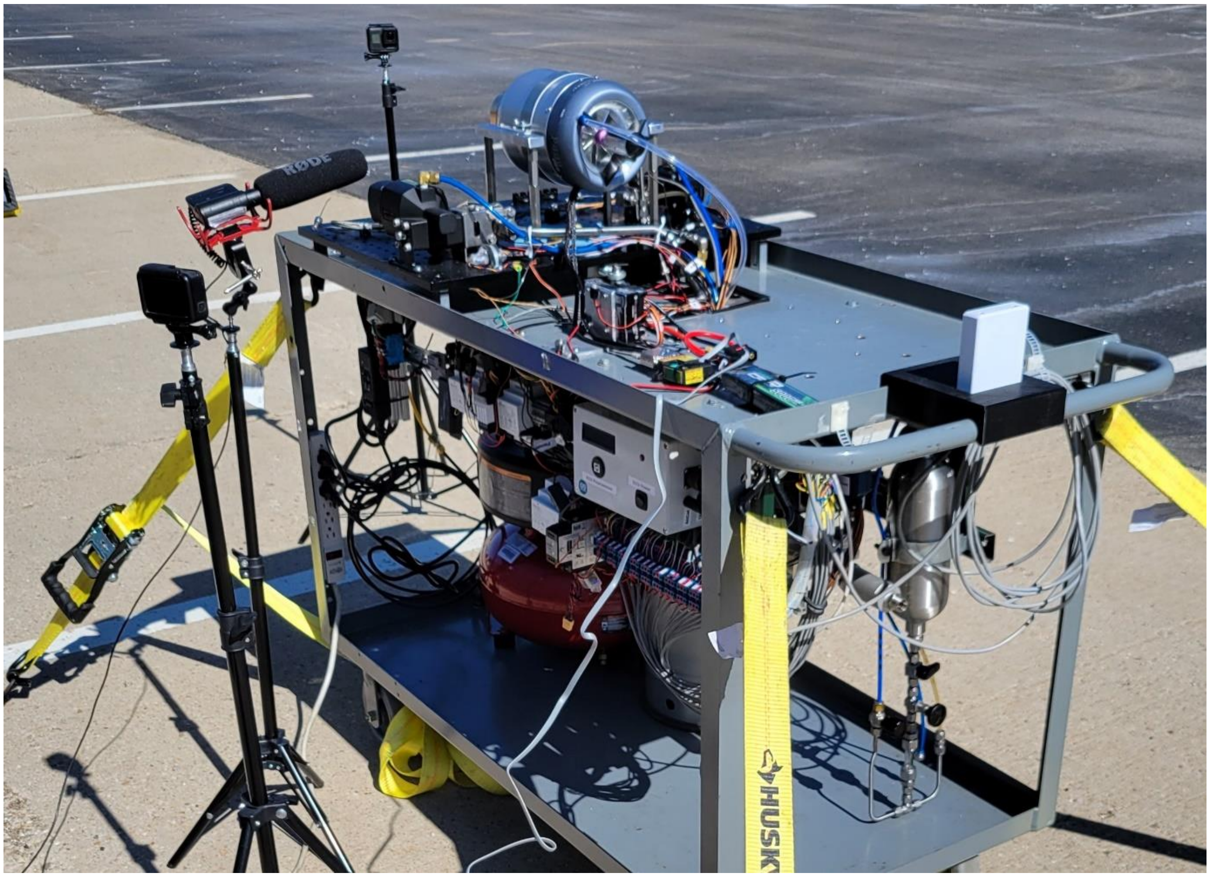


Figure 8. JetCat P400-Pro on Mobile Test Stand

In addition to this validation of the test setup, significant CFD analysis was done to validate the design & performance of the AM micro-turbine. Analysis of the compressor section of the engine was critical to understanding and validating the volumetric flow of air through the engine, which as previously noted was critical to establishing ignition and idling procedures. In addition, simulation of the combustion section of the engine helped establish the fuel feed rates for the engine and also helped ensure temperature distributions in the engine were safe and appropriate for the materials being used in the engine construction. And finally, an analysis of the engine as a whole and the interactions between the different engine stages verified that the engine design would be self-sustaining and showed what kind of efficiencies and thrust could be expected from the engine. Snapshots from the various CFD analyses completed are shown in Figure 9.

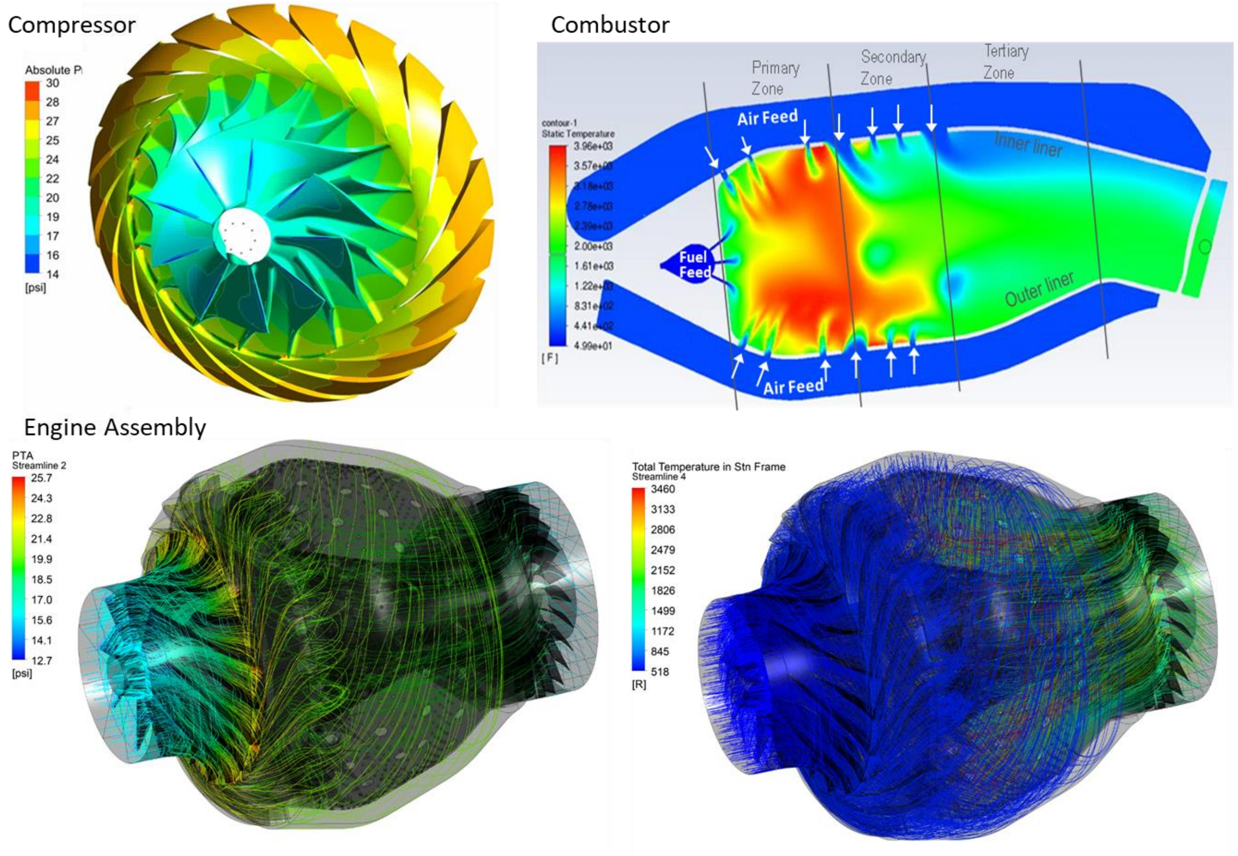


Figure 9. Engine CFD Analysis

5.3. DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1. AM Micro-turbine

The AM engine consists of four main printed components including the engine housing, rotor, nozzle, and starter motor mount. The engine housing was manufactured as one component, but then cut in half to form a clamshell style design enabling assembly of other components to the internals of the housing. Bolted flanges on the side of the engine housing allow for reassembly of the two halves. There are three main sections of the engine that support the engine cycle: the compression section, the combustor, and the turbine section. In addition to the printed hardware, the engine consists of two ceramic ball bearings that support the rotor, an electric motor to support startup, and miscellaneous hardware for assembly of the components. An outside view along with a centerline section view of the engine model are provided in Figure 10. The various components and sections of the engine are called out in these images.

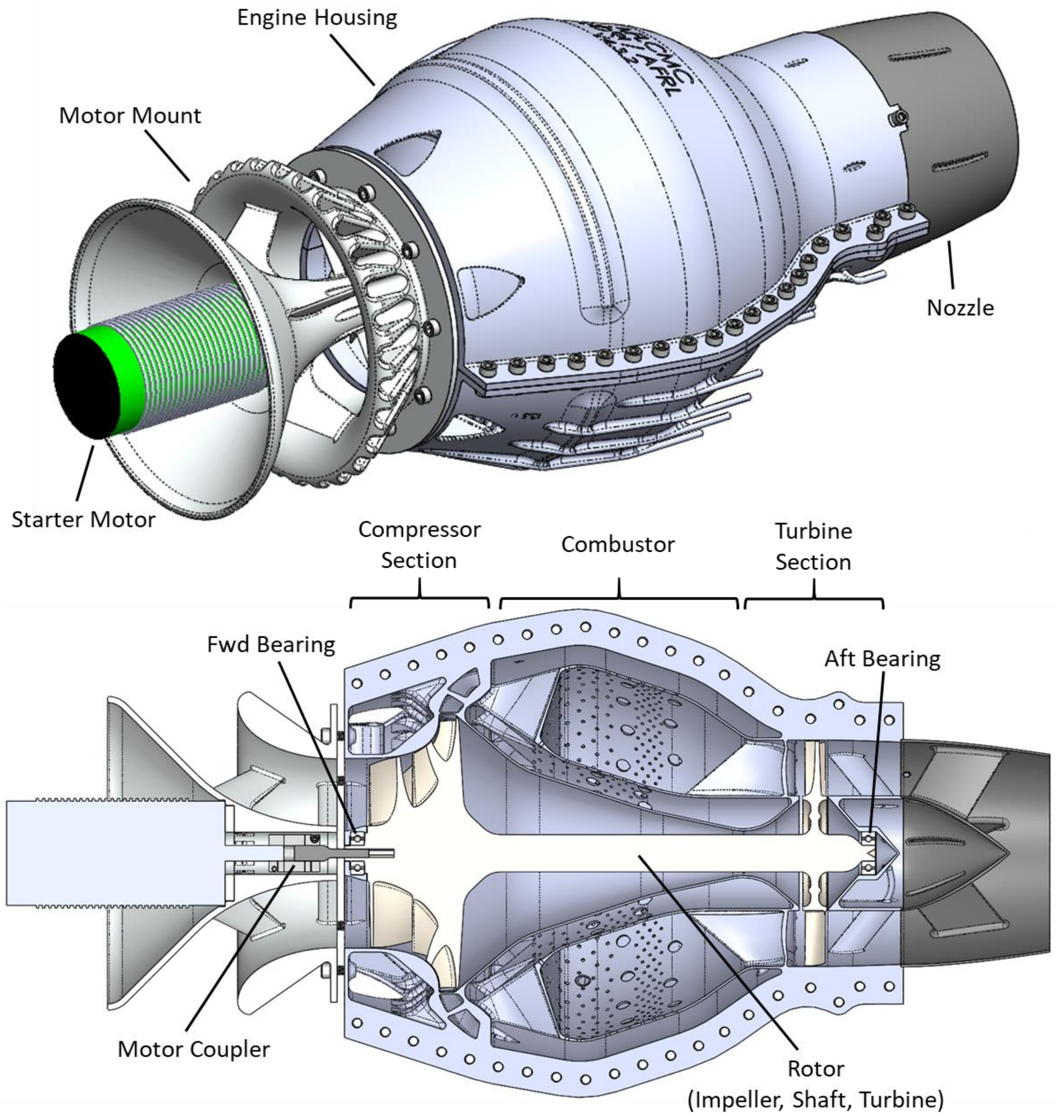


Figure 10. Engine Assembly Model Views

The engine starter motor, seen on the far left of Figure 10, supports startup of the engine by spooling the engine rotor to the proper ignition speed. The motor has a drive shaft that is coupled directly to the engine rotor. The motor's brushless design allows it to free spin when powered off and remain engaged with the engine during operation without creating any additional resistance to the engine's rotor. The motor mount is assembled to the forward face of the engine housing and supports the starter motor. The motor mount also serves as a radial inlet duct for air flowing into the engine. The radial duct shape was utilized to take the starter motor out of the engine inlet airflow path preventing disturbances that might have been caused by airflow passing over the motor.

The compressor section draws air into the engine. The compressor is made up of a split vane centrifugal impeller followed by a diffuser. The impeller is part of the larger engine rotor and is connected to the engine turbine via a drive shaft. As the rotor spins the impeller draws air into the engine and compresses it forcing it through the diffuser channels. The diffuser channels, incorporated directly into the engine housing, change the direction of the air flow from the impeller directing it into the combustor while also attempting to maintain the pressure rise achieved by the impeller compression. The impeller and diffuser fluid volume shape is shown in Figure 11.

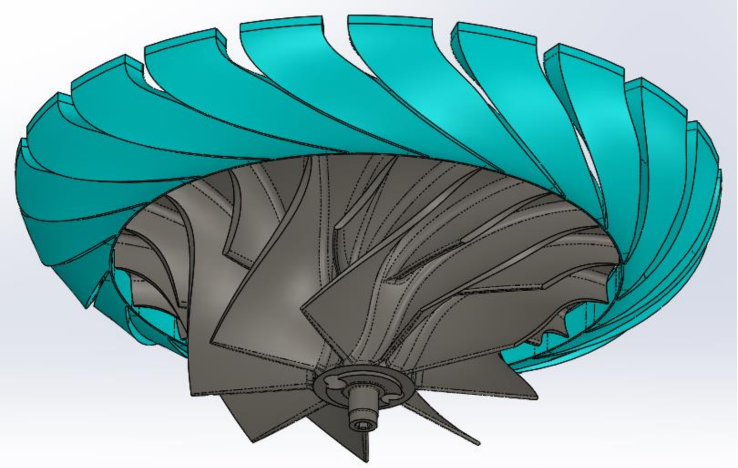


Figure 11. Engine Impeller and Diffuser Geometry

Incorporation of the diffuser geometry into the engine housing is visualized in Figure 12.

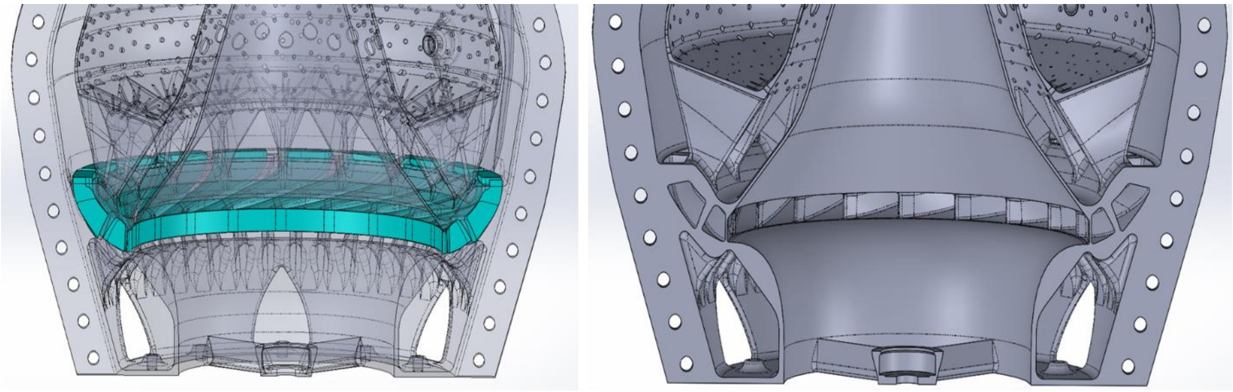


Figure 12. Diffuser Incorporated in Engine Housing

The combustion chamber of the engine is also directly incorporated into the engine housing. The chamber is comprised of an inner and outer liner wall both of which have patterns of perforations that allow for the air injection required by the combustion cycle. A section view of the combustion chamber is shown in Figure 13.

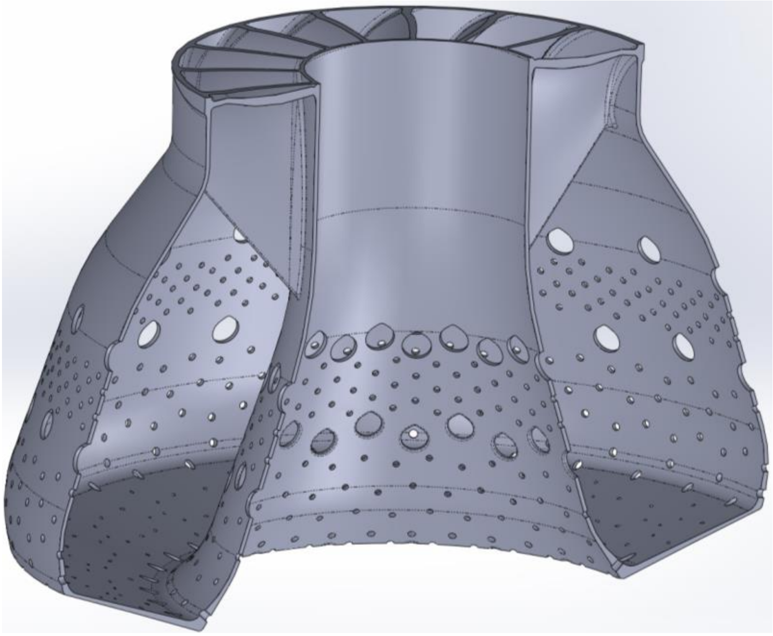


Figure 13. Combustion Chamber Section View

Fuel inputs are also needed to support the engine combustion cycle. Fuel is fed into the combustion chamber from a network of channels breaching the bottom surface of the combustor liner. These channels are fed via a fuel manifold made up of additional internal channels within the engine housing, which is supplied with fuel from ports on the outside of the engine housing. There are two separate manifolds and feed ports, one for each half of the engine housing, to ensure full radial supply of fuel to the combustion chamber. Figure 14 shows the fuel manifold geometry and how it is positioned within the engine housing component.

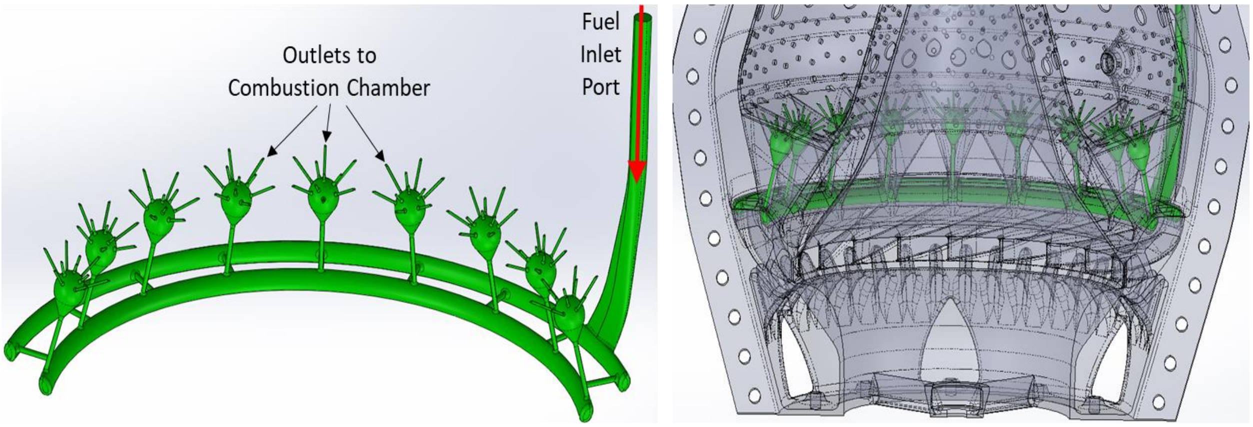


Figure 14. Fuel Manifold Geometry (Left) and Location in Engine Housing (Right)

Gases produced from the combustion process are ejected out the open end of the combustion chamber and pass through the turbine section of the engine. The turbine section is made up of a diffuser, which was also incorporated directly into the engine housing, and a turbine wheel, which again is part of the larger engine rotor. Airfoils of the diffuser direct the combustion exhaust gases into the turbine wheel airfoils in a manner that results in the rotation of the turbine wheel and rotor, which drives the impeller in the compression section at the front of the engine. A section view of the diffuser and turbine geometry is shown in Figure 15.

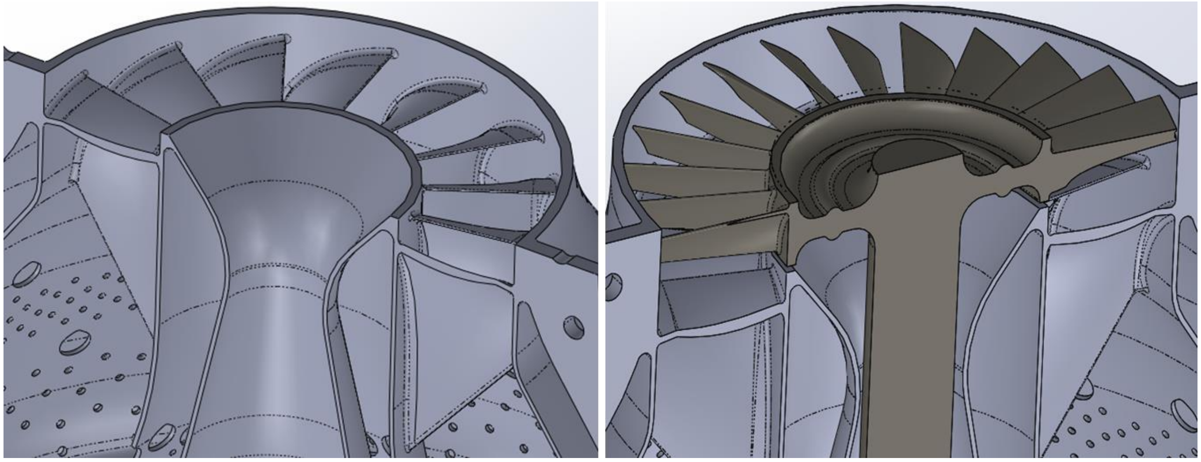


Figure 15. Stator and Turbine Section Views

Beyond the turbine section of the engine, the exhaust gases pass through the engine nozzle at the tail end of the engine. The nozzle mounts directly to the engine housing and was modeled after other stock nozzles for similar commercially available engines. Alternative nozzle geometries that could aid in optimizing thrust generated and reducing engine noise emissions have been studied, but have not been tested yet and are not presented in this document. The baseline nozzle design and a section view of how it is fitted to the engine housing are presented in Figure 16.

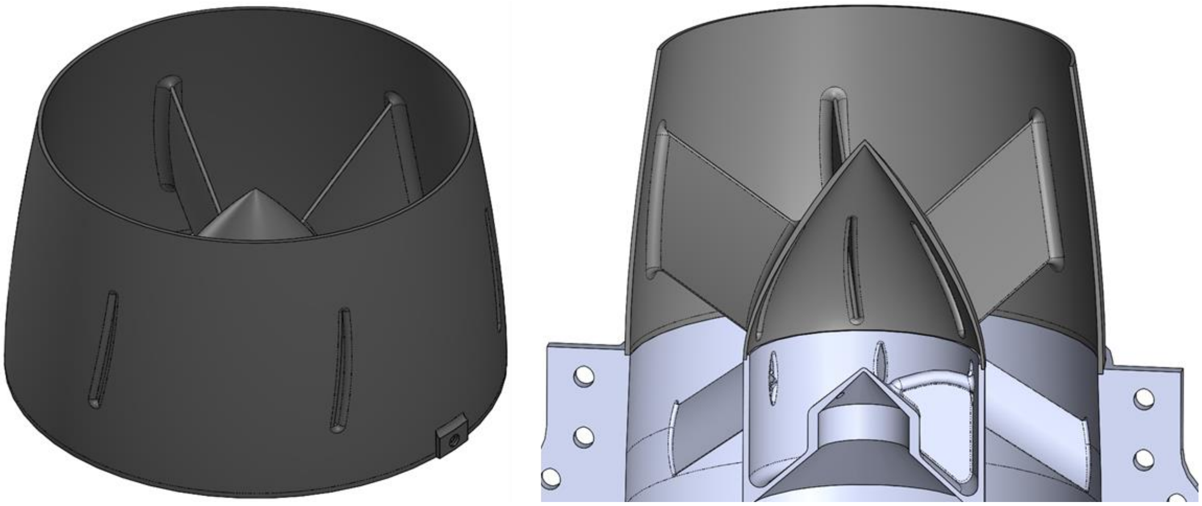


Figure 16. Engine Nozzle

As previously stated, two bearings are used to seat the engine rotor within the housing. Commercially available angular contact ball bearings from Boca Bearings Inc. were utilized. They are ceramic hybrid bearings, having stainless steel retainer rings and ceramic balls, which allow the bearings to operate in high temperature environments and withstand very high speeds. The bearings used are the same as those used in other commercially available engines. Figure 17 shows how the forward and aft bearing are positioned on the rotor and within the engine housing.

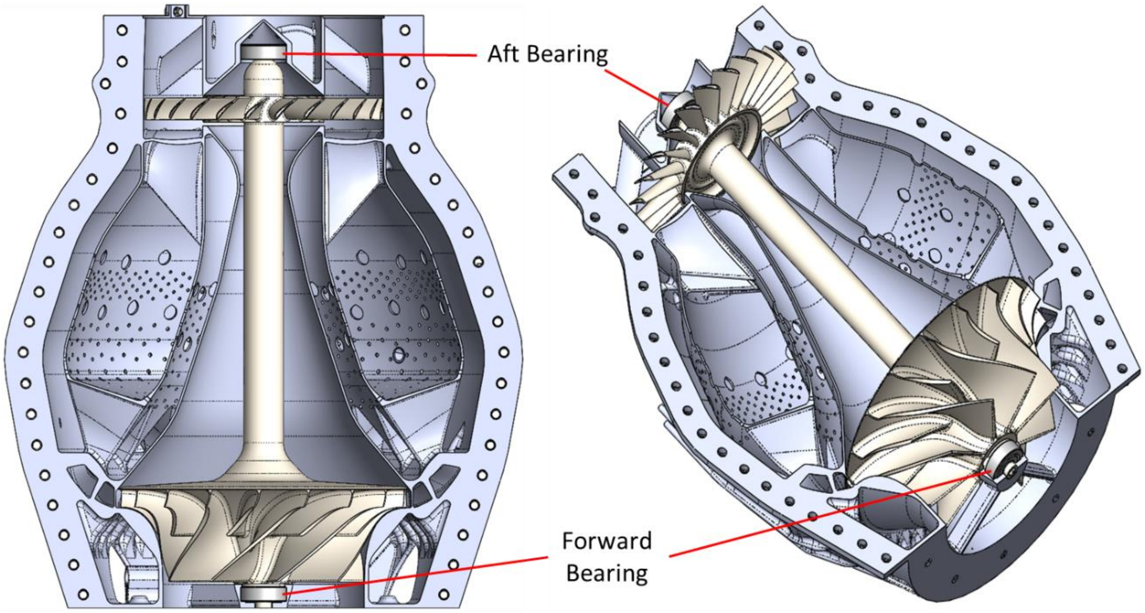


Figure 17. Engine Bearing Positions

After seating of the rotor with bearings into the engine housing, the second half of the housing is seated over top of the rotor enclosing it in the housing. The two halves of the housing are then bolted together and the nozzle and motor mount are bolted to the housing. The starter motor is bolted to the motor mount and the motor shaft is coupled to the impeller end of the rotor via a hex shaft as shown in Figure 18. Complete assembly of the engine can be completed in under an hour.

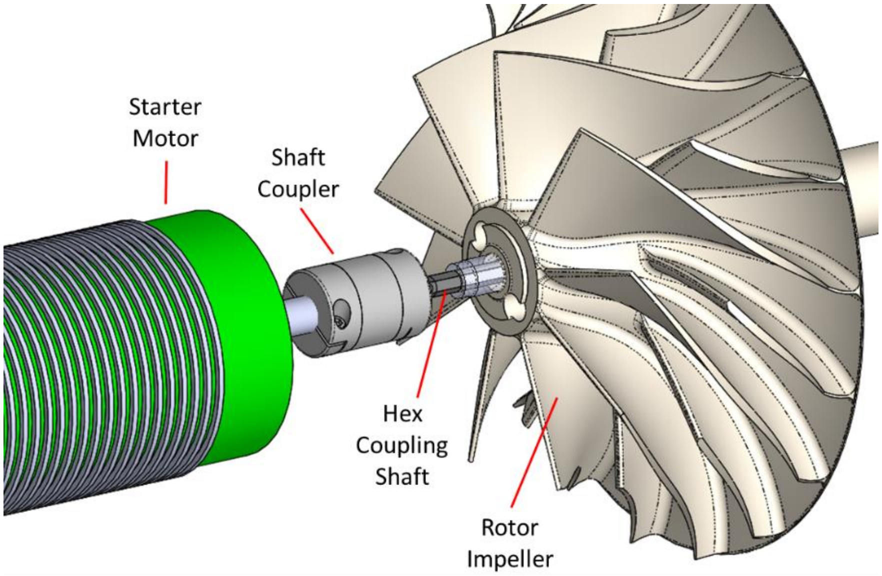


Figure 18. Starter Motor and Rotor Coupling

5.3.2. Test Stand

In order to facilitate the test requirements of a rapidly evolving printed engine, the test apparatus and its capabilities needed to be just as flexible. A mobile test, evaluation and demonstration stand, seen in Figure 19, was developed to fulfill this requirement to include fully self-contained operational controls and data collection capabilities. The mobility of the stand allowed for broad collaboration and flexibility in test and demonstration locations. The engine is operated through a custom control panel complete with real-time data feed and controls for the shut-off valves, electric starter and throttle, and an emergency shut-off.

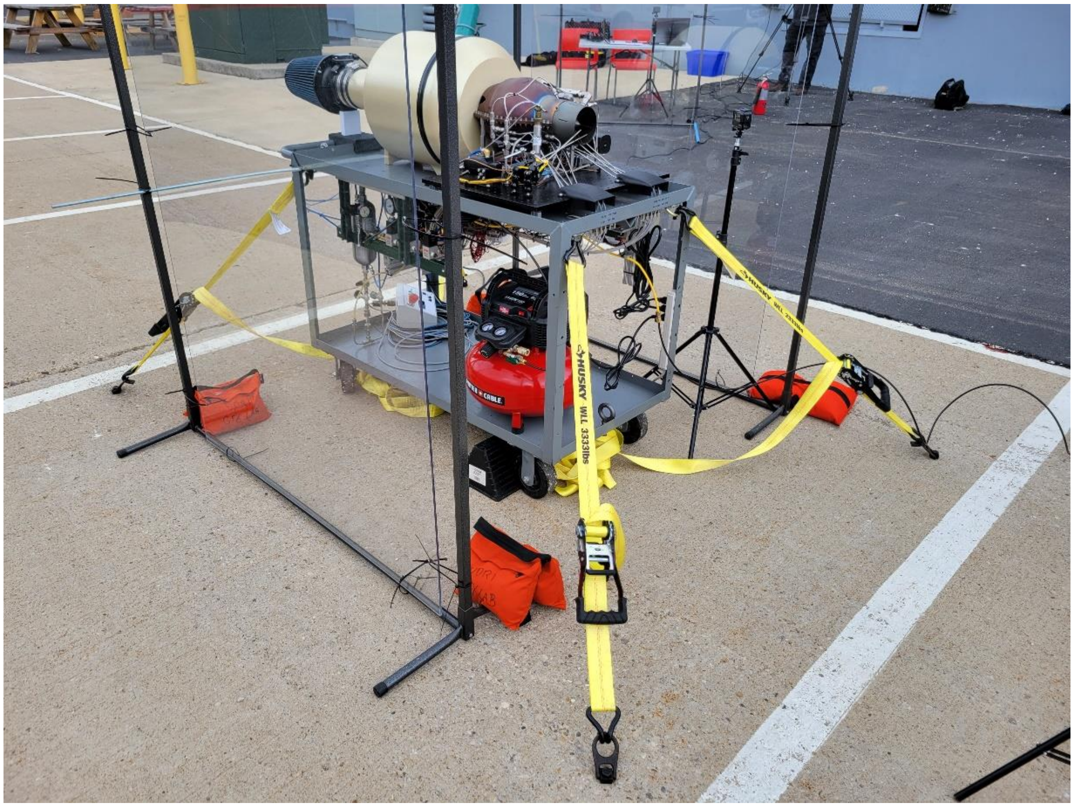


Figure 19. Mobile Engine Test Stand Setup

The test stand is outfitted with a data collection system for all onboard temperature, pressure, and vibration sensors. The stand is also fitted with a bearing lubrication feed system and a fuel flow controller capable of both controlling fuel feed rates, but also recording fuel feed rate data. Built into the test stand is a thrust stand on which the engine is mounted. The thrust stand utilizes a frictionless single axis of motion setup and S-type load cell to measure thrust generated by the engine.

Testing was conducted outdoors at the ATTC in Dayton Ohio. For the purpose of performance calculations, the temperatures ranged from 30-50°F, with 70-80% RH, at an altitude of 731’ above sea level. Precise temperature, humidity and barometric pressure conditions are captured at the time of each test. Ambient winds are not considered significant for the purposes of these tests because if they were high enough to impact the engine performance, testing would not be conducted. The cart is secured to a concrete pad and the control systems are situated on a table approximately 20' away behind two layers of polycarbonate.

5.4. FIELD TESTING

At the time of writing this report, testing at the idle condition and up to 43,000 RPM had been completed. The discussion in this section is limited to verification of the engine operational characteristics against the previously established analytical model at these lower speed operational points completed to date.

5.4.1. Idle Condition

The idle condition was held for 20 seconds to allow the engine to normalize so data could be recorded prior to decelerating the engine and shutting it down. After shutdown, the engine was disassembled to check for any damage or other issues; no concerns were found. Results for the idle condition are shown below. Figure 20 documents that the engine was indeed self-sustaining running on fuel alone after the starter motor was turned off. Figure 21 plots the various temperatures throughout the engine while it was running, while Figure 22 shows pressures.

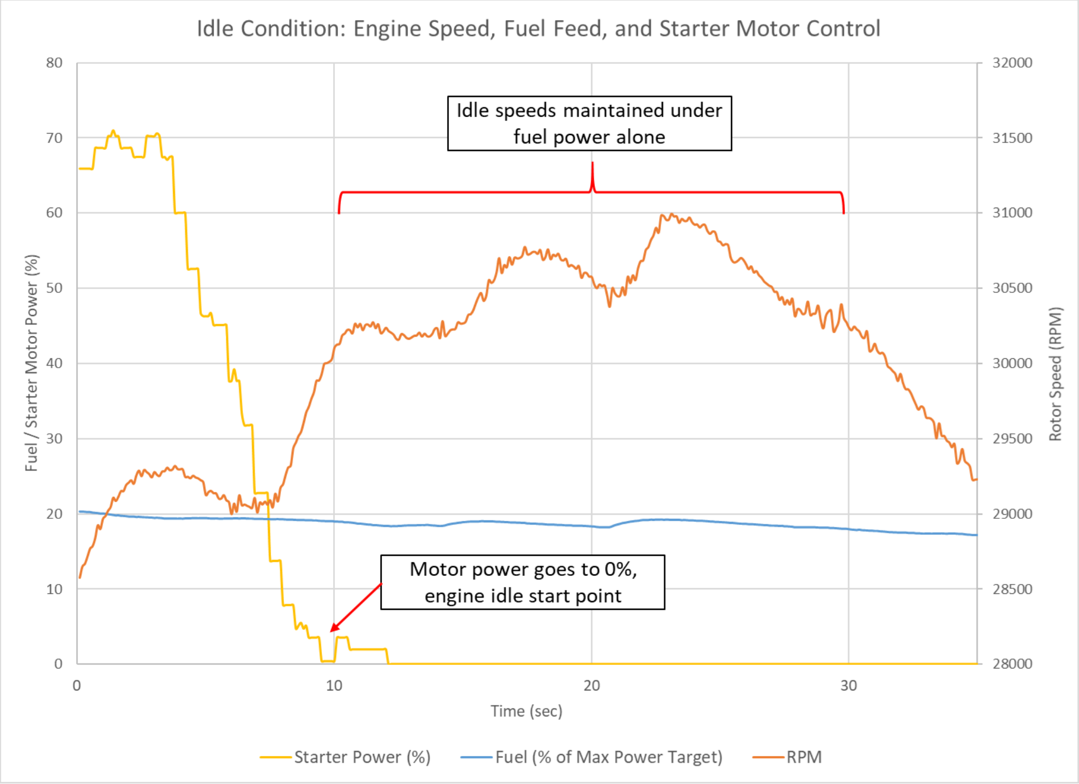


Figure 20. Idle Condition: Engine Speed, Fuel Feed, and Starter Motor Control

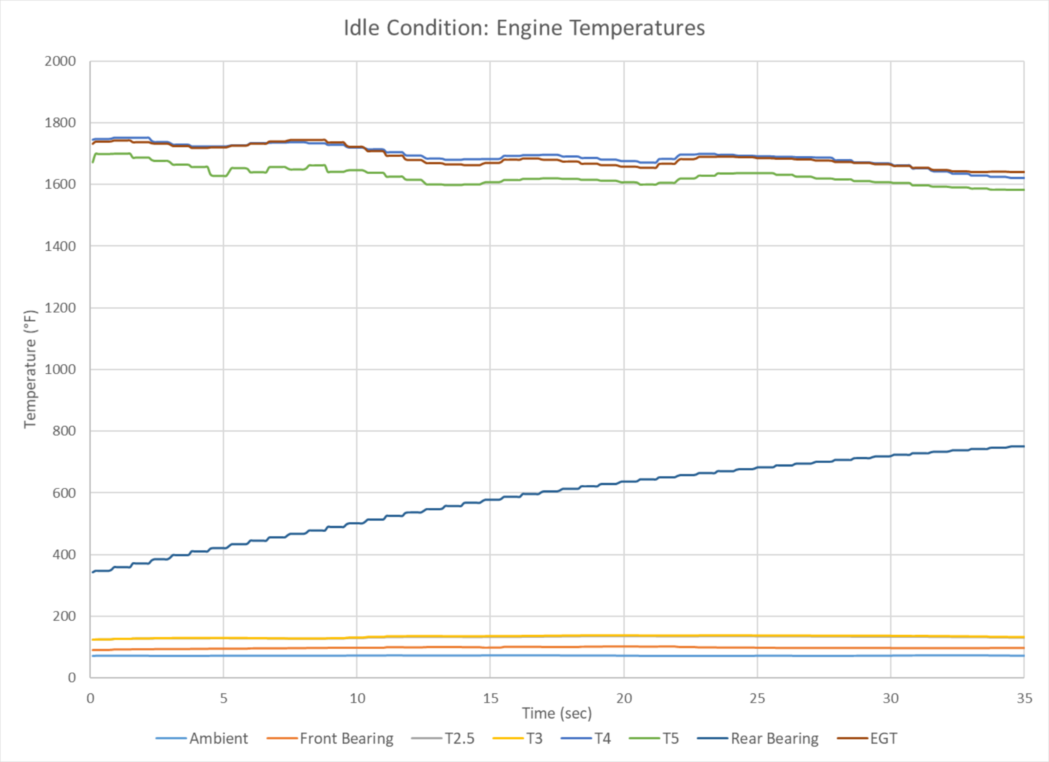


Figure 21. Idle Condition: Engine Temperatures

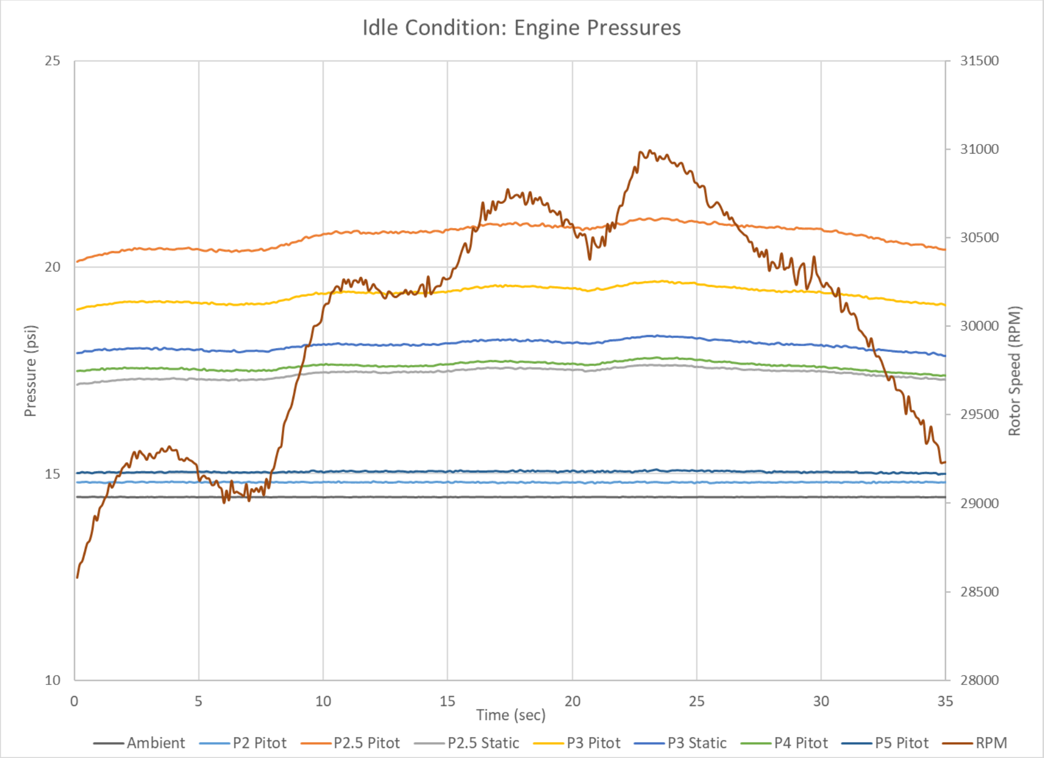


Figure 22. Idle Condition: Engine Pressures

From the idle condition data a few observations were made:

1. The idle fuel feed rate of 0.016 lbm/s of ethylene is exactly in line with what was predicted from the analytical model, however the mass airflow rate was lower than the 0.93 lbm/s expected reaching only 0.7 lbm/s.
2. Engine pressures are in line with the model predictions especially the pressure rise due to the impeller. A 1.46 pressure ratio was observed through the compressor section impeller, nearly matching the 1.47 value predicted.
3. The combustor temperatures are running slightly higher than expected, but do seem to stabilize at just under 1700°F. The turbine is doing the work required of it indicated by the temperature difference from the combustor outlet (T4) to the turbine outlet (T5).
4. These results were repeatable, as multiple runs at the idle condition were achieved and data values were comparable between runs.

No unusual vibration or damage was noted during idle operation. It was noted, however, that the rear bearing temperature rose quickly during test and ran higher than the bearing's rated max operational temperature. The team expected the rear bearing would see somewhat higher temperatures due to its position downstream of the engine turbine, but given that the bearing continued to operate at temperatures much higher than its design should allow the team hypothesizes there may be an issue with the measurement technique. The thermocouple used to monitor the rear bearing temperature passed through a channel in the engine housing to reach the rear bearing. The channel passes through the exhaust gas exit path and though it shrouds the thermocouple from direct contact with the gases, it's believed that the thermocouple is still being impacted by the high exhaust gas temperatures, thus it is reporting temperatures much higher than what the rear bearing is actually experiencing. This is a flaw in the current engine design layout and an alternative means of recording rear bearing temperature will need to be addressed in the future.

5.4.2. 50% Power (38,000 RPM) Condition

After successfully repeating idle operation, the engine was pushed to the 50% of max power condition or a speed of ~38,000 RPM. The engine was held at this operating point for a little over 12 seconds to collect data. There was a small one second drop in speed from the targeted speed during this duration due to a small interruption in the fuel pressure caused by an issue with the test equipment. The fuel pressure quickly recovered as did the fuel and engine operating set points. Temperature and pressure readings for this operating condition are reported below in Figure 23 and Figure 24, respectively. And again, no abnormal vibrations or damage were noted after running at this condition.

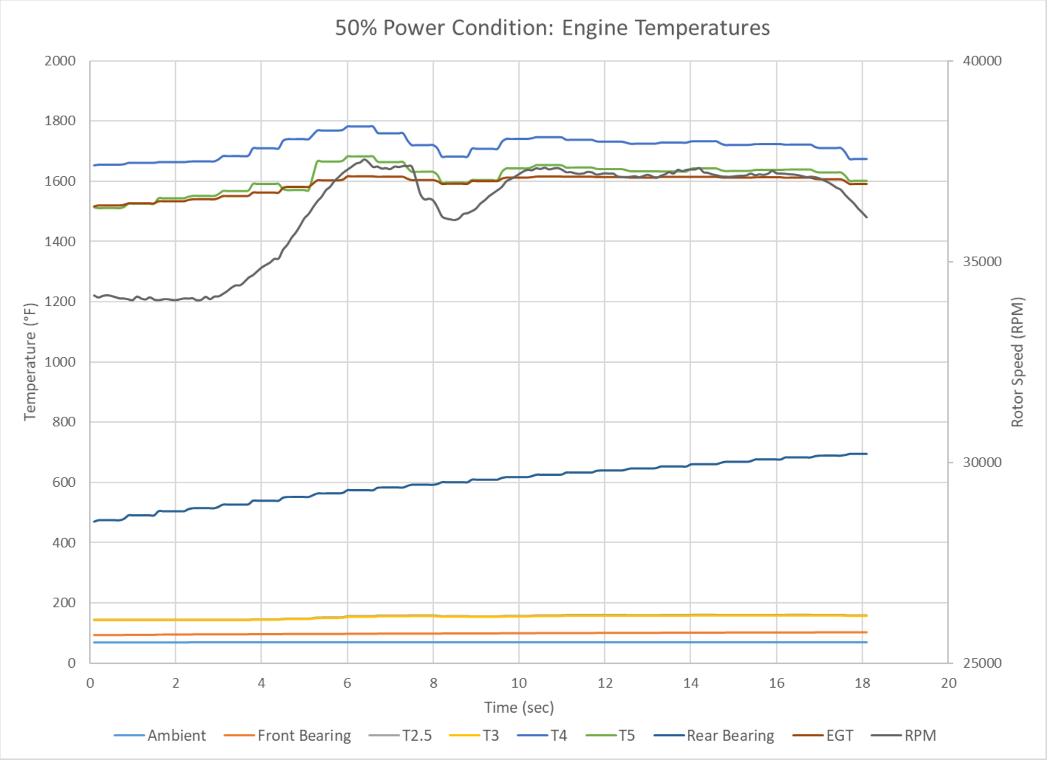


Figure 23. 50% Power Condition: Engine Temperatures

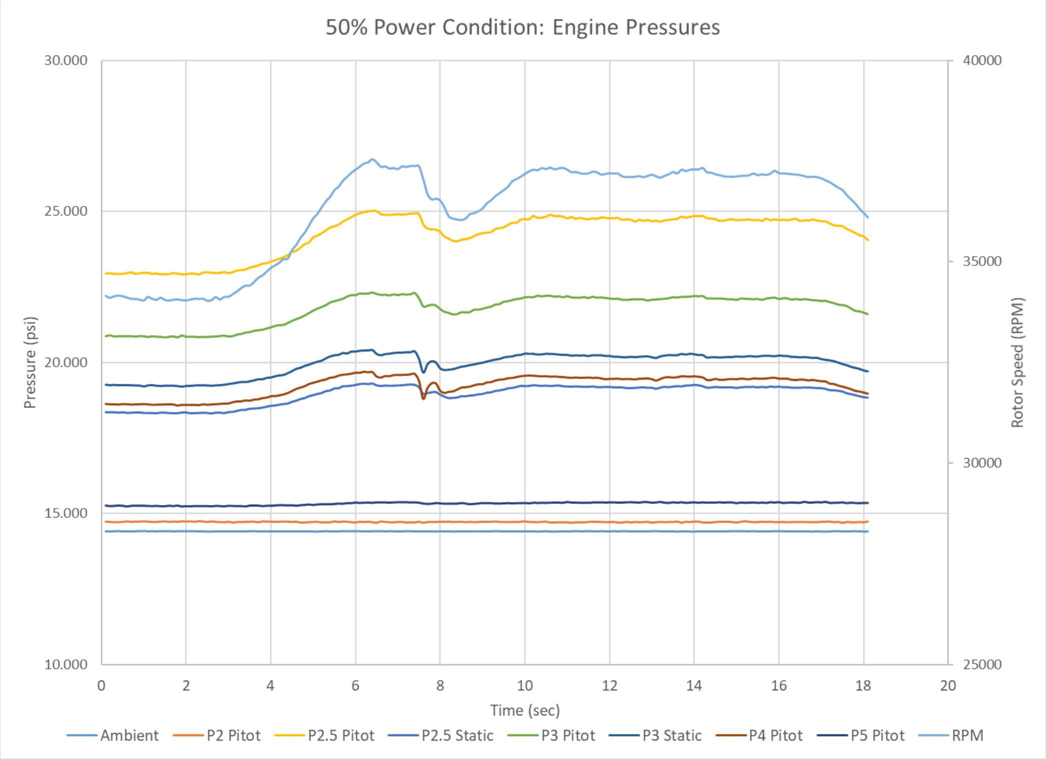


Figure 24. 50% Power Condition: Engine Pressures

Observations from the 50% power run include:

1. A fuel feed rate of .022 lbm/s was in line with the predicted fuel schedule, but again the mass airflow rate of 0.9 lbm/s was lower than expected.
2. Engine pressures still matched the predicted values very closely, with the impeller compression ratio predicted to be 1.80 and being measured at 1.75.
3. Temperatures were still operating at higher than expected levels, but the combustor operating temperature did appear to level out in the same range as what occurred at idle. This indicates the max temperature of the engine should be stable as the engine accelerates to even higher speeds. The turbine work is also increasing with higher speed as expected.

5.4.3. Acceleration Testing (Up to 43,000 RPM)

An attempt was made to accelerate the engine to higher speeds. Speeds of ~43,000 RPM were achieved prior to fuel inadvertently being added too quickly and the engine overheating. Upon overheating the rotor of the engine was damage requiring manufacturing of a new test specimen. However, before this damage occurred some data was collected for this operating point. At this operating condition the impeller pressure ratio rises to 2.02 nearly matching the predicted value of 2.08. However, the mass airflow value is still much lower than expected at 1.0 lbm/s. But, temperature drop through the turbine continues to grow again indicating that the turbine is performing additional work as the engine speed increases.

In addition to needing to print new test specimens after the test failure, an overhaul of the test stand fuel controls was conducted so as to prevent the same overheating issues from occurring in the future. Multiple delays were experienced manufacturing new test articles and the test control adjustments proved to be more time intensive than expected, which ultimately prevented further acceleration testing. And so the AM engine was not able to be tested to its max speed within the schedule allotted under this demonstration effort. This means judgement on the technologies performance related objectives can not be completed at this time. Future efforts are needed to complete the full docket of testing originally planned for the engine.

6.0 PERFORMANCE ASSESSMENT

As previously mentioned, field testing of the engine was unable to be completed by the time of writing this document so performance assessment here is limited to the tests completed to date. Without the full agenda of engine testing completed, it is difficult to fully assess the AM micro-turbine, but each performance objective, as outlined in Section 3.0, is discussed here.

6.1 Engine Thrust

Engine thrust has not been measured yet for the AM micro-turbine. On all test runs to date a mass airflow meter has been mounted to the engine in order to record volumetric airflow through the engine which is necessary for engine efficiency calculations. When the airflow meter is mounted to the engine, it interferes with the ability to accurately measure thrust. Once the project team has had the chance to measure mass airflow throughout the full engine operating range, the sensor will be removed allowing for thrust measurement on subsequent test runs. The project team has been able to validate the functionality of the thrust measurement stand via test runs of the JetCat P400 engine mentioned earlier. Thrust measurement recordings for this engine were within +/-5% of the manufacturer's specification, thus the project team is confident in the demonstration setup for the AM micro-turbine and expects no issues with thrust measurement during future testing.

It is worth noting that via analysis completed during design of the AM micro-turbine engine, it was predicted that thrust under the max power condition of the engine will be roughly 632 N. Given the agreement between the analysis predictions and recorded engine data at the operating points tested thus far, the project team is confident that the engine max thrust will fall close to this 632 N point once tested at max power.

6.2 Thrust Specific Fuel Consumption

The AM micro-turbine is expected to produce 632 N of thrust and consume ethylene fuel at a rate of 140.4 kg/hr at max power. This means the engine would have a TSFC rating of 0.222 kg/Nhr. These values have not been confirmed yet as max power testing of the engine has not been completed. But again, due to the alignment of the engine's performance to predicted values at lower speeds, the project team is confident these values will be confirmed correct once the engine has been tested at max speed conditions.

For comparison, the commercially available JetCat P400-Pro micro-turbine is capable of producing 425 N of thrust while consuming 66.82 kg/hr of a Jet-A fuel mixture at max power.[3] This engine thus has a TSFC of 0.157 kg/Nhr.

The AM micro-turbine has a higher TSFC value indicating poorer efficiency in comparison to the JetCat engine. This is at least in part due to the difference in fuel used for each engine. The AM engine is using ethylene at this point, which has a lower energy density as compared to the Jet A in the JetCat engine. A higher energy density allows for more efficient combustion in the engine and thus less fuel consumption. Gaseous ethylene was used for this version of the AM engine due to the simplification of the fuel delivery system afforded through use of gaseous fuel. Future iterations would switch to a liquid fuel such as Jet A and thus would be expected to have an improved TSFC. This is another detail that should be studied under future AM engine efforts.

6.3 Noise Emission (Sound Pressure Level)

Noise emission data was not able to be collected for the AM engine due to the testing delays experienced. Noise emission data was collected during testing of the JetCat engine on the developed test stand. If future testing of the AM engine is completed, the same setup will be used when testing the AM engine to be sure the noise emission data is comparable between the two engines. The AM engine noise emission data would also be comparable to worker safety standards for noise emissions to understand the engine's impact in its operating environment.

6.4 Start-up Procedure Establishment

A repeatable engine start-up procedure has been successfully established. The project team has documented proper rotor speed and fuel feed rate for achieving the engine idle condition. These conditions have been repeated and will be used for all future operation of the engine. Currently this procedure is done manually by the engine operator, but in the future it could be done automatically via a programmed engine controller. The steps of this start-up procedure are as follows:

1. Spin the engine to 18,500 RPM under the power of the starter motor;
2. Open the fuel valves and throttle the fuel feed up to a rate of 0.021 lbm/s;
3. Turn on the engine ignitor and wait for ignition.
4. Upon ignition of the engine, throttle down to a fuel feed rate of 0.016 lbm/s;
5. Wait for the engine speed to settle around 30,500 RPM;
6. Upon the engine speed settling at the idle point, turn off the starter motor and ignitor;
7. Ensure the engine speed is maintained at the idle point and that the engine combustor and EGT temperatures are settled in a safe range.

6.5 Operational Stability

Stable operation of the AM micro-turbine at the idle condition and up to 43,000 RPM has been demonstrated. Within this operating range, engine speed has responded smoothly to fuel feed adjustments, whilst engine temperatures and vibrations have remained safely stable. Fuel feed rates and corresponding speeds have been shown to be repeatable allowing for creation of a fuel feed rate schedule. Testing to verify engine stability at higher speeds was not able to be completed, but a fuel schedule for testing up to these higher speeds has been established. The fuel schedule defined for the AM micro-turbine is shown in Table 3. Estimated values are based on CFD analysis estimates and interpolation of operational data collected to date. Should future testing of the AM engine be completed, this fuel schedule should be utilized.

Table 3. Engine Fuel Schedule

	Engine Speed (RPM)	**Fuel Feed Rate (lbm/s)**	**Throttle Setting (V)**
Established	26,500	0.014	0.81
	31,000	0.016	0.96
	38,000	0.022	1.30
	43,000	0.026	1.51
Estimated	48,000	0.031	1.83
	53,000	0.037	2.21
	58,000	0.045	2.68
	63000	0.055	3.23
	68,000	0.066	3.91
	73,000	0.080	4.73
	76,000	0.086	5.08

7.0 COST ASSESSMENT

AM technologies offer the capability to rapidly prototype and manufacture the micro-turbine with the following expected benefits: manufacturing cost effectiveness; reduced carbon footprint through less CO_2 emissions during the production process; improved efficiency via optimized engine geometry made possible by the AM process.

Manufacturing cost benefits were demonstrated through use of cost benefit analysis tools and comparison to costs of similar commercially available engines. Likewise, environmental advantages related to the manufacturing of the AM engine were demonstrated via environmental studies conducted on the AM process and comparison to traditional engine manufacturing methods.

The analysis performed by UDRI engineering team compares the environmental impact of prototyping a micro-turbine engine using a traditional casting process versus an additive manufacturing process.

Traditional casting process was selected for analysis baseline. The Pratt & Whitney TJ-150 turbojet engine was used in this comparison. The TJ-150 is the engine used on military engines that power the MALD and SPEAR missiles, and is rated at 150 thrust pounds. The baseline engine is made up of six main components: the compressor, turbine or blisk, engine shaft, combustion chamber, exhaust nozzle, and the casing. It is the estimator's expert assumption that the compressor, turbine, combustion chamber, and exhaust nozzle are manufactured using the investment casting process.

The investment casting process was estimated using stereolithography (SLA) to manufacture the molds, as has become an industry norm for casting development.[4] The components are built directly from an STL file generated from CAD data. The SLA molds are used instead of hard tooling for the waxing process. All other investment casting processes are the same as traditional methods.

For AM micro-turbine engine the UDRI developed AM engine was used in this comparison. The engine has three components: the upper and lower casing with integral diffuser and combustion chamber and unitized compressor, turbine, and engine shaft (made as a one-piece rotor). The additive process used is direct metal laser melting (DMLM) using an EOS 290 additive printer. The components are built directly from an STL file generated from CAD data.

A summary comparison of the environmental impacts from the baseline investment casting process to additive manufacturing for eight design and development iterations is shown in Table 4. The analysis shows that investment casting process requires 95,780.52 more kilowatt-hours (kWh) than the additive manufacturing process.[5] Additionally, CO_2 emissions are 96,609.52 pounds higher for the investment casting process.[6]

Table 4. Summary of Environmental Data

Process	Total Particulate (lbs)	Sox (lbs)	Nox (lbs)	VOC (lbs)	One (1) Engine		Eight (8) Engines	
					kWh	CO_2 (lbs)	kWh	CO_2 (lbs)
Investment Casting Process								
Investment casting emissions	0.26	0.92	0.472	0.067		22.83		182.66
SLA mold making					2,646.61	2,615.91	21,172.85	20,927.25
Investment casting					8,794.61	8,692.60	70,356.90	69,540.76
Post processing					4,426.76	4,375.40	35,414.04	35,003.24
Transportation (5-ton truck/castings)	6.20		11.20	1.60		219.68		1,757.40
Total — Investment Casting					**15,867.97**	**15,926.41**	**126,943.79**	**127,411.31**
Additive Manufacturing Process								
Gas atomized powder					1,453.92	1,437.06	11,631.38	11,496.46
Additive manufacturing					1,625.60	1,606.74	13,004.80	12,853.94
Post processing					815.89	806.42	6,527.10	6,451.38
Total — Additive Manufacturing					**3,895.41**	**3,850.22**	**31,163.28**	**30,801.78**

The cost of the difference in kWh and CO_2 is summarized in Table 5 below.

Table 5. Cost Comparison

Process	kWh	Cost	Co_2 (lbs)	Cost	Total Cost
Investment Casting	126,943.8	7,616.63	127,411.3	6,370.57	13,987.19
Additive Manufacturing	31,163.3	1,869.80	30,801.8	1,540.09	3,409.89
Difference		**5,746.83**		**4,830.48**	**10,577.31**

Table 6 shows the lead-time comparison in weeks for eight iterations of design, design modification, and build for both investment casting (with SLA tooling) and additive manufacturing. The total weeks for the investment casting process using SLA-manufactured molds would take an estimated 148 weeks (2.86 years) for 8 iterations.[4] The additive process would only take 68 weeks (1.32 years) for the same number of iterations, saving 80 weeks (1.54 years) of development time.[7]

Table 6. Summary of Lead-time Data

Estimated Lead-time (weeks)	Iteration								Total (weeks)
	1	2	3	4	5	6	7	8	
Investment Casting									
Investment casting design/ SLA mold pattern/build	5.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	
Casting/post processing	15	15	15	15	15	15	15	15	
Total Casting Lead-time	**20.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**148.91**
Additive Manufacturing									
Additive design/build	6.35	4.35	4.35	4.35	4.35	4.35	4.35	4.35	
Post processing	4	4	4	4	4	4	4	4	
Total Additive Lead-time	**10.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**68.83**

The analysis shows that iterative design, manufacture, and test processing can be accomplished with less impact on the environment by additive manufacturing than by the baseline investment casting process. The additive manufacturing of eight engine iterations would require 75% less kWh and create 75% less CO_2 emissions than with the investment casting process. The results are that using AM will reduce the environmental cost by $10K and require nearly 54% less time than investment casting.

8.0 IMPLEMENTATION ISSUES

8.1. Technology Transition

Stakeholders from the US Air Force demonstrated interest in and support of this program. The stakeholders have interest in the demonstration and transition of the AM micro-turbine technologies to realize the potential performance and regulatory related benefits outlined in previous sections. The success of the AM micro-turbine could also usher in wider adoption of AM technologies for other USAF applications. In addition, the DoD as the stakeholder could significantly benefit from the use of AM in engine production because it could greatly simplify the supply chain of these engines. The supply chain is improved via reduction in part count within the engine as AM allows for much consolidation of engine components. AM may someday even allow for production of engines at DoD facilities, making the DoD less dependent on outside suppliers.

However, testing related setbacks experienced during this program mean that there is still much developmental work needed to be done on this type of engine before wider adoption can occur. Immediately, extensive performance verification testing needs to be completed to demonstrate that the engine does perform as expected and that its performance is comparable to similar commercially available engines. Completion of this step will aid in identifying appropriate ground and air applications for the engine. Extensive field testing in these identified platforms will then also need to be completed. After this, the stakeholders will be able to determine which areas of adoption are appropriate for the AM engine technology.

8.2. Production Requirements

The AM engine was manufactured on a commercially available DMLS printer to ensure production could occur anywhere this type of machine is available whether that be at a DoD facility or a service provider. And the reduction in part count within the AM engine assembly further simplifies the procurement and manufacturing of the engine. In addition to the printer, facilities for heat treatment and some CMM machining of the printed components are necessary. But these facilities are typically included in the establishment of a AM facility and are not specific to the AM engine manufacturing process. The DMLS process, while not suited for large volume production of the engine, does allow for low volume on-demand manufacturing. The design approach taken for the engine also requires minimal post-processing and traditional machining of the components, further simplifying the procurement of the engine as compared to similar traditionally manufactured engines.

8.3. Opportunities for Further Development

Due to the need to further mature the AM engine technology, there are no current plans for transition of the technology. However, the engine articles and test facilities developed under this project are readily available for further development work. In addition, the engine could easily be transferred to other existing DoD engine test facilities for further development work. While they were unable to be realized during this effort, opportunities do exist to further optimize the AM engine design and performance. And further advancement could be made in the manufacturability of the engine by exploration of newer, more cutting-edge printing technologies. The current stakeholders at the USAF and UDRI would be well suited to continue this development.

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APPENDICES

Appendix A: Points of Contact

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Appendix B: Joint Test Protocol

Joint Test Protocol

Environmental Advantages of an Additively Manufacturing Micro-turbine Engine

7 January 2021

ESTCP Project Number # WP20-D4-5083

INTRODUCTION

1.1. Problem Statement

There is a need across all Department of Defense (DoD) services for power plants that yield a reduced environmental impact through improved efficiency, reduced byproducts of the manufacturing process and a reduction in noise emissions. Existing turbine engines have a number of barriers that limit their application: high initial cost, relatively high maintenance and life cycle costs, and anthropogenically harmful high-frequency noise. The advantages of additive manufacturing (AM) can mitigate the cost barriers to wider adoption by application to micro-turbine engines. However, the noise level of the micro-turbine engine is above the acceptable human exposure limits, and requires special noise reduction techniques (*e.g.,* geometry optimization and nozzle design) to decrease to permissible levels. A byproduct of the traditional manufacturing process includes chemical and material waste, which can also be reduced by using AM. One way to reduce noise emissions is to increase the engine's efficiency through lower thrust specific fuel consumption (TSFC). The proposed effort is to demonstrate these environmental advantages (reduced noise and TSFC) of a newly developed low-cost AM micro-turbine engine over current micro-turbine power plant with traditional design and manufacturing.

1.2. Program Background and Technical Objectives

The program focuses on demonstration of a low-cost AM micro-turbine engine's environmental advantages over traditionally manufactured micro-turbine jet engines. The overall program technical objectives are:

1) Demonstrate AM micro-turbine for multiple applications, ensuring cost effectiveness of newly developed AM turbine engine for DoD services;

2) Demonstrate improved performance in thrust specific fuel consumption and noise emissions of AM micro-turbine engine by establishing baseline performance criteria and performing geometry optimization (as required);

3) Validate reduced thrust specific fuel consumption and noise emissions of AM micro-turbine and provide recommendations for implementation at DoD installations.

The demonstration of improved performance and environmental advantages of AM engine will be conducted through experimental testing and comparison of test data generated for a commercial off-the-shelf (COTS) micro-turbine engine (JetCat P400) and a low-cost AM engine designed and manufactured at University of Dayton Research Institute (UDRI) under the Sustainment Technologies Transition program funded by Air Force Life Cycle Management Center (AFLCMC).

2. TECHNICAL APPROACH

The Joint Test Protocol (JTP) contains the critical requirements and tests necessary to demonstrate the environmental advantages that AM can bring to micro-turbine engines. This protocol describes the test procedures and performance requirements necessary to demonstrate the environmental benefits and improved engine performance in TSFC and noise emissions of an additively manufactured micro-turbine engine.

2.1 Baseline Performance Criteria

Baseline performance criteria established for a printed micro-turbine engine through a collaborative effort between UDRI, AFLCMC, and Air Force Research Laboratory (AFRL) are presented in Table 1.

Table 1. Baseline Performance Criteria

Performance Criteria	Units	Description
Thrust	lb_f	Thrust force generated by engine
Thrust Specific Fuel Consumption (TSFC)	$(lb_m/hr) / lb_f$	Measure of engine efficiency: fuel mass flow rate divided by engine thrust
Sound Pressure Level (SPL)	dB	Measured noise level from the engine in various running conditions

Engine thrust will be measured by a custom designed micro-turbine engine thrust stand, built by AFRL.

TSFC will be calculated from thrust and fuel mass flow rate according to the equation below [1]:

$$TSFC = \frac{\dot{m_f}}{F_t},$$

where $\dot{m_f}$ is the fuel mass flow rate and F_t is the thrust. The fuel mass flow rate is determined by applying the measured fuel pressure and orifice size to a predetermined calibration curve.

Noise from the engine will be measured at multiple locations around the engine using an acoustic microphone array. These microphones will be used to detect the noise level emissions of the engines being evaluated. Per MIL-STD-1474E [2], an acoustic array will be used in a micro-turbine engine test cell to capture overall Sound Pressure Level (SPL, dB) and noise frequency (Hz) data. Due to space limitation inside the engine test cell, the specifications for the acoustic array will be modified as necessary. The measured sound pressure level (dB) will be used primarily for evaluation and comparison purposes of the different engines being tested. The frequency data (Hz) will be used primarily to identify the source location and mechanism of the sound generation inside the engine. This will provide target areas for optimization on the original AM engine and validation in the AM optimized engine by single source identification.

Test runs will be performed, and a variety of performance and noise data collected for COTS JetCat P400 and the AM micro-turbine engines (original and optimized) manufactured at the UDRI Advanced Technology Transition Center (ATTC) in Dayton, OH.

2.2 Testing Objects: Traditional and AM Engines

The testing will be performed on COTS JetCat P400 micro-turbine engine and the AM micro-turbine engines manufactured at the UDRI ATTC in Dayton, OH.

2.2.1 Traditional Micro-turbine Engine – JetCat P400 Pro (JetCat)

Figure 1. P400-PRO JetCat Turbine Engine [3]

The performance of AM micro-turbine engine will be validated against a reference (traditional) micro-turbine engine (JetCat P400, Appendix I [3]). The reference engine is selected due to its similar size and operational characteristics; it also is the basis for the design of the UDRI AM engine. Results for the reference engine will be compared to the original and optimized AM engine at a variety of test conditions.

2.2.2 AM Engine Manufactured at ATTC (UDRI)

The AM micro-turbine engine (Fig. 2) is manufactured from Inconel 718 powder (powder particle size avg 22.46 μm) in 40 μm thick slices with a commercially available EOS M290 AM machine that employs powder bed fusion, Direct Metal Laser Melting (DMLM) technology at the UDRI ATTC in Dayton, OH. The AM machine deposits a layer of powder and then melts it with the laser, creating a single-layer slice of the part. A new layer of powder is then laid down and melted.

This process is repeated until the part is complete. Specific details for printing the AM micro-turbine is presented in Appendix II.

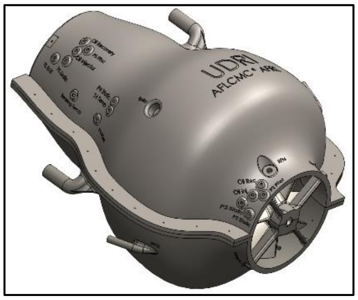

Figure 2. AM Engine Model - Assembled Case

2.2.3 Optimized AM Engine Manufactured at UDRI

The micro-turbine design optimization will be performed in collaboration with turbine engine experts at AFRL. It will be carried out to achieve the desired performance improvements (decreased TSFC) and decreased noise. Engine design software (AEDSys) will be used to aid in the geometry optimization from a mathematical perspective. Computational Fluid Dynamics (CFD) software (ANSYS Fluent, v19.2) will refine the geometry for airflow control as needed. The CFD model will use single reaction chemical kinetic mechanism for jet fuel (Jet-A) combustion already provided by Fluent, k-ε turbulence model for fluid dynamics, and FW-H acoustic model for noise prediction.

Upon confirmation of improved engine performance and decreased noise emissions through simulations, the modified engine design will be printed and experimentally tested. Comparison of the optimized AM engine's results to the AM baseline model's results will determine the extent to which the design changes impacted the engine's performance and noise emissions.

2.3 Engine Test Equipment

Testing of the traditional and AM micro-turbine jet engines will be performed at AFRL's Small Engine Test Cell (Figure 3) located at Wright-Patterson Air Force Base, OH. The test cell is well equipped with all equipment required to test the engine: air and fuel supply, sensors, data communication, electronic control systems, and all regulatory safety and fire suppression systems.

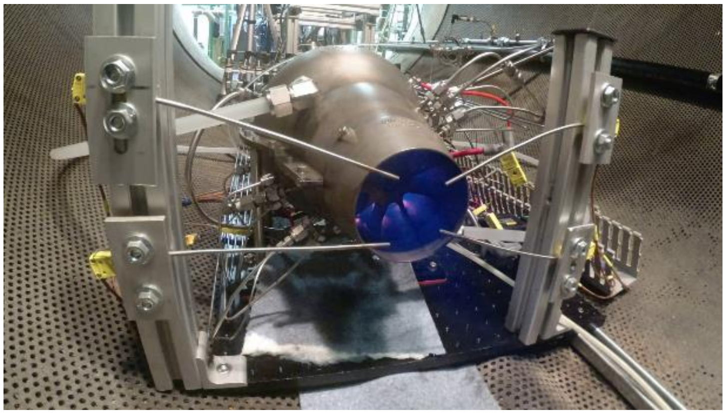

Figure 3. AM Engine Test Run in AFRL's Micro-Turbine Engine Test Cell

A schematic of the experimental setup is displayed in Figure 4. The engine is mounted to a custom made micro-turbine engine thrust stand to measure thrust. A variety of sensor ports are placed throughout the engine to collect an array of data, including engine speed, and internal pressures and temperatures.

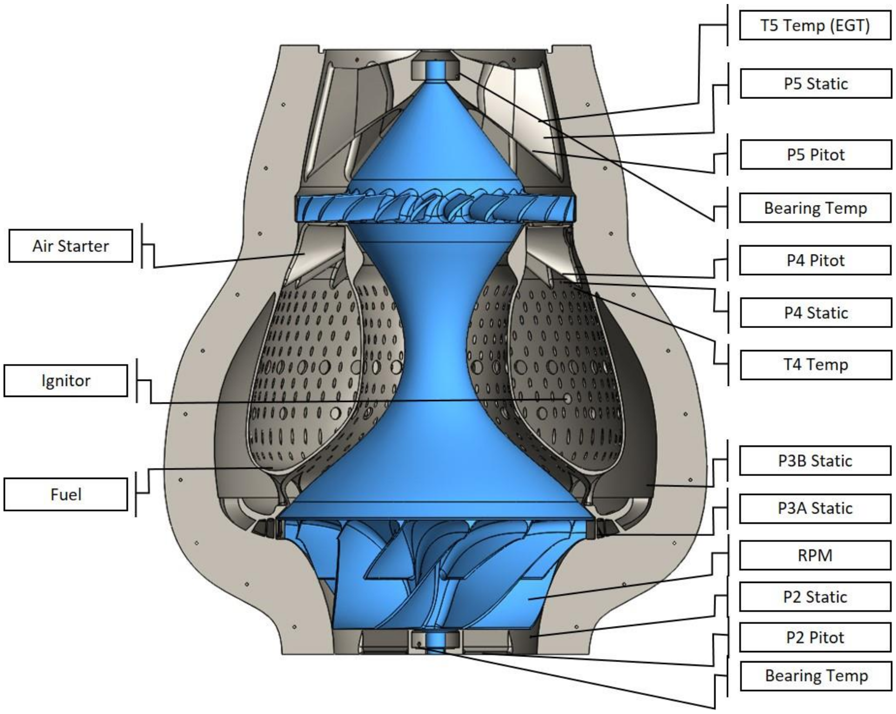

Figure 4. Schematic of Experimental Setup

Details of the various measurements made on the engine are listed in Table 2.

Table 2. Engine Sensors Measurements

Sensor	Measurement, units	Make / Model
Magnetic Pickup	Revolutions per Minute (RPM)	Custom (AFRL)
Vibrations	Engine vibration (Hz)	Custom (AFRL)
Ambient Temp	Temperature – ambient air (°F)	Omega KQIN-116G-12
T5 Temp	Temperature – station 5 (°F)	Omega KQIN-116G-12
T4 Temp	Temperature – station 4 (°F)	Omega KQIN-116G-12
T3 Temp	Temperature – station 3 (°F)	Omega KQIN-116G-12
EGT Array 1	Temperature – exhaust gas (°F)	Omega KQIN-116G-12
EGT Array 2	Temperature – exhaust gas (°F)	Omega KQIN-116G-12
EGT Array 3	Temperature – exhaust gas (°F)	Omega KQIN-116G-12
EGT Array 4	Temperature – exhaust gas (°F)	Omega KQIN-116G-12
Ambient Pressure	Pressure – ambient air (psi)	Omega PX419-100A5V
P5 Static	Pressure – station 5, static (psi)	Omega PX419-100A5V
P5 Pitot	Pressure – station 5, static (psi)	Omega PX419-100A5V
P4 Pitot	Pressure – station 4, pitot (psi)	Omega PX419-100A5V
P4 Static	Pressure – station 4, static (psi)	Omega PX419-100A5V
P3.5 Static	Pressure – station 3.5, static (psi)	Omega PX419-100A5V
P3 Static	Pressure – station 3, static (psi)	Omega PX419-100A5V
P2 Static	Pressure – station 2, static (psi)	Omega PX419-100A5V
P2 Pitot	Pressure – station 2, pitot (psi)	Omega PX419-100A5V
Fuel Manifold Pressure	Pressure – fuel manifold (psi)	Omega PX419-100A5V

The digital signals from the sensors are sent to a LabView (National Instruments) data acquisition system which converts the digital signals to engine data (engine speed, internal pressures, and temperatures). Collected data is stored on a local computer and exported to Microsoft Excel for processing and analyzing. Upon completion of data processing and analyzing, evaluations will be conducted with AEDSys and ANSYS for engine optimization, as described previously.

2.4 Acoustic Test Equipment

An acoustic array apparatus with data recording capability will be used to capture noise emissions. The acoustic array is composed of 12 microphones (PCB Piezotronics) with calibration capability connected to a chassis (National Instruments, PXI) with a capability of 16 bit, 24 channels, 0.5 MHz (per channel) data collection rate. The microphones will be arranged in a typical pattern appropriate for engine measurements [4, 5] according to the expertise of AFRL/RH acoustic subject matter experts (SMEs).

3.0 TESTING PROCEDURES

3.1 Acoustic Measurements

Acoustic measurements (Table 3) will be made by a microphone array in an appropriate arrangement, as previously described (section 2.4). These measurements will be made at a distance downstream of the engine determined by AFRL acoustic SMEs.

Table 3. Acoustic Measurements

Sensor (Make/Model)	Measurement (units)
Acoustic array (National Instruments PXI chassis with 12 PCB microphones)	Sound Pressure Level (dB) Noise Frequency (Hz)

3.2 Trust/TSFC Measurements

The thrust and fuel flow rate to the engine are continuously measured by the thrust stand and recorded fuel rail pressure, respectively. Data is collected and recorded by the data acquisition system (section 2.3). Statistical values of temporal measurements are used for calculations to determine the engine performance at each test condition. TSFC is a characteristic of an engines performance. This characteristic will be used as a criteria by which the traditional JetCat P400, original and optimized AM engines will be evaluated. Fuel flow in this case is going to be used to determine a fuel consumption rate and correlated with the thrust achieved in that condition.

3.3 Test Conditions

The engines will be tested across a range of engine power settings: idle (~10% max power), cruise (~80% max power) and max power. Thus, the impact of engine design changes on performance and noise emissions will be observed over a wide range of engine power settings. Table 4 presents test conditions summary (Test Matrix) for tested engines.

Table 4. Engine Test Matrix

Engine	**Power Setting**	**Measurement/ Performance Criteria**
1) JetCat P400 (reference) 2) AM Original 3) AM Optimized Design	Idle (~10% max power)	SPL, dB Noise Frequency (Hz) TSFC, $(lb_m/hr) / lb_f$ Thrust, lb_f
	Cruise (~80% max power)	
	Max Power	

4.0 ENGINES PERFORMANCE EVALUATION

The goal of these efforts is to ensure a complete evaluation of the AM turbine engine in performance and noise emissions against developed criteria. This requires testing on a) traditional JetCat P400 engine (as the reference) and b) original and optimized AM engines.

Testing will start by making measurements for the traditional JetCat P400 engine as the reference, and reference data collected. Another round of tests will then be conducted on the original AM engine design and optimized design. Data comparison will be made between reference data from JetCat P400 and data from original AM engine and optimized AM engine. Success of AM engines (original and optimized) will be determined upon comparing their results for the three data points (SPL, TSFC, and thrust) at each power setting against the data for the reference engine (Table 5).

Table 5. Engines Performance Evaluation

Engine	Power Setting	Success Criteria
1) JetCat P400 (reference) 2) AM Original 3) AM Optimized Design	Idle	$SPL_{AM\ opt,\ idle} < SPL_{AM,\ idle} < SPL_{P400,\ idle}$
		$TSFC_{AM\ opt,\ idle} < TSFC_{AM,\ idle} < TSFC_{P400,\ idle}$
		$F_{T\ AM\ opt,\ idle} \approx F_{T,\ AM,\ idle} \approx F_{T,\ P400,\ idle}$
	Cruise	$SPL_{AM\ opt,\ cruise} < SPL_{AM,\ cruise} < SPL_{P400,\ cruise}$
		$TSFC_{AM\ opt,\ cruise} < TSFC_{AM,\ cruise} < TSFC_{P400,\ cruise}$
		$F_{T\ AM\ opt,\ cruise} \approx F_{T\ AM,\ cruise} \approx F_{T,\ P400,\ cruise}$
	Max Power	$SPL_{AM\ opt,\ max} < SPL_{AM,\ max} < SPL_{P400,\ max}$
		$TSFC_{AM\ opt,\ max} < TSFC_{AM,\ max} < TSFC_{P400,\ max}$
		$F_{T\ AM\ opt,\ max} \approx F_{T,\ AM,\ max} \approx F_{T,\ P400,\ max}$

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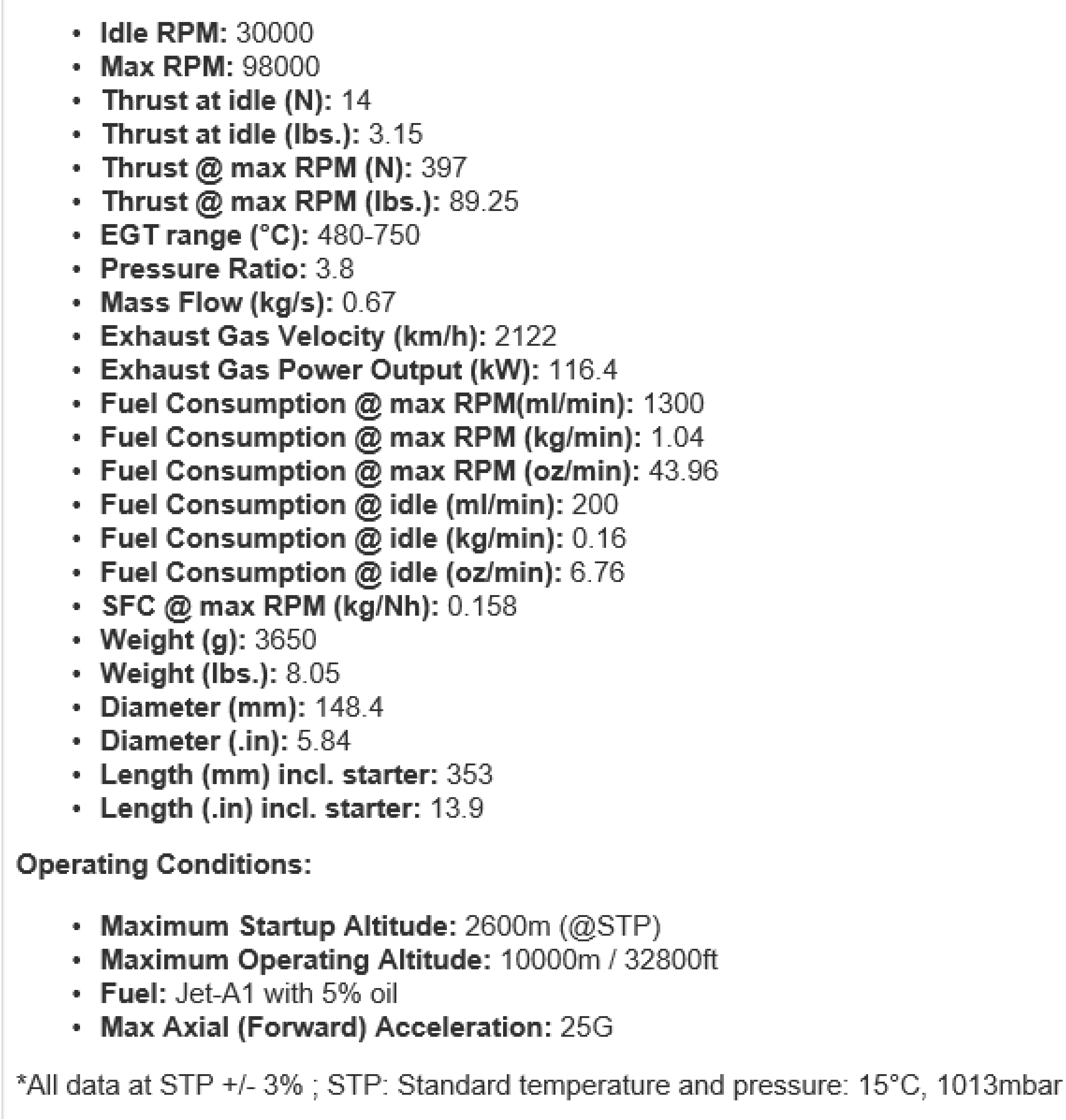
Appendix 1. P400-PRO Turbine Engine, 89 lbs Thrust, by JetCat [3]



- **Idle RPM:** 30000
- **Max RPM:** 98000
- **Thrust at idle (N):** 14
- **Thrust at idle (lbs.):** 3.15
- **Thrust @ max RPM (N):** 397
- **Thrust @ max RPM (lbs.):** 89.25
- **EGT range (°C):** 480-750
- **Pressure Ratio:** 3.8
- **Mass Flow (kg/s):** 0.67
- **Exhaust Gas Velocity (km/h):** 2122
- **Exhaust Gas Power Output (kW):** 116.4
- **Fuel Consumption @ max RPM(ml/min):** 1300
- **Fuel Consumption @ max RPM (kg/min):** 1.04
- **Fuel Consumption @ max RPM (oz/min):** 43.96
- **Fuel Consumption @ idle (ml/min):** 200
- **Fuel Consumption @ idle (kg/min):** 0.16
- **Fuel Consumption @ idle (oz/min):** 6.76
- **SFC @ max RPM (kg/Nh):** 0.158
- **Weight (g):** 3650
- **Weight (lbs.):** 8.05
- **Diameter (mm):** 148.4
- **Diameter (.in):** 5.84
- **Length (mm) incl. starter:** 353
- **Length (.in) incl. starter:** 13.9

Operating Conditions:

- **Maximum Startup Altitude:** 2600m (@STP)
- **Maximum Operating Altitude:** 10000m / 32800ft
- **Fuel:** Jet-A1 with 5% oil
- **Max Axial (Forward) Acceleration:** 25G

*All data at STP +/- 3% ; STP: Standard temperature and pressure: 15°C, 1013mbar

Appendix II. AM Engine Manufacturing Processing

Pre-Processing

After the design work is completed in SolidWorks, the model is converted to an .stl file. The .stl file is then put into Magics Software for creating support. The build package, with part, support, ghosted part and sacrificial protective structures are loaded into EOS print software which is used to slice the build into 40μm slices and create laser paths. This creates the .eosjz file which will be loaded into the machine for printing.

Manufacturing

The EOS M290 is loaded with the print file (.eosjz) and filled with Praxair TruForm 718-35 Inconel 718 powder. The High Speed Steel recoater arm is inspected and a Steel build plate (2” ±0.25” thickness) installed and leveled. Once machine setting are verified, the build plate is heated to 80°C and the print can begin. For planning purposes, the Case takes approximately 168 hours (295mm build height) and the Rotor takes approximately 117 hours (279mm build height) to complete.

Post Processing

After the print completes, the part is unpacked from the machine and loose powder is removed from all cavities and tubes. Once all loose powder is removed, the part is vacuum heat treated at1950°F ± 25°F for 90 min +15/-5 min per ASTM F3055 [6], followed by IN718 solution + precipitation heat treatment per AMS 5662 [7]. Following heat treatments, the part is separated from the build plate using a wire EDM and media blasted as required.

EOS M290 Manufacturing Process Parameters

Parameter Name	PraxAir_In718_40um_RevD
Description	
Layer Thickness (µm)	40
Build Plate Temp (°C)	80
_Default_OuterSkin_DrectPart **Stripes**	
Distance (mm)	0.11
Speed (mm/s)	960
Power (W)	285
BOS (mm)	0.015
Stripe Width (mm)	10
Stripes overlap (mm)	0.12
Upskin	
Distance (mm)	0.09
Speed (mm/s)	600
Power (W)	153
Thickness (mm)	0.12
Downskin	
Distance (mm)	0.1
Speed (mm/s)	2040
Power (W)	167
Thickness (mm)	0.12
Overlap with inskin (mm)	0.1
min length (mm)	2
_Default PostContours **Contour Tab 1**	
Standard Speed (mm/s)	300
Standard Power (W)	138
OnPart Speed (mm/s)	300
OnPart Power (W)	138
Downskin Speed (mm/s)	300
Downskin Power (W)	138
BOS (mm)	0.012
Thickness (mm)	0.04
Contour Tab 2	
Standard Speed (mm/s)	800
Standard Power (W)	80
OnPart Speed (mm/s)	800
OnPart Power (W)	80
Downskin Speed (mm/s)	800
Downskin Power (W)	80
BOS (mm)	0
Thickness (mm)	0.04
Edges	
Edge Factor	2
threshold	3
Min Radius Factor	0
BOS (mm)	0
Speed (mm/s)	900
Power (W)	100
_Default_ExternalSupport	
Speed (mm/s)	900
Power (W)	100

Appendix C. Environmental and Cost Study

AM Micro-turbine Manufacturing Environmental Impact Analysis on the Prototyping Process

This analysis compares the environmental impact of prototyping a micro-turbine engine using a traditional casting process versus an additive manufacturing (AM) process.

Analysis Baseline:

Traditional Casting Process: The Pratt & Whitney TJ-150 turbojet engine was used in this comparison. The TJ-150 is the engine used on military engines that power the MALD and SPEAR missiles, and is rated at 150 thrust pounds. The baseline engine is made up of six main components: the compressor, turbine or blisk, engine shaft, combustion chamber, exhaust nozzle, and the casing. For this analysis, it was assumed the compressor, turbine, combustion chamber, and exhaust nozzle are manufactured using the investment casting process.

The investment casting process was estimated using stereolithography (SLA) to manufacture the molds, as has become an industry norm for casting development.[1] The components are built directly from an STL file generated from CAD data. The SLA molds are used instead of hard tooling for the waxing process. All other investment casting processes are the same as traditional methods.

AM Process: The UDRI additive manufacturing process was used in this analysis. The engine has three components: the upper and lower casing with integral diffuser and combustion chamber and unitized compressor, turbine, and engine shaft (made as a one-piece rotor). The additive process used is direct metal laser melting (DMLM) using an EOS 290 additive machine. The components are built directly from an STL file generated from CAD data.

A summary comparison of the environmental impacts from the baseline investment casting process to additive manufacturing for eight design and development iterations is shown in Table 1. The analysis shows that investment casting process requires 95,780.52 more kilowatt-hours (kWh) than the additive manufacturing process.[2] Additionally, CO_2 emissions are 96,609.52 pounds higher for the investment casting process.[3]

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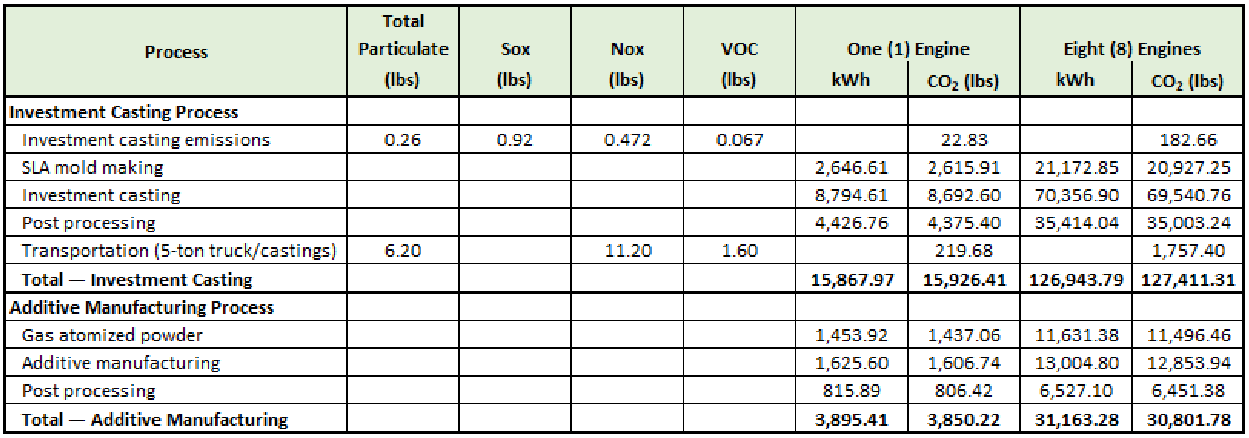
[1] MakerOS. “How to Price for SLA 3D Printing” 04 May 20.

[2] Energetics, Incorporated. “Energy and Environmental Profile of the U.S. Metalcasting Industry” Sep 99.

[3] MDPI. “Investigation of Energy Requirements and Environmental Performance for Additive Manufacturing Processes” 10 Oct 18.

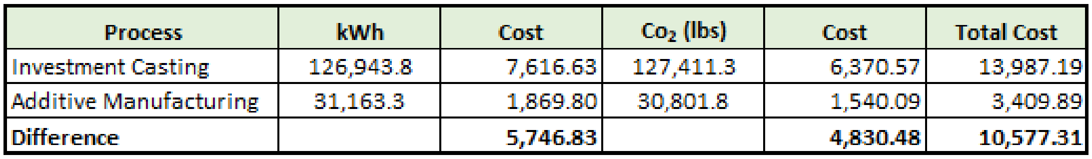
Table 1. Summary of Environmental Data



Process	Total Particulate (lbs)	Sox (lbs)	Nox (lbs)	VOC (lbs)	One (1) Engine kWh	One (1) Engine CO_2 (lbs)	Eight (8) Engines kWh	Eight (8) Engines CO_2 (lbs)
Investment Casting Process								
Investment casting emissions	0.26	0.92	0.472	0.067		22.83		182.66
SLA mold making					2,646.61	2,615.91	21,172.85	20,927.25
Investment casting					8,794.61	8,692.60	70,356.90	69,540.76
Post processing					4,426.76	4,375.40	35,414.04	35,003.24
Transportation (5-ton truck/castings)	6.20		11.20	1.60		219.68		1,757.40
Total — Investment Casting					**15,867.97**	**15,926.41**	**126,943.79**	**127,411.31**
Additive Manufacturing Process								
Gas atomized powder					1,453.92	1,437.06	11,631.38	11,496.46
Additive manufacturing					1,625.60	1,606.74	13,004.80	12,853.94
Post processing					815.89	806.42	6,527.10	6,451.38
Total — Additive Manufacturing					**3,895.41**	**3,850.22**	**31,163.28**	**30,801.78**

The cost of the difference in kWh and CO_2 is summarized in Table 2 below.

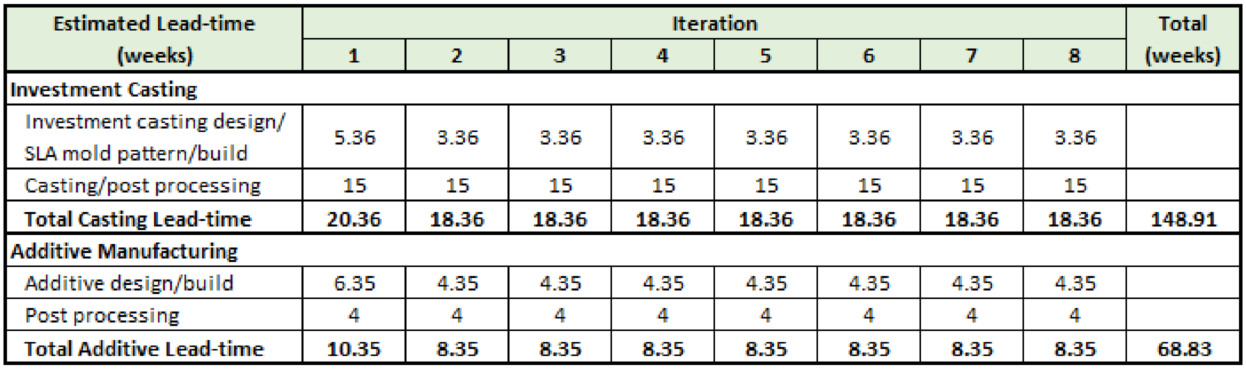
Table 2. Cost Comparison



Process	kWh	Cost	Co_2 (lbs)	Cost	Total Cost
Investment Casting	126,943.8	7,616.63	127,411.3	6,370.57	13,987.19
Additive Manufacturing	31,163.3	1,869.80	30,801.8	1,540.09	3,409.89
Difference		**5,746.83**		**4,830.48**	**10,577.31**

Table 3 shows the lead-time comparison in weeks for eight iterations of design, design modification, and build for both investment casting (with SLA tooling) and additive manufacturing. The total weeks for the investment casting process using SLA-manufactured molds would take an estimated 148 weeks (2.86 years) for 8 iterations.[1] The additive process would only take 68 weeks (1.32 years) for the same number of iterations, saving 80 weeks (1.54 years) of development time.4

Table 3. Summary of Lead-time Data



Estimated Lead-time (weeks)	Iteration 1	2	3	4	5	6	7	8	Total (weeks)
Investment Casting									
Investment casting design/ SLA mold pattern/build	5.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	
Casting/post processing	15	15	15	15	15	15	15	15	
Total Casting Lead-time	**20.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**18.36**	**148.91**
Additive Manufacturing									
Additive design/build	6.35	4.35	4.35	4.35	4.35	4.35	4.35	4.35	
Post processing	4	4	4	4	4	4	4	4	
Total Additive Lead-time	**10.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**8.35**	**68.83**

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4 Digital Alloys. “Energy Consumption in Metal Additive Manufacturing” 28 Mar 19.

Summary

The analysis shows that iterative design, manufacturing, and test processing can be accomplished with less impact on the environment by additive manufacturing than by the baseline investment casting process. The additive manufacturing of eight engine iterations would require 75 percent less kWh and create 75 percent less CO_2 emissions than with the investment casting process. The results are that using AM will reduce the environmental cost by $10K and require nearly 54 percent less time than investment casting.