Optimized Tip Cooling Using AM Process
Final Design Review

by

Project Members:

Alberto H. Gamez ahgamez@calpoly.edu

Lourdes Sarmiento Martinez lsarmien@calpoly.edu

Andrew VanBogelen avanboge@calpoly.edu

Sponsor: Rick Rogers, Solar Turbines

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

December 3, 2021

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

ABSTRACT

This Final Design Review (FDR) reports on the senior design project undertaken by our team of mechanical engineering seniors at California Polytechnic State University, San Luis Obispo. This project seeks to use the additive manufacturing process to improve the existing design of a Taurus 60 gas turbine injector tip. The current injector tip is owned by Solar Turbines, a designer and manufacturer of gas turbines for electric generation, propulsion, as well as natural resource transportation. The challenge at hand is to design a new injector tip that will be reliable for at least 60,000 hours and provide ease of replacement, whilst employing a cost-effective additive manufacturing process. Our Final Design Review (FDR) report will be divided into seven categories: compiled research findings, our understanding of the challenge, a design strategy outline, concept designs and design direction, current design iterations, manufacturing plan, design verification, and project management strategy. Furthermore, the Final Design Review will document the progress of design validation through a series of computational analyses. Current analytical results show that there is potential for our designs to meet specifications of the 1350 °F threshold and additive manufacturing compliance. Some details have been omitted for sponsor privacy.

Table of Contents

Chapter 1: Introduction ….. 1

Chapter 2: Background ….. 1

Chapter 3: Objectives 7

Chapter 4: Concept Design Development 12

Chapter 5: Final Design 20

Chapter 6: Manufacturing 44

Chapter 7: Design Verification 46

Chapter 8: Project Management 50

Chapter 9: Conclusions & Recommendations 52

References 53

Appendix I: Patent Reference 56

Appendix II: QFD- Quality Function Deployment House of Quality 58

Appendix III: Functional Decomposition 59

Appendix IV: Tip Cooling Ideation List 58

Appendix V: Pugh Matrices 61

Appendix VI: Morphological Matrix 63

Appendix VII: Weighted Matrix 64

Appendix VIII: Preliminary Calculations 65

Appendix IX: Design Hazards Checklist 69

Appendices X: Failure Mode and Analysis 70

Appendices XI: DVP & R 71

Appendices XII: Indented Bill of Materials 72

Appendices XIII: Drawing Package 73

Appendices XIV: Gantt Chart 76

LIST OF FIGURES

Figure 1. Schematics of a gas turbine engine..1

Figure 2: Nozzle Failure which occurred after combustion but prior to turbine blades................2

Figure 3: Swirling Air through Injector Arm...4

Figure 4: Vascular engineering structure lattice. 5

Figure 5: Combustion chamber (left), Injector cross section (right) 5

Figure 6: Alternative methods to provide film cooling. 6

Figure 7a: Injector cutaway...6

Figure 7b: Injector Air passage A cutaway...6

Figure 8: Solar Turbines' Additive Manufacturing combustion process.....................................7

Figure 9. Boundary sketch of problem and design location..8

Figure 10. Function brainstorming activity 12

Figure 11. Ideation Models.…………...13

Figure 12. Helical fins with thin stems..13

Figure 13. Helical fins at 45 degrees...14

Figure 14. Porous structure with fuel tunnels at up to 45 degrees..14

Figure 15. Porous structure with 45-degree angle holes..15

Figure 16. Tall vertical fins..15

Figure 17. Porous structure for turbulent airflow..15

Figure 18. Changing AM dimensions with fins and thin-rounded stems......................................16

Figure 19. Physical Concept Prototype 17

Figure 20. Porous Structure with Fuel Tunnels at 45-degrees..17

Figure 21. Concentric Circular Fins and Vertical Fins 18

Figure 22. Porous Structure with 45-degree angled holes..18

Figure 23. Finite Element Heat Transfer (FEHT) Temperature Contour.......................................19

Figure 24: Fuel Tunnels shown without tip face...21

Figure 25: Fuel Tunnels shown with sectional view..22

Figure 26. Heat fin design cross sectional view at 45 degrees..23
Figure 27. Heat fin design cross-sectional view...24
Figure 28. Porous design cross-sectional view...25
Figure 29. Porous design cross-sectional isometric view...25
Figure 30. Porous design left side view...26
Figure 31. Porous design left isometric view..26
Figure 32. Structural prototypes 3D printed from plastic..27
Figure 33. Porous Design 3D printed structural design..28
Figure 34. Heat fin design 3D printed with no structural defect...28
Figure 35. Inner face average temperature convergence study..31
Figure 36. Isometric FEA view of current design with tip boundary condition…......................32
Figure 37. Cross-section FEA view of current design...32
Figure 38. Isometric FEA view of fin design with tip boundary condition.................................33
Figure 39. Cross-section FEA view of fin design temperature contour.....................................33
Figure 40. Cross-section FEA view of porous structure design temperature contour.................34
Figure 41: Pressure and Velocity analysis using Ansys Fluent..35
Figure 42: Pressure and Velocity analysis using Ansys Fluent..35
Figure 43. Velocity profile of Heat Fins injector tip using SolidWorks Internal Flow...............36
Figure 44. Pressure profile of Heat Fin injector tip using SolidWorks Internal Flow.................37
Figure 45. Pressure profile of Porous injector tip prototype #3 using SolidWorks External.......38
Figure 46. Velocity profile of Porous injector tip prototype #3 using SolidWorks External.......38
Figure 47. Temperature Profile of Porous Injector tip prototype #3 using SolidWorks External.39
Figure 48. Base model CFD temperature contour...40
Figure 49. Pressure contour of CFD simulation on Fin design...40
Figure 50. Temperature contour of CFD simulation on Fin design...41
Figure 51. Velocity contour of CFD simulation on Fin design...42
Figure 52. Pressure contour of CFD simulation on porous structure..42
Figure 53. Temperature contour of CFD simulation on porous structure....................................43

Figure 54. Velocity contour of CFD simulation on porous structure..44
Figure 55. The Fin Design and the structural prototype ………………………………………..45
Figure 56. The Fin Design with gradual horizontal structure ……………….........................45
Figure 57. The simplified Fin Design and the Flat-plate………………………………………..46
Figure 58. AM printed Alloy X Fin Design by Solar Turbines…………………………………47
Figure 59. Plastic Fin Design structurural prototype, final CAD model, AM part.……………..48
Figure 60. Heat Dissipation Test Diagram..49
Figure 61. Heat Dissipation Test performed in Mustang 60...50
Figure 62. Heat Dissipation Test, run 1..51
Figure 63. Heat Dissipation Test, run 2..51

LIST OF TABLES

Table 1. Solar Turbines Needs and Wants. ……..9

Table 2. Specifications Developed in QFD...10

Table 3. Hazards Table...20

Table 4. Boundary Conditions Table...29

Table 5. Convection Coefficients...30

Table 6. Bill of Material Cost Breakdown...43

Table 7: Test Overview Table...46

Table 8. Test apparatus component descriptions...49

Table 9. Heat Dissipation Test Data and Results...50

Table 10. Final pass/fail result criteria...51

Table 11. Project Timeline 54

Chapter 1: Introduction

Our team of mechanical engineering seniors aimed to use the additive manufacturing process to improve the existing design of a Taurus 60 gas turbine injector tip. The injector current tip is owned by Solar Turbines, a designer and manufacturer of gas turbines for electric generation, propulsion, as well as natural resource transportation. The challenge of this process was to design a new injector tip that would significantly decrease heat dissipation, increase reliability, provide ease of replacement, and employing a cost-effective manufacturing process. Our report was divided into eight chapters: compiled research findings, our understanding of the challenge, a design strategy outline, concept designs and design direction, Final Design, Manufacturing process for prototype, Design Verification of the prototype, and Project Management. The following Final Design Review (FDR) outlines the technical research, ideation process and verification, manufacturing, and testing conducted to redesign the injector tip using additive manufacturing (AM) compatible geometry to lower injector tip temperature, allowing Alloy X to be used. Furthermore, this report will display the ideation models and necessary computer analysis to derive validation.

Chapter 2: Background

A gas turbine engine, example shown in Figure 1, is commonly found in commercial aviation as well as industrial gas extraction and power generation. The turbine operates by drawing a working fluid (ambient air) through an axial compressor at the front and compressing the working fluid by means of rotating fan blades. The combination of blades and stationary veins cause the air to achieve a highly energized state. The working fluid enters a chamber where fuel in a gaseous state is injected, and combustion occurs. The combustion expands providing work in the form of spinning turbine blades after the chamber. This energy from spinning turbine blades accomplishes the overall purpose of the assembly, that being gas extraction, power generation, or a task not stated.

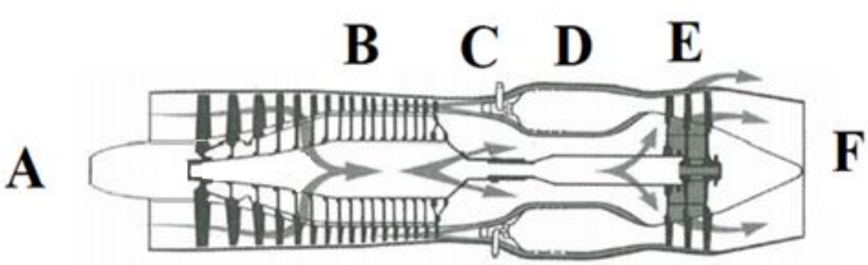


Figure 1. A, working fluid (ambient air) drawn in, B, working fluid compressed, C, Fuel injected into chamber, D, combustion in combustion chamber, E, energy spins turbine to accomplish task, F, spent exhaust exits aft of turbine blades [1]. The area covered by our research will pertain only to the injector and its injection method thereof at point C in Figure 1, while all other points are beyond the scope of our project.

2.1 Technical Research

Taking a closer look at the injection process at point C in Figure 1**,** gas is delivered through 12 injectors that spray fuel into the chamber and serve as the critical bridge between compressed working fluid, and useable energy production. Typically, the injector on an industrial gas turbine is made of nickel-based or cobalt-based superalloy [2]. This is a unique metal with high fatigue resistance and extreme temperature capabilities. However, the production cost of the typical injector is exceedingly large, which translates to steep expenditures for prototyping, testing and repairs. To combat these costs, our sponsor, Solar Turbines, has implemented a new manufacturing process called Additive Manufacturing Process (AM Process). The AM Process is a branch of 3D printing but differs by using a combination of a laser and a bed of powdered metal rather than the usual extrusion-injector method. This method aims a laser at a powder bed of the desired metal and melts the powder together in an extremely precise fashion. The AM Process dramatically decreases the production timeline from computer models to full-scale prototypes.

When selecting materials, a few materials were first prototyped by Solar Turbines on a smaller Centaur 50s gas turbine. One design consisted of a monolithic silicon nitride nozzle. This was promising at first, but early testing showed early oxidation of the silicon nitride components. After just 68 hours of testing, catastrophic failure occurred in the nozzle vanes [3]. See Figure 2 below for evidence.

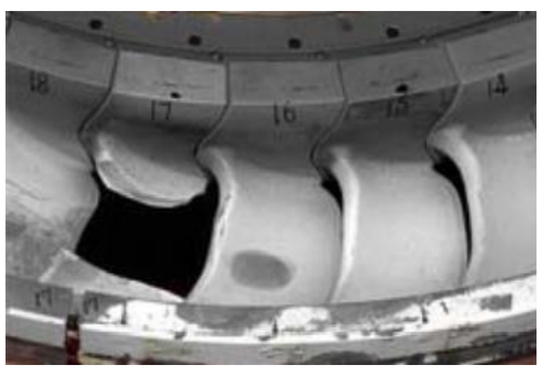


Figure 2. Nozzle Failure occurred after combustion but prior to turbine blades.

Once the AM process was selected for injector tip production, the details of the material properties still had to be ironed out. These details are observed in a study conducted by Oak Ridge Laboratories [4]. This study establishes that laser beam powder bed infusion is "well suited for the fabrication of intricate geometries needed for turbine engine fuel injector components". This specific research article compared low and high Silicon alloys. High Si correlated with "faster oxidation rates" and found that low Si alloys display less "micro-cracking". The heat treatment used for metal powder Additive Manufacturing parts is known as "Hot Isostatic Pressing (HIP)". HIP has been used by turbine engine manufacturers for improving the fatigue life and for "AM Nickel Alloy X to mitigate the effect of sub-surface discontinuities".

Another factor to consider when using additive manufacturing is a term called "spatter." This applies to the previously mentioned laser powder bed fusion method. When a bright powerful laser is shined at the powder, a splashing-like phenomenon occurs where some of the un-melted particles escapes from the melt pool caused by the laser and splashes onto the surface of completed segments of the created part [5]. This creates risks as the local surface will have inconsistent characteristics compared to its surroundings. A differing surface roughness can cause anisotropic behavior at a microscopic level, and ultimately lead to the creation of stress risers. With the addition of stress risers, the fatigue properties are negatively impacted. Although this occurs on a microscopic level, all aspects should be considered before further design.

This technical research guided the team to ask our sponsor which powder beam method was being used by Solar Turbines and what was the heat treatment for the injector tip after being laser-printed.

During injector design, many design difficulties arise due to the many constraints. As stated in the case study carried out by Pratt and Whitney, "Issues that fuel injector designers have to face are numerous. The requirements of the fuel injectors include proper droplet size range, fuel mass flow distribution, spray cone angle, circumferential uniformity, emissions and smoke controls," [6]. What is more, each of these variables have an associated reaction based on their characteristics. For example, decreasing the size of the fuel droplet more thoroughly mixes the fuel leading to improved fuel emissions [7]. However, the Taurus 60 uses fuel in the gas phase (not liquid), droplet size is not a design consideration. Another characteristic to consider is the carbon content of the fuel. As the carbon content increases, a process called "coking" occurs. General Electric states, "Fuel with high levels of carbon residue can potentially create coke deposits on fuel nozzles," [8]. Coke deposits refer to the carbon build-up on the injector as well as the injector passageways. Therefore, an increase in coking leads to shorter intervals between maintenance and overhaul.

Material properties were obtained directly from the Haynes International material catalog [9]. Temperature dependent properties were critical for analytical verification using simulation software. Additionally, surface roughness and tolerances using Alloy X in additive manufacturing were obtained from a technical report by Solar Turbines [10]

2.2 Sponsor Requirements:

The sponsor of this project was the industrial gas turbine manufacturer Solar Turbines. Recently, the company developed a strategy of printing their fuel injectors using the material "Alloy X." As previously stated, this material greatly improves the existing injector process; however, new requirements have emerged. After an interview with our sponsor, the requirement specifics were made clear. To be a viable replacement design, the new tip design needs to double the service life of the existing injector which translates to a service life of 60,000 hours and overall reduce the companies' replacement and repair times. To achieve this goal, the tip temperature must not exceed 1350°F. Anything above this temperature will produce unfavorable material conditions and degradation in the long run. Furthermore, if fuel was used as a working fluid to cool the injector tip, the fuel temperature shall not extend above 750°F, to avoid premature detonation. Another set of requirements are due to the additive manufacturing technique. The geometry must be carefully considered since the structure has difficulty supporting its own weight if the surface angle exceeds 45° from vertical. This makes sections with overhangs especially difficult to manufacture.

Similarly, straight vertical holes relative to the printing surface have trouble maintaining a smooth edge. These two limitations are feasible but require extra design considerations.

As one can imagine, printing an injector tip and running a full-scale rig test is an expensive process. Before our sponsor entertained the idea of manufacturing our prototype and testing, our team was required to put the computer-designed injector tip through a series of simulations. This included a preliminary finite element analysis (FEA) of heat transfer followed by computational fluid dynamic (CFD) simulations. Additional research into FEA and CFD, with turbine simulation in mind, was carried out. Once the injector design proved to be a viable concept, the prototyping and testing phase began.

Given these key design requirements, a research study was conducted to find designs with similar interests. The results are shown in section 2.3.

2.3 Existing Solutions:

Our new tip was to be made of Alloy X that is able to sustain current tip temperatures. To find solutions to this issue, a research study was conducted finding patents with similar interests. The results are as follows, with each patent cited in Appendix I.

Patent US 2016/0201917, filed by United Technologies Corporation, handles the high temperature issue through an air-cooling technique shown in Appendix I. In this process, an air duct draws in discharged air from the compressor and sends the air in a helical pattern around the fuel rod before the fuel is delivered to the combustion chamber. This technique seeks to lower the tip temperature by using the air as a working fluid providing forced convection. The lower the entering fuel temperature, the higher yields of forced convection. This is a clever method of removing heat, but it comes with the price of research and development of an external air loop.

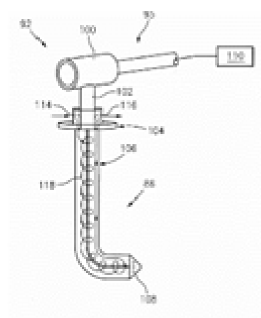


Figure 3. Swirling Air through Injector Arm.

An additional patent US 2020/0018234 was filed by United Technologies Corporation with the same goals. This method of cooling the injector involves an adjusted convection loop as well as a proprietary wall structure (Appendix I). The wall structure is made using additive manufacturing methods and behaves as a heat exchanger between the fuel and the cooling air loop. The same loop is applied from the previous patent but instead of a simple loop, the air travels through the fuel walls because of a lattice-like structure. The company calls this design a “vascular engineered structure lattice” because of its apparent lattice-like structure.

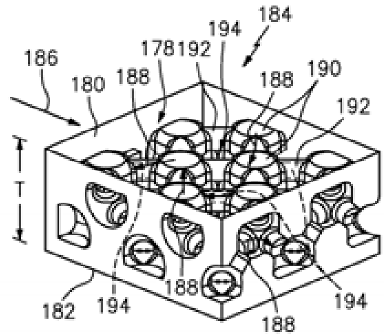


Figure 4. Vascular engineering structure lattice.

A simpler yet effective method of cooling is using the fuel as a working fluid around the combustion chamber. Here, the fuel runs through the walls of the combustion chamber, eventually making its way to the injector. This provides a simple way to cool the walls of the injector, using the fuel as a means of convection. This would typically work on an injector design, but since the injector housing geometry is beyond the scope of the project, this is not a viable option. Patent US 8,863,523 shown in Figure 5 (Appendix I).

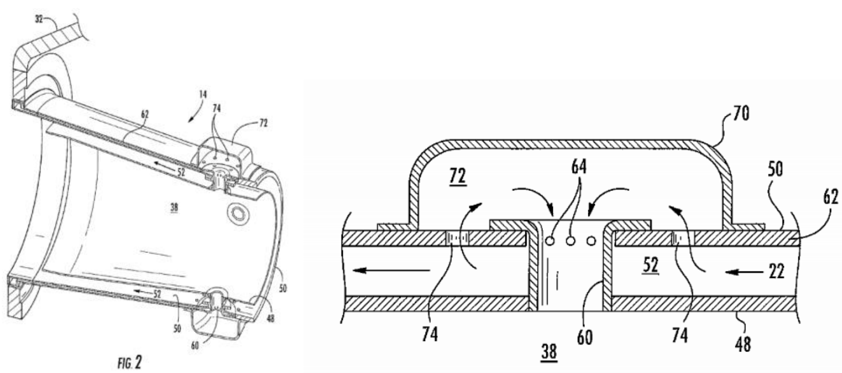


Figure 5. Combustion chamber (left), Injector cross-section (right)

Additional structure concepts exist for directing the air around the combustion chamber by Pratt and Whitney. Rather than a hollow passageway surrounding the combustion chamber, these methods demonstrate different construction methods and complexities, shown in Figure 6. Each concept utilizes film cooling yet contain quite different means of achieving this. In design A, film cooling occurs because of air passing through a corrugated structure. This method is somewhat simple as far as manufacturing and is straightforward as to air delivery. In design B, air enters through a series of holes in a ring surrounding the combustion chamber. In design C, compressed air “splashes” into the combustion chamber by means of angled slots around the outside of the combustion chamber. By far the most complicated structure takes place in design D. Here, a complex network of channels provides passageways for the air to cool the combustion chamber walls. Although these designs outline means of cooling the combustion chamber, and chamber cooling are beyond the scope of this project, these designs may lend expertise to a new injector tip design.

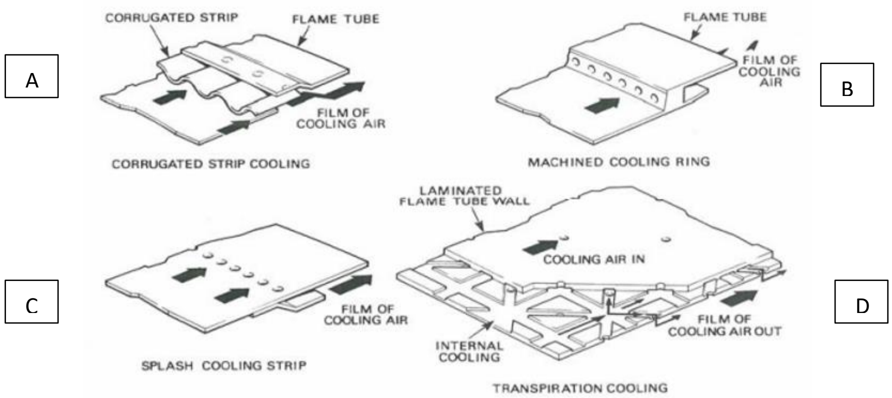
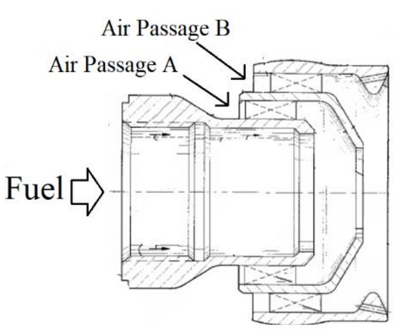


Figure 6. Alternative methods to provide film cooling.

The next design to be examined is a patent US 6,560,964 filed by Parker-Hannifin Corporation. This patent outlines the process for atomizing fuel through the injector nozzle (Appendix I). This design is mentioned for both its fuel delivery system, and air management. The fuel travels axially through a straight tube. However, the air flows through two separate passageways, A or B (Figure 7a). Air passage A is the preliminary air stream containing aerodynamic vanes (Figure 7b) causing the air to follow a helical path as it discharges into the flame tube. Next, air traveling through passage B also takes the helical shape as it runs through a separate set of air foils. This air intersects the combined swirling air of the fuel tube and air passage A. Finally, the total amount of air from all three paths exits into the combustion chamber as a highly atomized yet controlled spray of fuel. This patent capitalizes on the use of simple aerodynamic vanes rather than more complex geometrical shapes due to their tendency to minimize pressure drops of the fuel. Large fuel pressure decreases may form larger droplets resulting in non-uniform velocity profiles and therefore inconsistent combustion geometry. This design is of particular importance as it allows for benefits such as increased surface area, cooler injector temperatures, and better emissions. Droplet size is not relevant for our gas-only injector but provides background for injector design.



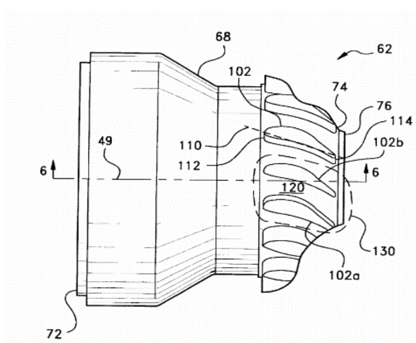


Figure 7a. Injector cutaway **Figure 7b.** Injector Air passage A cutaway

The final patent US 9,808,865 under review is filed by our sponsor, Solar Turbines, and outlines a method for carrying out the Additive Manufacturing process (Appendix I). This patent is shown in Figure 8 below. Since choosing powder bed fusion as the preferred AM process of choice, a common issue with dust is inevitable. When printing materials in this process, remaining powder can be time consuming and therefore costly to remove from the printed microstructures. To aid in production time and cost, Solar Turbines patented a method involving a controlled combustion within the printing space. The process goes by removing all air in the control volume and inserting a precise amount of combustible fuel into the chamber. Next, a carefully measured volume of oxygen is inserted into the combustion chamber allowing the two fluids to mix. Then, by a spark, the pre-determined mix ignites, removing burrs and dust from the inaccessible passageways of the printed part. This patent is important to our design because it outlines the finishing manufacturing process of the project.

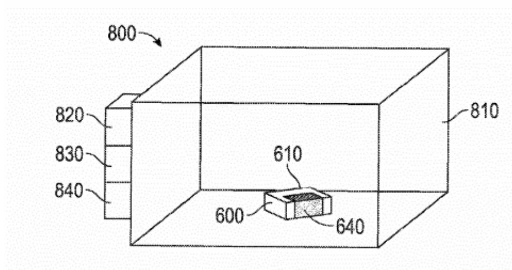


Figure 8. Solar Turbines' Additive Manufacturing combustion process

Chapter 3: Objectives

For the project to be successful and beneficial, the team had met or exceeded the requirements set by Solar Turbines. Results and validation of compliance with the requirements is necessary for the product to be a replacement for the current injector tip in use.

3.1 Problem Statement

Solar Turbines, one of the leading gas turbine designers and manufacturers, has requested a redesign of the injector tip in the Taurus-60 engine using Additive Manufacturing (AM) to decrease injector tip temperatures below 1350 degrees Fahrenheit. The current injector tip only has a service life of 30,000 hours and has many overhaul and maintenance costs. The new injector was to be printed as one piece using Alloy X, rather than using a material with higher thermal and corrosion resistance for the tip alone, requiring both pieces to be joined. Our goal was to redesign the injector tip and run Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) simulations to validate compliance with requirements, and with a desired service life of 60,000+ hours.

3.2 Boundary Sketch

Figure 9 depicts the boundary within the system where our design takes place. The fuel injectors are 12-total within the Taurus 60 engine, located along the circumference of the combustion chamber. The injectors are small part of the entire system, not being visible or interacted with by the operators when in use.

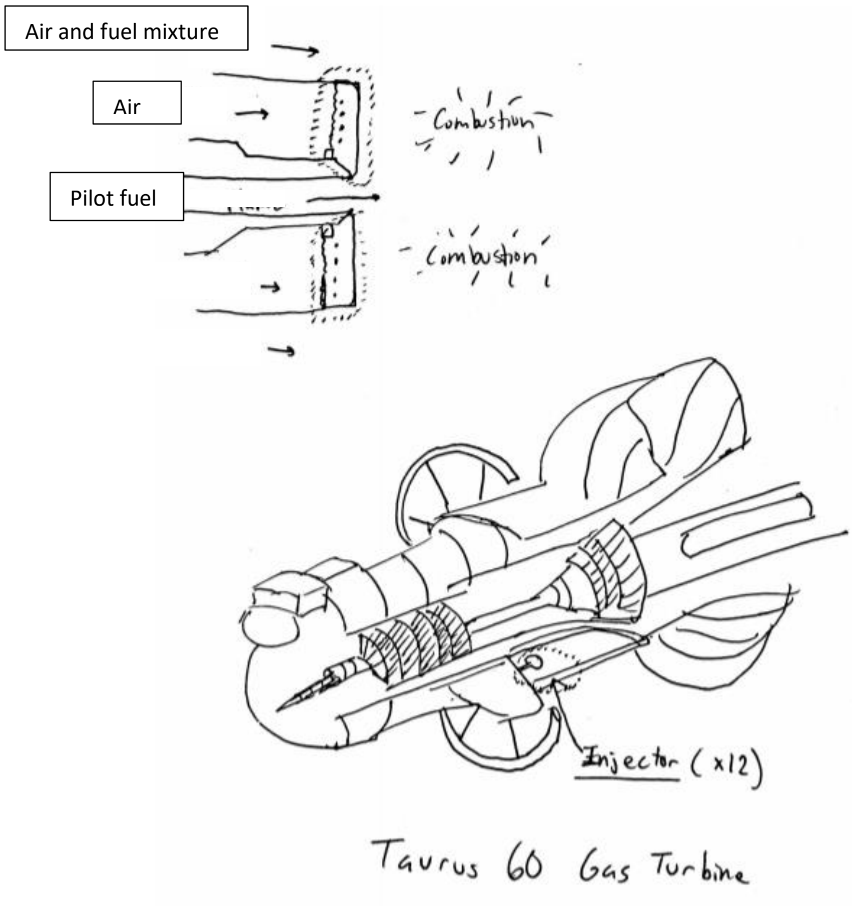


Figure 9. Boundary sketch of problem and design location.

3.3 Customer Wants and Needs

Requirements and limitations were provided by Solar Turbines to guide our design. These included a thermal limit, dimension constraints, and additive manufacturing compliance for the structure of the design. Table 1 lists the required "Needs" set by Solar Turbines for a successful product, and the "Wants" lists the additional characteristics of the project that would be beneficial if they could be developed or accomplished.

Table 1. Solar Turbines needs and wants table.

Needs	Wants
Product needs to be below 1350 ºF	Product to last two TBO's
AM compliant using Alloy X	Create a repair scheme
Fuel kept under 750 ºF	Create a clad process for multiple materials (bonding two AM materials)
No modifications outside of injector tip boundaries	Increase print capacity of AM machine
FEA and CFD simulations; modal analysis verifying compliance with needs	
Air flow limited to compressor discharge	
Injector printable as single piece	
1.57 in OD, 0.232 in ID	

Technical Acronyms:

1. Time Before Overhaul (TBO): 30,000 hours
2. Finite Element Analysis (FEA)
3. Computational Fluid Dynamics (CFD)

3.4 QFD House of Quality

The use of Quality Function Deployment is a method of defining the quantitative parameters needed for a design, garnered from, and compared to customer wants and needs, and considering how well other products compete. The output of the Quality Function Deployment (QFD) was represented as the "House of Quality", shown in Appendix II. The "WHO" section lists the customers and users our product is aimed at, namely Solar Turbines and the manufacturers. The "WHAT" section lists the customer requirements (needs and wants) that the product must meet, summarized in Table 1. Weight was assigned to each need/want, showing the importance of that requirement to each customer in the "WHO" section. The current product and similar competition were listed in the "NOW" section, with values displaying how each meets the requirements given by the customers. To meet the requirements of the customers, the "HOW" section lists specifications that are tailored to meet the variety of requirements, summarized in Table 2. The relationship between each specification and requirement is shown visually. Relationships between specifications are noted in the roof of the house of quality. Finally, the "HOW MUCH" section denotes specific target values that must be met for each specification, and how each product in the "NOW" section meets these target values.

3.5 Specifications

Final specifications required to qualify for potential replacement of current injector tips in use were determined from the Needs of Solar Turbines. The specifications were defined with emphasis on thermal compliance, additive manufacturing design forethought, and durability. Table 2 lists specifications and their relative characteristics. These specifications have been developed in our Quality Function Deployment, represented visually in our "House of Quality" provided in Appendix II.

Table 2. Specifications Developed in QFD

Spec #	Description	Target (units)	Tolerance	Risk	Compliance	Tests
*1	Service Life	60,000 hours	Min	H	T	Rig/Engine Test
2	Cost	$1500	Max	M	A	Cost Analysis
*3	Fuel Temp	750°F	Max	H	T	Rig/Engine Test
4	Tip Temp	1350°F	Max	H	A, T	FEA and CFD Thermal Analysis, Comparative Test
5	AM Compliant Geometry	45°	Max	M	A, I	3D Modeling and Printing
6	Size	Injector Boundary	Max	L	I	3D Modeling
7	AM Slot Geometry for Thermal Expansion	.001 in	Max	L	I	3D Modeling and Printing
8	Injector Tip Outer Diameter	1.57 in	Max	L	I	3D Modeling
9	Pilot Tube Outer Diameter	0.232 in	Min	L	I	3D Modeling
*10	Combustion Vibration	0.1 psi	Max	H	A, T	Modal Analysis

Risk of meeting specification: (H) High, (M) Medium, (L) Low; Compliance Methods: (A) Analysis, (I) Inspection, (T) Test

* Specifications 1,3, and 10 can only be analyzed or tested by Solar Turbines.

Specification descriptions:

1. Service life of the new design was required to last two Time-Before-Overhaul (TBO) periods with the new thermal environment and material of the successful design. The experienced environment of the tip was to be tested using computer simulation and a potential rig test. The rig test can only be done by Solar Turbines after submission of this report. Furthermore, Solar Turbines needs to implement this design and collect data to validate the service life.
2. Fuel temperature was limited to avoid the risk of premature combustion, verified using computer simulation and testing if fuel was rerouted for tip cooling.
3. Tip temperature was the primary limiting specification for our design, allowing the use of Alloy X for the entire injector and directly affecting service life. This was verified and analytically tested with computer simulation and potential rig test after report submission.
4. Compliant geometry for additive manufacturing was required due to the limitations in direction and angles of the AM method.
5. AM produces better results when holes/bores are at angles other than perpendicular.
6. Slot geometry in our design was specified for thermal expansion in the tip.
7. Production using AM has a generally high cost for our dimensions, limiting our test prints.
8. Outer dimensions of the injector tip have been specified to maintain compatibility with the injector structure.
9. Outer dimensions of the pilot tube have been specified to maintain compatibility with the injector structure.
10. Vibration amplitude may cause destructive resonance with the turbine. Modal analysis is required to verify amplitude is kept within limits. This can only be simulated with the rest of the turbine by Solar Turbines. The vibration test requires a combustion test, this Combustion Test can only be done by Solar Turbines.

3.6 Design Risks

The high-risk specifications for our design are the service life, fuel temperature, tip temperature and vibration amplitude. High risk specifications mean that they are difficult to achieve design-wise due to the complexity of the injector tip and design constraints. Previously, injector tips required replacement after one Time Before Overhaul (TBO) or 30,000 hours, due to corrosion in the high heat environment. With increased heat dissipation and lower tip temperature, it was expected for the new tip design to last two or more TBO’s. Fuel, if used in heat dissipation of the tip, was to be kept below 750 ºF to avoid premature combustion within the injector, potentially causing inefficient turbine operation and severe damage to the components. Lowering injector tip temperature was high risk due to the complex geometry needed to increase surface area. The design required analytical results (simulation) and then a rig test to prove that it lowered temperature within the limits specified. The viability of the design relied heavily on achieving this goal, as lowering the tip temperature was the parameter that allowed AM production of the entire injector using Alloy X. Vibration amplitude caused by combustion could cause significant damage to the entirety of the turbine and rig test. The combustion rig test will end prematurely if safety detectors note high vibration amplitude, which can lead to increased testing costs. Ensuring our design will meet the vibration threshold is high risk in the viability of the design. Verification of vibration compliance can only be accomplished by Solar Turbines after submission of our report and project.

Chapter 4: Concept Design Development

4.1 Ideation Process

Once the design parameters had been established, the ideation process followed. The beginning of the ideation process began with a functional decomposition of the product where the top three functions were identified: Comply with Additive Manufacturing (AM), Increase heat dissipation, and increase durability. An example of the function brainstorming process is shown in Figure 10. These functions were then broken up into subfunctions to provide more specific function requirements such as use of complex geometry, support additive manufacturing structure, lower tip temperatures, spread heat through body, increase surface area, and decrease corrosion. These functions are outlined in the Function Decomposition chart, which is provided in Appendix III.

Figure 10. Function brainstorming activity.

Next, models and prototypes were constructed with the main functions in mind. Physical models were built by each team member elaborating on a specific function using household items such as paper, tape, and glue. Each member constructed various function models with regards to heat dissipation, AM compliancy, and durability. Figure 11 displayed some of these ideation models. Once the models had been laid out, a formal decision process started.

The results may be found in Appendix IV.

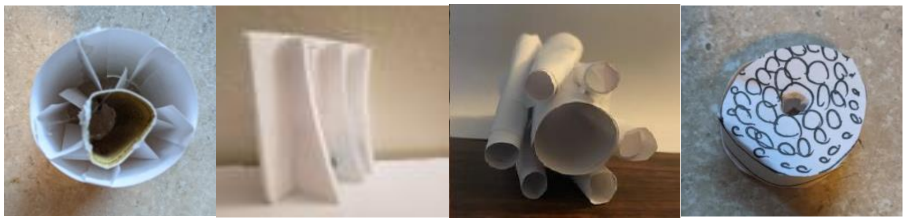


Figure 11. Ideation models

4.2 Selection Process

The first stage of design direction selection came in the form of Pugh Matrices. These are tables where each of the models are ranked better, worse, or the same as the existing design regarding the sponsor criteria. Each group member made their own matrix for a certain function. The three Pugh Matrices may be found in Appendix V. The purpose of the matrices was not necessarily to decide a winner but help guide the brainstorming process. The results of the matrices proved that the team's ideas were valid yet needed more qualifying criteria if an idea were to be selected.

Morphological Matrices provide a template for viewing all possible combinations of models that fulfill the necessary functions. From the combination of our Pugh Matrices, the top models were then inserted into the Morphological Matrix, shown in Appendix VI, and the feasible combination of models for each function were combined sequentially into system concepts. The resulting top 6 ideas, chosen through group decision, are displayed next.

4.2 System Concepts

Figure 12 depicts our first idea from the morphological matrix (Appendix VI). The helical-like fins follow additive manufacturing (AM) geometry, increase heat dissipation, and thin stems to increase durability. Based on the preliminary calculations, the fins would aid in dissipating heat and increasing the surface area would lead to more convection with the helical structure of the fins. The thin stems give it a dense fin layout, increasing surface area for convection. The radially increasing space between fins helps guide the airflow away from the path of least resistance at the center to the outer sections of the fins, allowing more airflow over the entirety of the fins.

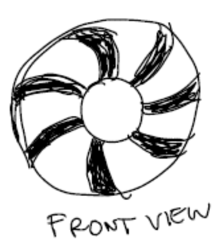


Figure 12. Helical fins with thin stems.

Figure 13 depicts the second idea with helical fins revolving at up to a 45-degree slope from the horizontal plane. The helical fins fall under the Additive Manufacturing (AM) complex geometry requirement, heat dissipation requirement, and the 45-degree angle fulfills the feasibility function (Appendix VI). The high angle creates a winding path through the injector, in theory forcing the airflow to dissipate more heat due to the longer contact with each fin. Furthermore, the angled fins will create a swirl effect that may help dissipate heat faster after combustion.

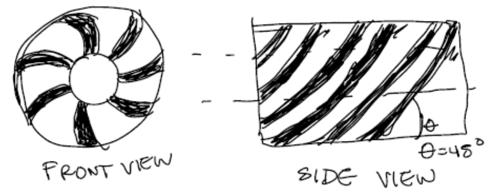


Figure 13. Helical fins at 45 degrees.

Utilizing the fuel to aid in lowering the tip temperature was a possible design consideration. By implementing a porous structure for the fuel to pass through, the higher convection coefficient of fuel in comparison to air would, in theory, increase heat dissipation at the injector tip. Figure 14 shows a possible porous structure that could be used with the fuel to lower the tip temperature. The fuel tunnels discussed in Figure 14 would be angled at up to 45 degrees to comply with additive manufacturing restrictions, increase heat dissipation through surface area, and increase additive manufacturing (AM) complexity (Appendix VI).

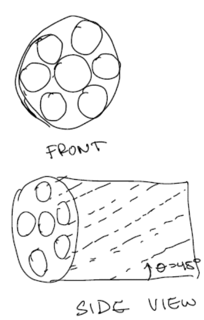


Figure 14. Porous structure with fuel tunnels at up to 45 degrees.

A porous structure for airflow at the injector tip may allow for sufficient heat dissipation. Figure 15 shows a simplified porous structure, where the entrance for air and fuel mixture are at 45-degrees. The variety of pathways for airflow increases surface area promoting more heat dissipation via convection (Appendix VI). This is similar to an idea already proposed, but the change with the holes' linearity increases surface area and heat transfer to the air.

Figure 15. Porous structure with 45-degree angle holes.

Tall vertical fins, shown in Figure 16, are the simplest of the outputs from the morphological matrix. Tall vertical fins support the additive manufacturing (AM) geometry, increase heat dissipation through its greater surface area, and fins have proven to be durable (Appendix VI). The vertical fins would potentially the lowest drop in the air or fuel used. Additionally, a dense structure allows for high surface area greatly increase heat dissipation. A variety of vertical fin designs may be implemented.

Figure 16. Tall vertical fins.

Figure 17 shows a porous structure that could be implemented in a way promoting turbulent flow and increases in surface area. In general, higher turbulence promotes greater heat dissipation for convection. The porous structure fulfills the additive manufacturing (AM) geometry, turbulent flow to increase heat dissipation, and the 45-degree angle holes to increase print viability and part durability. A structure such as Figure 15, potentially layered with angled holes or encapsulating more of the interior of the injector, could allow for large surface area and turbulence, dissipating great amounts of heat from the tip (Appendix VI).

Figure 17. Porous structure for turbulent airflow.

Changing the inner dimensions of the injector tip into a nozzle form could allow for nozzle effects that promote increased flow over the fin structure, shown in Figure 18. Thin rounded stems for the fins can allow for a dense fin structure, creating much surface area for heat dissipation. The inspiration behind this idea was through the increased flow velocity achievable in converging-diverging nozzles, but the relevance relies on the flow conditions of the air supplied (Appendix XI).

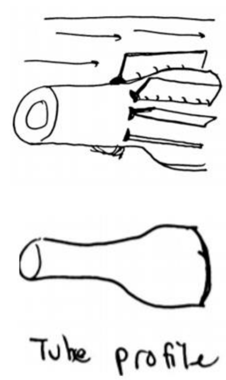


Figure 18. Changing AM dimensions with fins and thin-rounded stems.

4.3 Weighted Decision Matrix

A weighted decision matrix was used to compare the design direction combinations and attempt to qualify the best design direction. This lead our concept design direction to incorporating fuel and porous structures in our design (Appendix VII). This system-level idea maximizes the fulfillment of the specifications needed by Solar Turbines on a qualitative estimate basis. The reliance of the design on analysis to definitively choose a concept prototype design direction caused difficulty in pinpointing the design that would produce the best results and consequently made it impossible to choose a definite design direction. Highly involved analysis using finite element analysis and computational fluid dynamics, planned for later in this design project, was required to choose the design direction. As a result, our team opted to create the top three concept prototypes as CAD concept models. The concept prototypes are explained in the next section.

4.4 Concept Prototypes and Preliminary Analysis

The following preliminary design models are the top three ideas by the weighted decision matrix. The team started the preliminary design models by creating a concept prototype, shown in Figure 19. The vertical fin design was chosen for a physical model due to the ease of prototyping compared to the porous structure, and it was a close second in the weighted decision matrix. The concept prototype features fins that would help dissipate heat, but the team quickly realized that we could not make the complex shapes desired by conventional prototyping. Hence, the team opted to create CAD concept models to better capture the complex shapes of the proposed concept prototypes. The top three concept prototypes are explained along with the CAD visuals below.

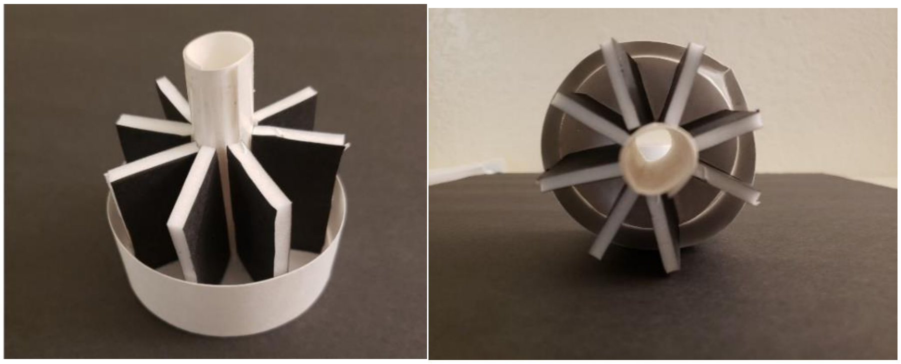


Figure 19. Physical Concept Prototype of design 1.

The fuel routing and porous structure at 45-degree angles in design 1 is shown in Figure 20. Compressor discharge air would travel around the pilot fuel tube and enters the tip through a series of holes cut at 45 degrees. Some fuel would be routed through fuel tunnels that extend radially on the other side of the porous structure. Air would exit through an exit orifice with previously approved dimensions.

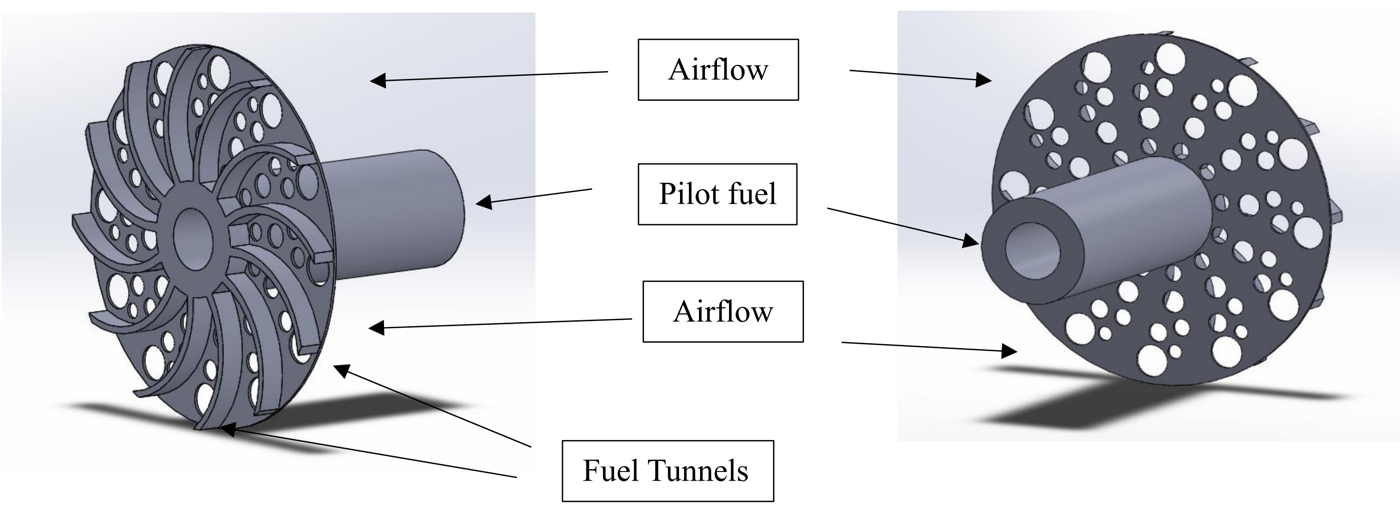


Figure 20. Design 1 using a porous structure with fuel tunnels at 45-degrees

Design 2 is shown in Figure 21 where concentric circular and vertical fins are used to increase heat dissipation. This design builds off the concept prototype, where limitations of physical modeling limited the structure. The concentric and vertical fins increase surface area and increase heat dissipation abilities. The spacing between the concentric fin structures can be used to guide airflow based on spacing between the concentric fins. The model shown in Figure 21 was simplified and does not completely adhere to Additive Manufacturing limitations, serving more as a visual concept. The design could be adjusted to allow AM production.

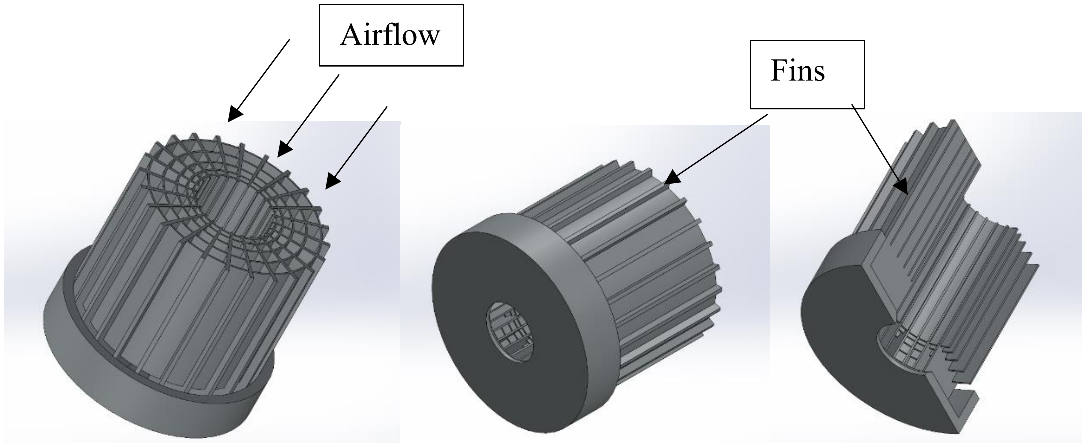


Figure 21. Concentric circular fins and radial vertical fins

Figure 22 features the third concept design of a porous structure at 45-degree angled holes to help focus the air and fuel mixture at the tip. The 45-degree angled holes complies with additive manufacturing (AM). The angled holes increase surface area and increase heat dissipation abilities.

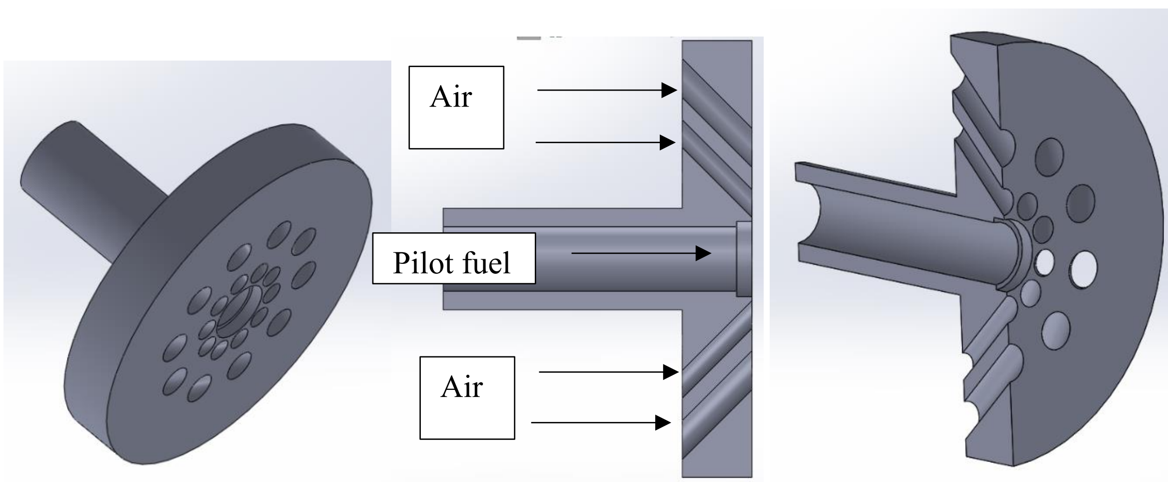


Figure 22. Porous structure with 45-degree angled holes

In terms of preliminary analysis, the team used thermal contour, shown in Figure 23, to demonstrate the temperature difference between fins versus no fins. Furthermore, a crude heat transfer calculation between the given parameters such as the ambient temperature, injector tip temperature, the coefficient of thermal convection, and the coefficient of thermal conduction heat transfer coefficient provided some validation for our designs (Appendix VIII). The results of the simplified heat transfer show that if we assumed the tip temperature to be at our threshold of 1350 ºF, along with some other assumptions shown in Appendix VIII, the heat dissipation into the air from the injector tip is greater than the heat into the injector from the combustion. The calculations were inherently wrong from an energy balance and steady-state perspective but were simplified to give some confidence as to the heat dissipation abilities.

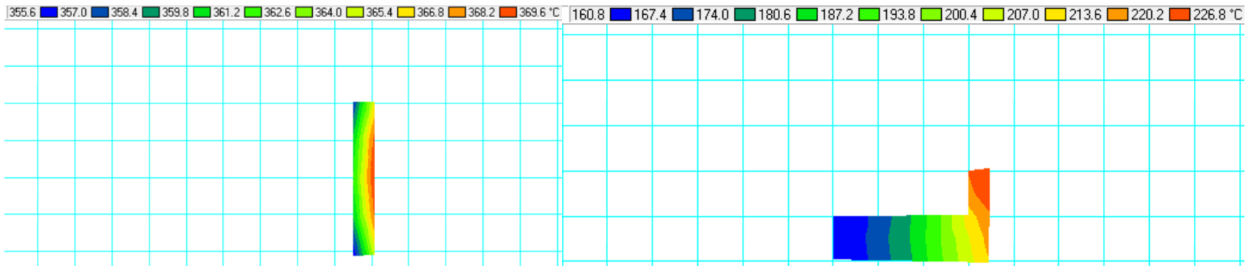


Figure 23. Finite Element Heat Transfer (FEHT) Temperature Contour; non-fin structure (left), fins (right)

4.5 Design Hazards and Unknowns

The concept prototype selection process for our injector tip had certain unknowns as well as a few hazards. The Design Hazard Checklist, shown in Appendix IX, summarizes the lack of many hazards in this design project. One hazard in Additive Manufacturing is the presence of metal powders; however, the risk of being exposed to enough powder to cause metal toxicity is low. Safety protocol practices are in place at Cal Poly and at Solar Turbines to limit exposure.

One potential hazard not listed in the Design Hazard checklist was the potential for catastrophic failure with one of our concept prototypes using fuel for heat dissipation. The purpose of the injector is to efficiently supply fuel into a combustion chamber; however, utilizing the fuel to dissipate heat would raise the fuel temperature, creating a risk of pre-detonation that could lead to an even larger failure within the gas turbine. For this reason, the Specification Table in Section 3.5 lists the fuel temperature as a high risk.

As for unknowns, each of the concept models was an educated guess for the thermal effectiveness as the initial analysis is quantitatively limited and inaccurate. This created the risk that potentially none of our designs would succeed in replacing the current injector tip if the temperature is not within our design threshold. Table 3 provides a summary for the hazards.

Table 3. Hazards Table

Description of Hazard	Corrective Action	Planned Date	Actual Date
Alloy X material for AM printing	Inhaling this metal powder can be dangerous, but Cal Poly has implemented safety protocols to handle this material	Spring 2021	Spring 2021
Using Fuel for heat dissipation	Fuel for heat dissipation must be tested or design direction deviate.	Spring 2021	Spring 2021
High Tip injector Temperatures	No user in direct interaction with the injector tip while it is experiencing high temperatures.	Winter 2021	Winter 2021

From the hazard checklist, the project also falls within exposure to high temperatures. The extreme temperatures witnessed by the injector would be harmful if anyone were to come into proximity with the assembly. The entire process takes place within a controlled room, so no one would be in direct interaction with the injector tip while it is experiencing high temperatures. In addition to the hazard checklist, the high temperatures were also rated as a high risk on the Specification table. This is due to high corrosion of the injector tip if the temperature exceeds 1350°F. Once enough corrosion happens to the part, the turbine must be overhauled, and the part would be replaced. For this reason, the high temperatures imposed a high risk on the project.

Other cautions were previously listed in the specifications in Table 2 found in Section 3.5. Each specification's risk was rated as low, medium, or high. Most of the specifications are low yet were listed as high risk and should be mentioned. The service life was ranked as a high risk for several reasons but most importantly it was the driving force behind this project. The original injector designed by Solar Turbines can sustain high temperatures for 30,000 hours which equates to one Time Before Overhaul or TBO. Our new design must improve on service life by surviving 2 TBO's for the project to be validated.

Another important risk the team must address was vibration of the injector. Vibration may occur inside the injector itself, in the combustion chamber, and propagate through the entire turbine. When fuel and air flows through the injector at high velocities, the fluid could create waves and therefore vibrations. Inside the combustor, the shockwave from the explosion could also cause vibrations on the injector. Both scenarios yield unwanted results as vibrations cause mechanical stress and lead to decreased service life. This vibration can only be tested during a controlled combustion test by Solar Turbines. Table 3 summarizes the description of hazards and corrective actions.

Chapter 5: Final Design Iterations

5.1 CAD

After undergoing the comprehensive selection process previously mentioned, three of our final designs were selected for further testing. This included the model provided by Solar Turbines with the addition of fuel tunnels (Design 1), a design utilizing fin structures (Design 2), and a model that combined the use of a porous structure (Design 3). Detailed two-dimensional drawings can be found in our drawing package, Appendix XIII. The following showcases the final CAD models for all three different models used in simulation, along with an explanation of their design.

5.1.1 Design 1

Figure 24 and Figure 25 are SolidWorks drawings of our first iteration of Design 1, having fuel tunnels that run through the face of the tip. The idea behind this design was that gaseous fuel would be diverted from the main fuel-carrying spars and sent through small tunnels that pass through the face of the tip. This would provide more effective cooling since the specific heat capacity of natural gas is much larger than that of air. This design would be effective if the temperature of the fuel stays below the critical flashpoint temperature of 750°F. This is a concern of the design and is mentioned in the potential hazards section of this report (Section 4.5) as wells as the Failure Modes and Effects Analysis (Appendix X). Previously, the walls were originally 0.08 inches thick but were increased to 0.16 inches to support the tunnel and shield the fuel from heat. Figure 24 shows the basic tip structure with a cross-section of the outlet face. Figure 25 shows a sectional view of the tunnels. This drawing took the outer bounds of the existing tip from Solar Turbines, doubled the wall thickness, and made a fuel passage through the walls. The complex lattice structure was erased so that this design can serve as an addition to existing tip iterations. If this design provesd as a viable solution to the cooling issue at hand, the tunnel design would be added to any other design by simply importing the thicker walls and tunnel passages. This would cause the overall diameter to increase to a diameter greater than allowable parameter of 1.57 inches, so the adapted part must be scaled by a factor so that the original diameter returns. Furthermore, the tunnels placed just behind the tip face did not alter the existing tip wall thickness at the combustion chamber. This allows for a smooth process if the fuel tunnels were imported into another drawing.

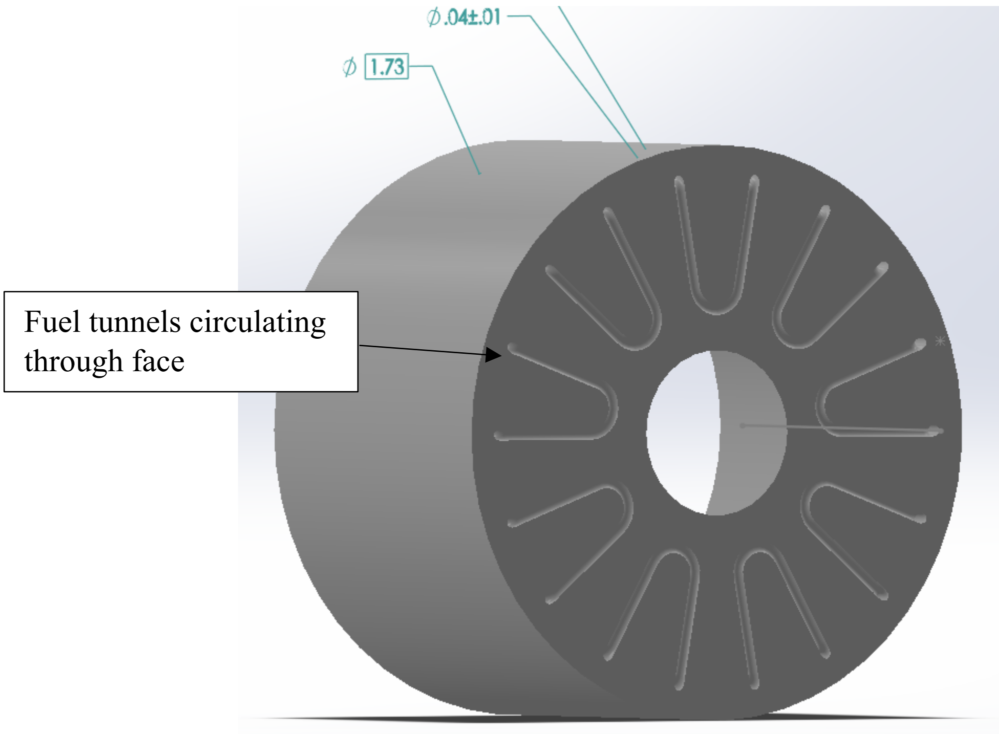


Figure 24: Fuel Tunnels shown without tip face.

Inlets/outlets of fuel tunnels through face

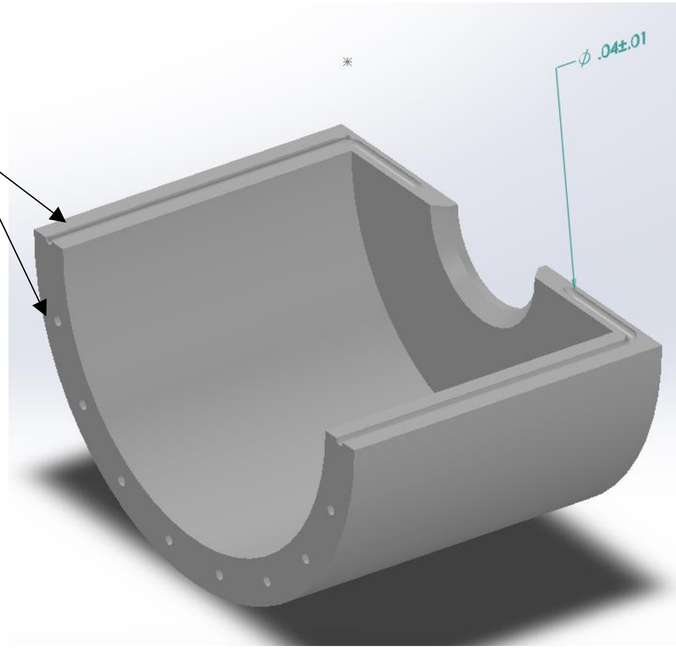


Figure 25: Fuel Tunnels shown with sectional view.

5.1.2 Design 2

The Design 2 iteration is pictured below in Figure 26 and 27. This design built off the original tip dimensions and combustion chamber hole geometry with added heat dissipating fins. The theory was that the compressor discharge air would pass between the protruding heat fins and exit through the slot geometry at the base. Conduction would transfer heat along the fins towards the rear of the injector tip. This provided convective cooling as the discharge air enters the tip at a temperature supplied by sponsor while the outside tip is at approximately at a temperature supplied by sponsor. The design of the fins provided structural stability to the tip and would help the cooling air reach into each of the corners of the injector tip. The fins and connections had fillets to meet production guidelines.

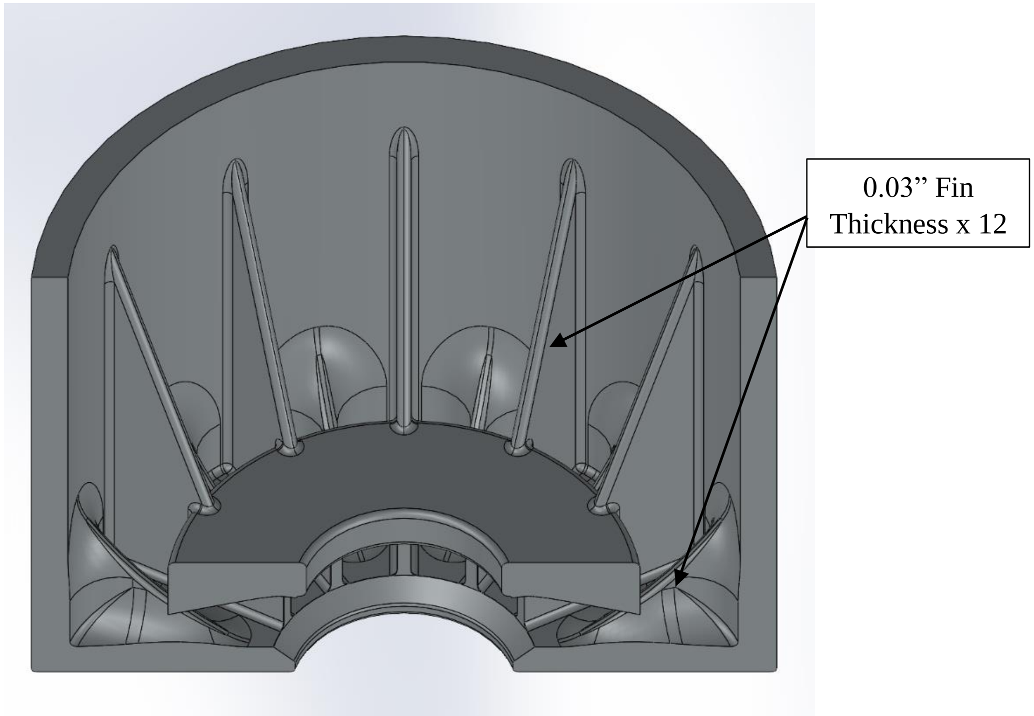


Figure 26. Design 2, fin design cross sectional view at 45 degrees.

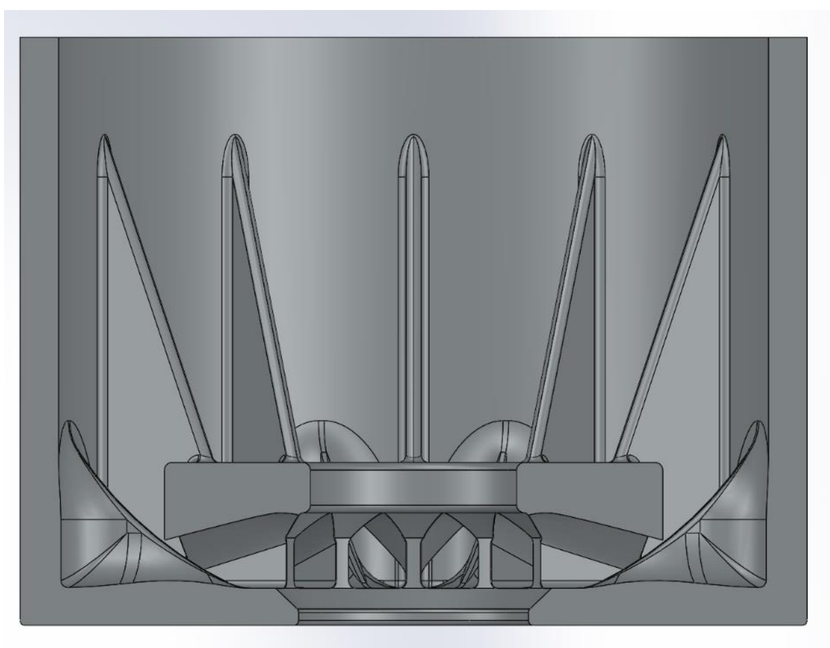


Figure 27. Design 2, fin design cross-sectional view.

5.1.3 Design 3

Design 3 involved a mix of the ideas discussed in the ideation sections of this report and the existing model supplied by Solar Turbines. This design also built off the base dimensions and hole geometry as in the previous model. Here, compressor discharge air was to flow through the injector through a series of linear cut holes. A series of 4 holes radially replicated 15 times regulates the air volume so that exiting velocity and pressure could be controlled. Each of the 15 sets of holes would direct the air flow through an individual channel. These channel walls provided support for the structure printed on top and act as heat fins to contribute to heat dissipation for the outer parts of the tip. The channels share similarities with the lattice structure in the existing design. Figure 28 shows a cross-section of the porous design, Figure 29 is a cross-sectional isometric view, Figure 30 is a left side view of the design, and Figure 31 is a porous design left side isometric view.

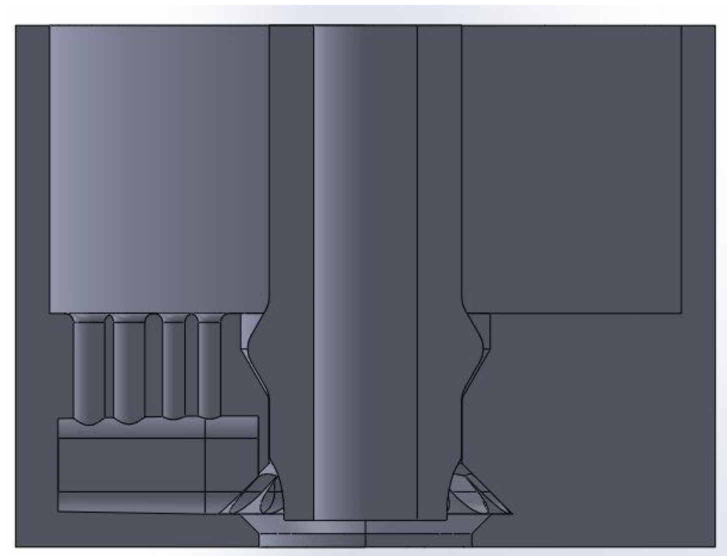


Figure 28. Design 3, porous design cross-sectional view.

Shown above is a sectional view of the third design iteration. Notice the linearly cut passageways for the air to pass through as well as the radial slots at the exit.

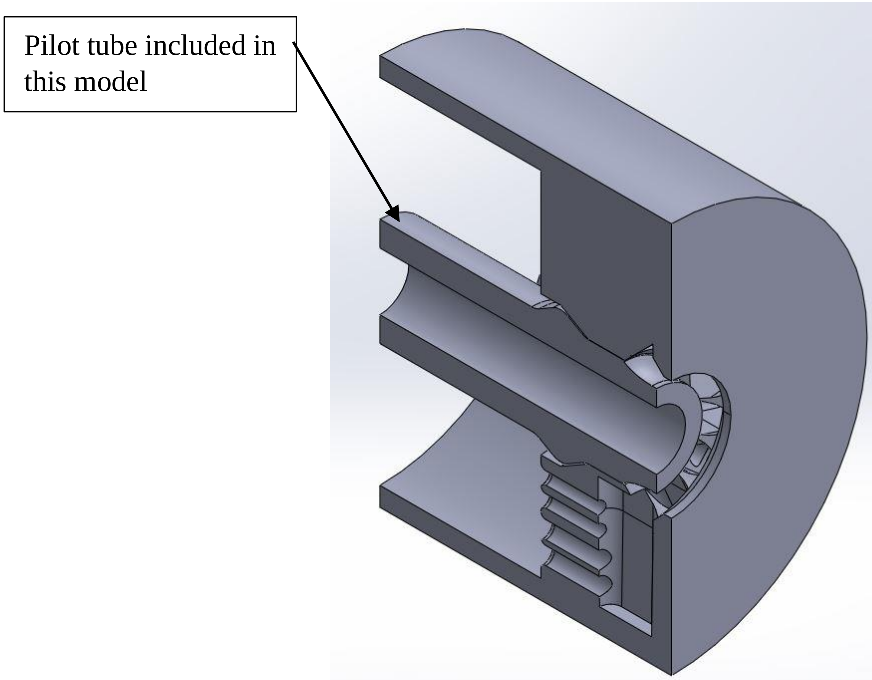


Figure 29. Porous design cross-sectional isometric view.

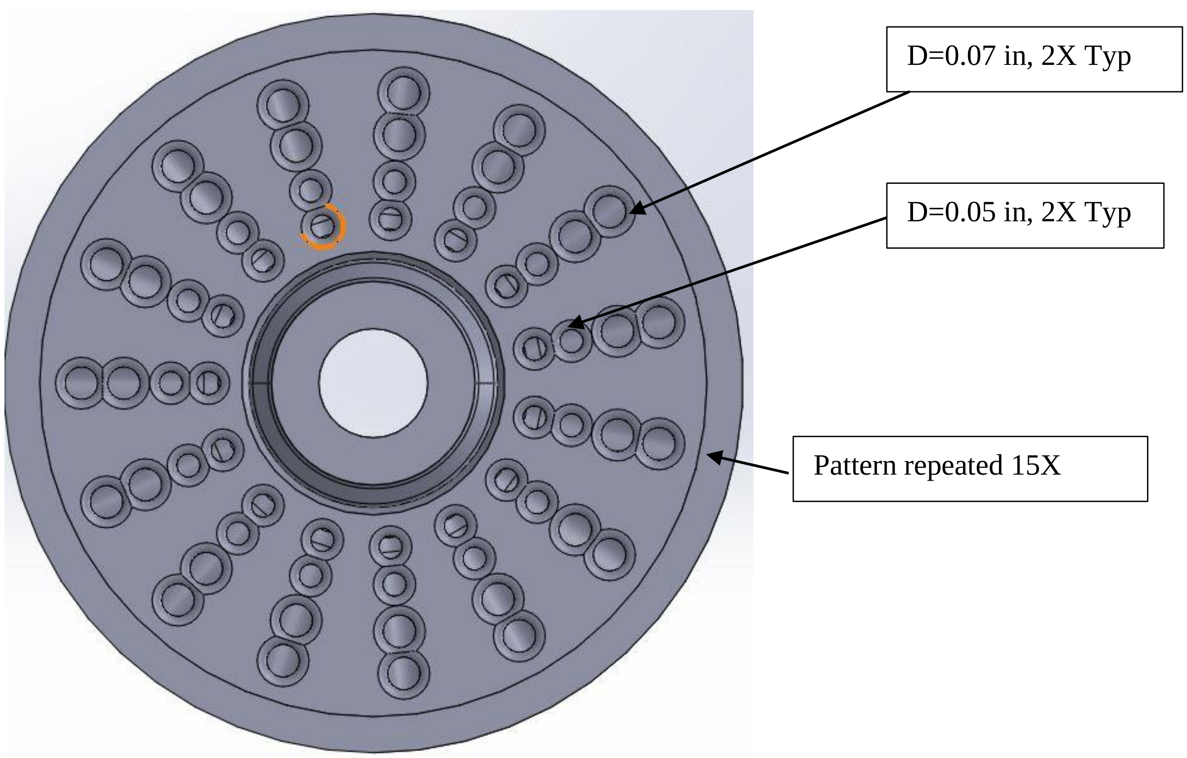


Figure 30. Porous design left side view.

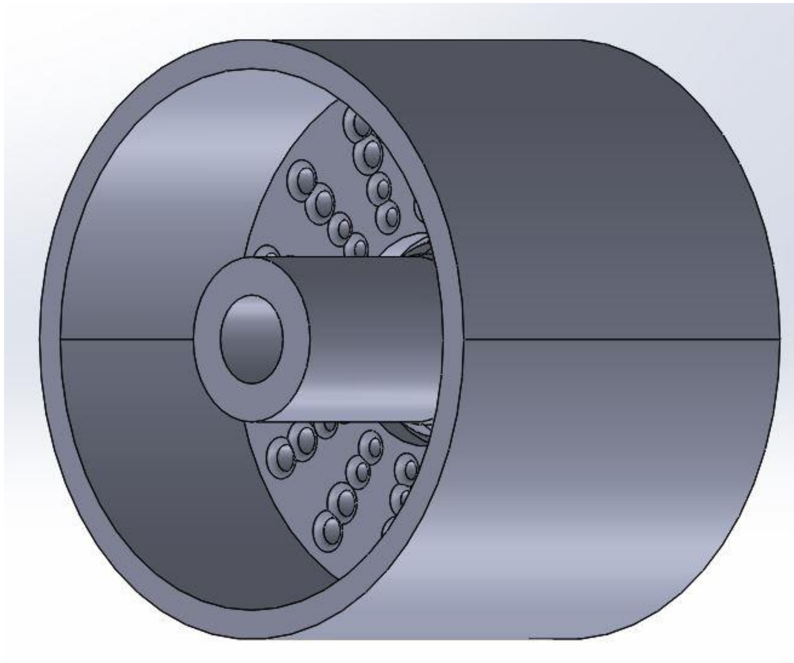


Figure 31. Porous design left isometric view

5.2 Structural Prototypes

The final three iterations shown above were sent to The Innovation Sandbox to be 3D printed. These structural prototypes served as AM printing verification and affordable way to see whether the prototypes follow Additive Manufacturing (AM) printing constraints. Figure 32 showcases the 3D printed designs of the Solar Turbines model provided, the fin prototype, and the porous prototype. Figure 33 is an individual picture of the porous design and Figure 33 is the Fin Design. These 3D printed parts served as proof that an AM printer will be able to print these prototypes with an easier ability because 3D printed plastic has worse tolerances and rougher surface finishes.

In Figure 32, the final three design iterations have been printed. From left to right are the existing design proposal, heat fins, and porous structure.

Figure 32. Structural prototypes 3D printed from plastic.

Figure 33. Porous Design 3D printed structural Design.

Figure 34 shows the fin structure print in greater detail. A cross-section was taken to verify the integrity of the channels.

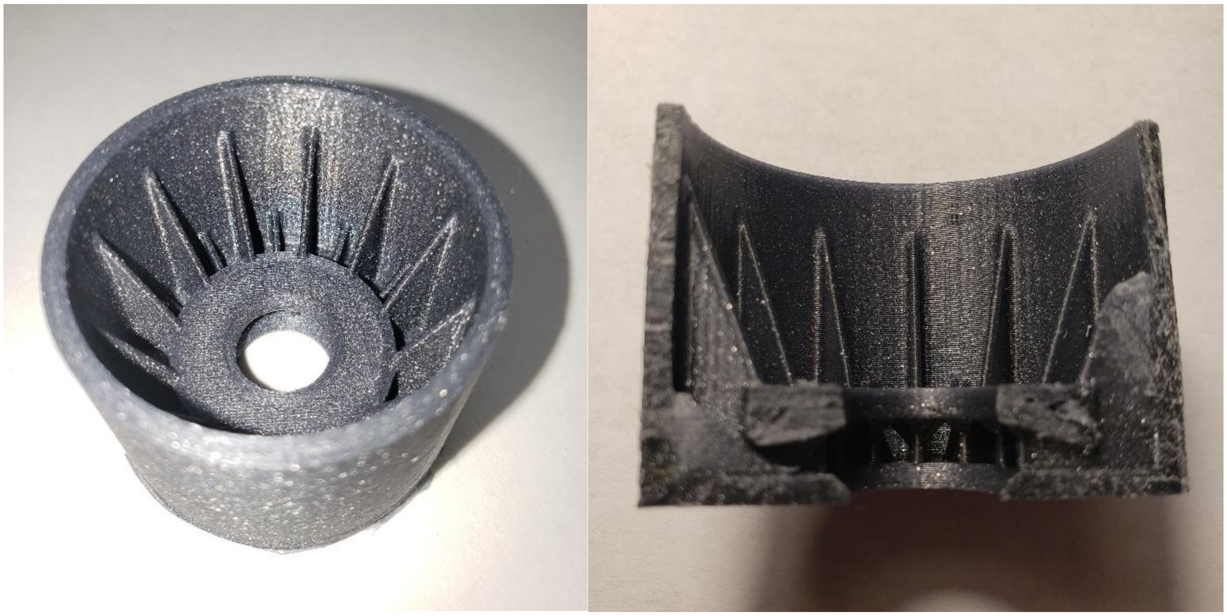


Figure 34. Heat fin design 3D printed with no structural defects.

These 3D printed models gave a sense of how the designs would result in a full-scale additive manufactured print. Since the models printed with high detail and little imperfection, this gave confidence that these models had a high possibility of printing without error. The approval by the additive manufacturing team on campus was likely. This possibility is discussed in further detail in Section 5.4.

5.3.1 Analysis

Given these designs, the models were analyzed to measure heat transfer, pressure gradients, and velocity distributions. Further analytical tests are still needed such as analysis of stresses and modal analysis. It is important to state the team has limited experience in the simulation programs and techniques used. The methods developed were obtained from research and guidance from professional engineers with experience. The approaches were deemed reasonable when speaking to a simulation engineer at Solar Turbines.

Analytical results from simulation were obtained, namely Abaqus FEA to model heat transfer and both SolidWorks and Ansys for Computational Fluid Dynamics (CFD). In short, each of these programs used computational methods to produce quantifiable approximate results. Regardless of the program used, each simulation started with initial boundary conditions that specify the properties of the part and conditions in question. Shown in Table 4 are the values for compressor discharge air pressure, inlet velocity, outlet velocity, air temperature, surface roughness, and outer tip temperature. Velocities at specific locations were estimated from a given contour of flow in a rig test simulation. Material properties were obtained directly Haynes International and converted to required units [10].

Table 4. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) Boundary Conditions Table

Name	Value	Units	Description
Compressor Pressure (Reference)	*	Psi	The compressor discharge (Pcd) pressure used as a reference.
V_{in}	*	ft/s	The velocity of air inside injector tip.
V_{out}	*	ft/s	Velocity of air outside of injector tip.
T_{air}	*	ºF	Temperature of air from compressor
ε (surface roughness)	*	μin	The average surface roughness of laser printed parts. This surface will be considered for both FEA and CFD analysis.
Tip outer surface temperature	*	ºF	The outer surface of the injector tip has been given to experience this temperature.

***Supplied by sponsor**

5.3.2 Finite Element Analysis Heat Transfer

The limited knowledge and resources for computation fluid dynamics for our team had caused the analytical verification of our designs to initially rely on heat transfer analysis using finite element analysis (FEA) in Abaqus to estimate heat dissipation and thermals experienced throughout the injector tip. The main goal of the injector tip redesign was to dissipate the most heat possible using the surface area and its geometry. Boundary conditions, flow conditions, and boundary temperatures were averaged from cross-sectional velocity and temperature diagrams provided by our sponsor. It is important to note that Abaqus is a unitless solver, and as such, great care was taken to include material properties and boundary conditions in consistent units. Values listed in ft were converted to inches for unit consistency when input.

The approach for modeling the combustion heat flux and convective heat dissipation conditions is shown explicitly in Appendix XII. The pressure and air temperature changes were relatively small, and thus assumed constant for calculation of properties. Reynold's number calculations indicated that turbulent flow was present at both the inner and outer flows at the injector tip. Assumptions for the Reynold's number included assuming the characteristic length for the inner flow conditions to be the inner diameter of the injector tip and the length an estimated characteristic length of the injector body. The different characteristic lengths for the two flows were a result of the Nusselt correlation used for each case. The surface roughness of a final AM part, after the HIP treatment [9], is noteworthy and yielded the use of the Gnielinski correlation for pipe flow with rough surfaces (Appendix XIII). Pipe flow was assumed for the inner injector flow; however, this was only justifiable prior to the flow contact with the complex structures near the exit of the injector tip. This assumption was taken to be conservative as greater turbulence at these structures would result in greater convective heat dissipation. For the outer flow over the injector tip, a flat-plate Nusselt correlation was assumed. The heat transfer at the outer surface was taken to be constant across models compared to the heat transfer from the internal structures. The convection heat transfer coefficients are listed in Table 5.

Table 5. Convection coefficients for finite element analysis surface conditions at interior and exterior.

Convection Coefficient	Value	Units
$\hbar_{in}$	112	Btu/hr °F ft
$\hbar_{out}$	206	Btu/hr °F ft

Analysis of the models was accomplished using a steady-state condition. All models were meshed using a 4-noded linear tetrahedron element. Due to the 100,000 nodal limits of the academic Abaqus license, a lower order element was preferred to allow for a finer mesh. Figure 33 displays the results of the convergence study on the inner face temperature of our base model, a mockup of Solar Turbines' current model in use. It is expected that additional increase in element number would result in a clearer asymptote. This asymptotic behavior is seen in the convergence study seen in Figure 35.

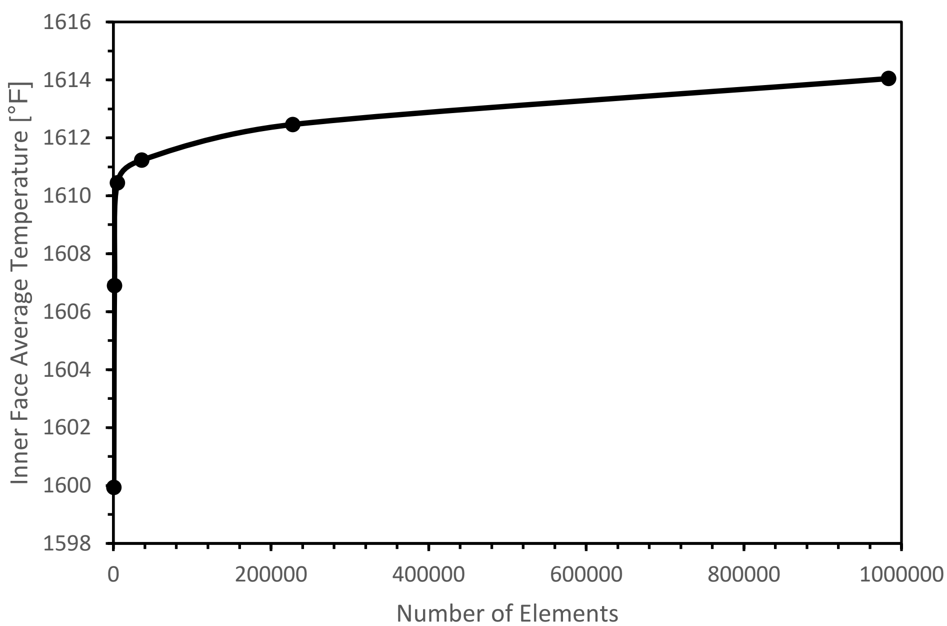


Figure 35. Inner face average temperature convergence study.

A boundary condition of 1650 °F was placed on the surface of the injector tip. Figure 36 below shows the boundary condition and the heat conduction through the base of the injector tip where no structure is used for the purpose of heat dissipation through convection. This model approximates the current design surface in use by Solar Turbines and it will serve as a reference point.

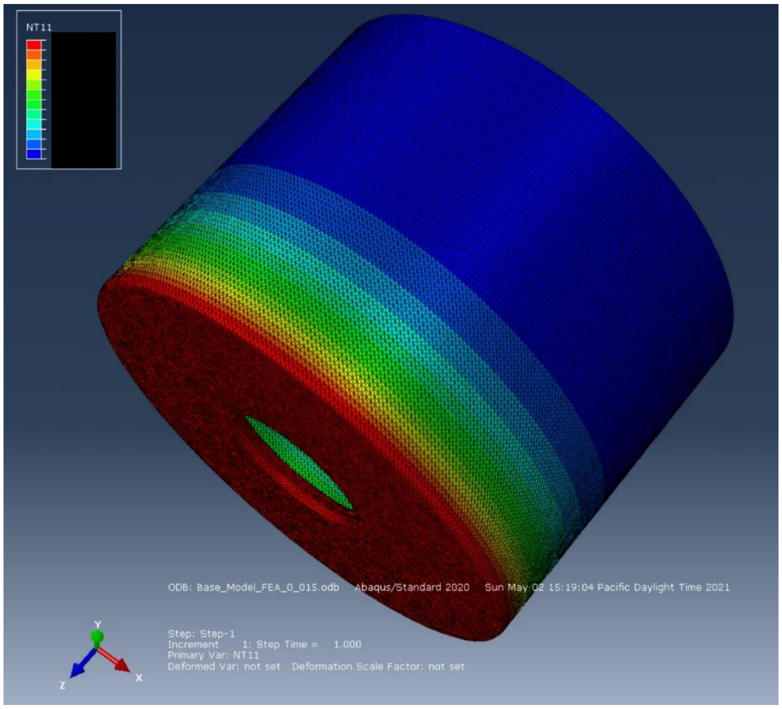


Figure 36. Isometric FEA view of current design with tip boundary condition shown.

The convection heat transfer was modeled as a film interaction on the surface of the injector tip. The relevant heat transfer coefficient was used for the inner and outer surfaces, with the sink temperature set to the assumed constant air temperature. Figure 37 depicts the cross-section of the injector tip. Heat propagates through the solid. In both cases, due to the lack of structures to dissipate heat through convection, it is seen that the high thermals are focused on the outlet face.

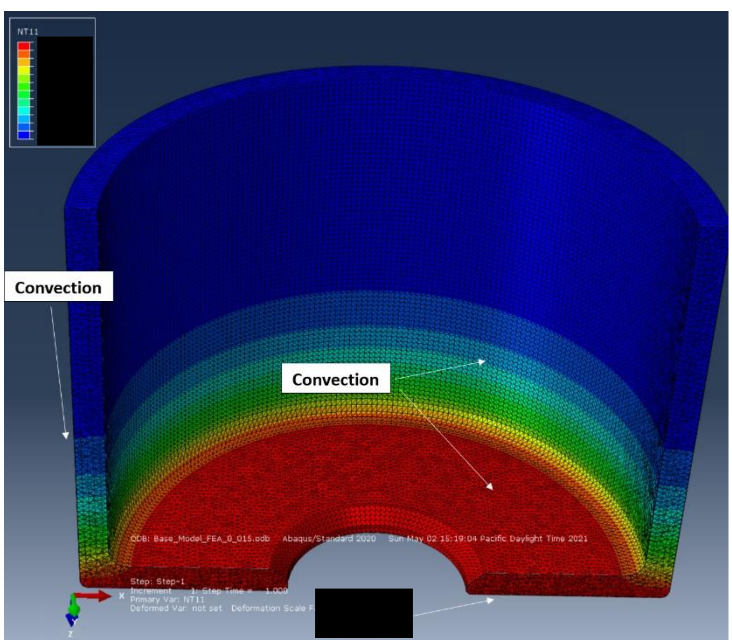


Figure 37. Cross-section FEA view of current design.

The tip surface temperature at 1650 °F and convective heat transfer interactions were placed on Design 2 utilizing fin structures to conduct heat away from the tip and dissipate through convection, shown in Figure 38.

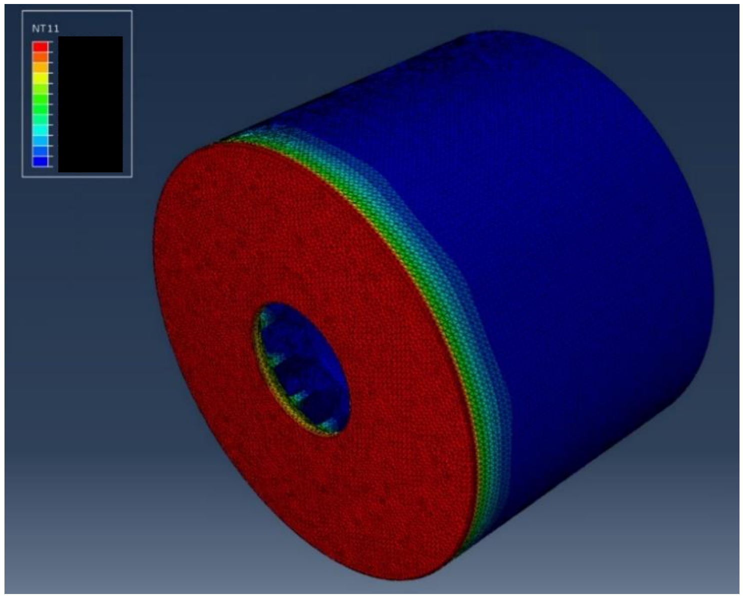


Figure 38. Isometric FEA view of fin design with tip boundary condition shown.

Figure 39 depicts a cross-section view of the fin design, Design 2. In this design heat propagates through conduction towards inlet of the injector through the heat fins. Convection dissipated the heat through the surface film condition. An average inner surface temperature was found 1548 °F, a 66-degree decrease compared to the base model.

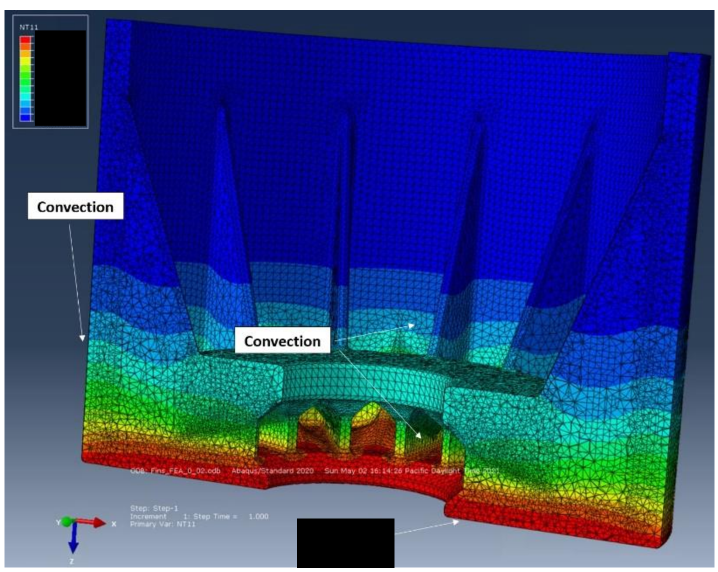


Figure 39. Cross-section FEA view of fin design temperature contour.

The exact conditions and mesh were applied to the porous structure design, Design 3. Heat transfer through the dense structure and the effects of convection are shown cumulatively in

Figure 40. An average inner surface temperature of 1557 °F was found, a 57-degree decrease compared to the base model.

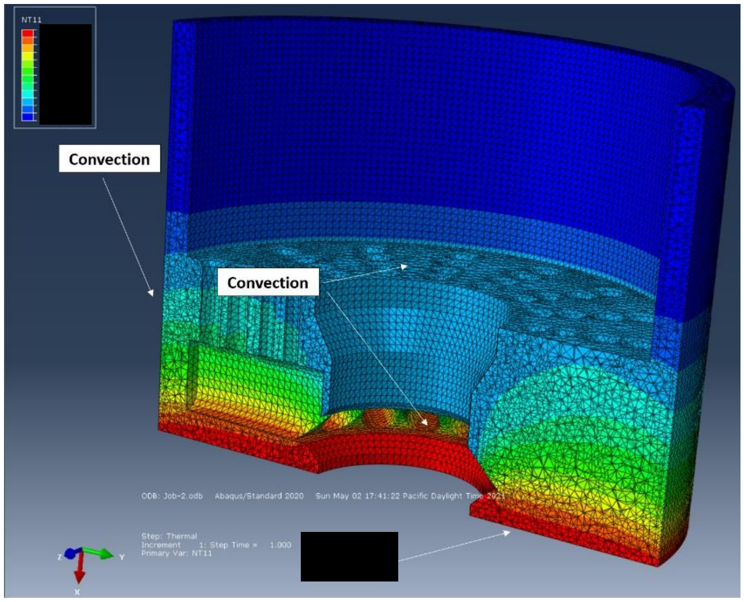


Figure 40. Cross-section FEA view of porous structure design temperature contour.

Due to the difficulty of modeling convection through correlations, the finite element analysis of the designs first produced approximate relative performance numbers. Although the numbers shown in the FEA are not exactly those seen in tests, temperature readings as a metric for performance are comparable to one another. The analysis of Design 1 was not undertaken due to safety concerns with use of fuel for cooling.

5.3.3 CFD- Ansys

The difficulties of modeling convective heat transfer guided the analysis towards the use of computational fluid dynamics (CFD). Simulations utilizing Ansys started in a similar method to the previously mentioned simulation programs with boundary condition data being the center of the simulation. At the beginning of the process, three-dimensional part geometry is either imported or created. An enclosure must be made around the part so that the simulation is bounded. Next, the part was taken to different meshing program where Ansys divides the given geometry into small triangular sections. Each of these small triangles underwent calculations for the specified tests. Now that the part had been meshed, boundary conditions were entered which depend on the analysis being carried out. Ansys takes these values and uses relevant equations to obtain results for each individual element of the mesh. These results are color-coded and displayed based on the user's criteria.In Figure 41 below, Ansys Fluent was used to compute both velocity and pressure within the base model for the injector tip. The tip was used for its simplicity since this was a simulation that occurred early in the simulation process. Below, Figure 41 left shows the velocity of the sectional view while Figure 42 right displays pressure at the same sectional view.

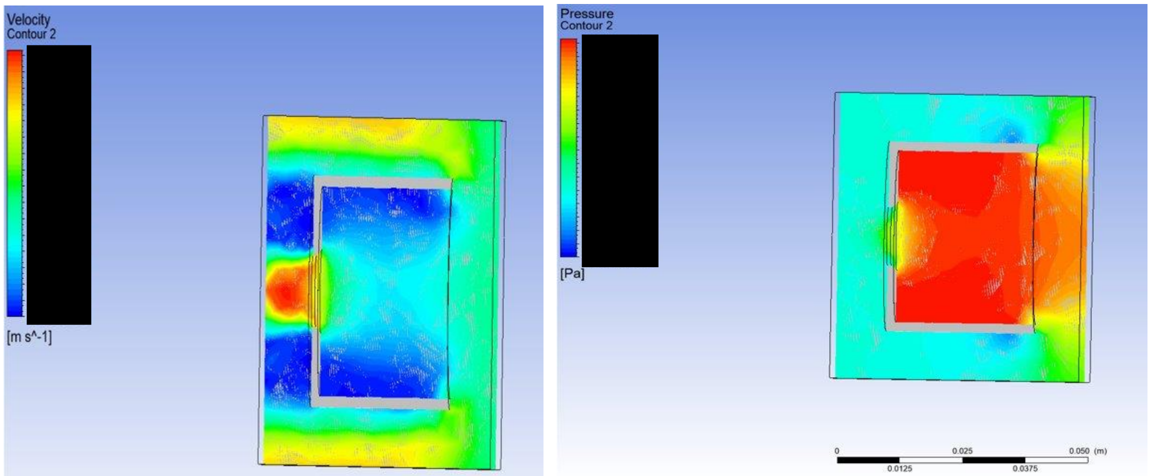


Figure 41: Pressure and Velocity analysis using Ansys Fluent

Figure 42 shows the velocity and pressure given the full part view. Although the simulations look the part, fundamental errors exist in the simulation. First off, boundary conditions were imputed in SI units rather than imperial, making the results several orders of magnitude greater than actual. Although this simulation was not successful, it proved valuable for gaining a better understanding of the program and how to properly set up the correct boundaries. Ultimately, a transition to SolidWorks Flow Simulation was chosen due to more experience with this software and access to turbomachinery engineers with relevant experience.

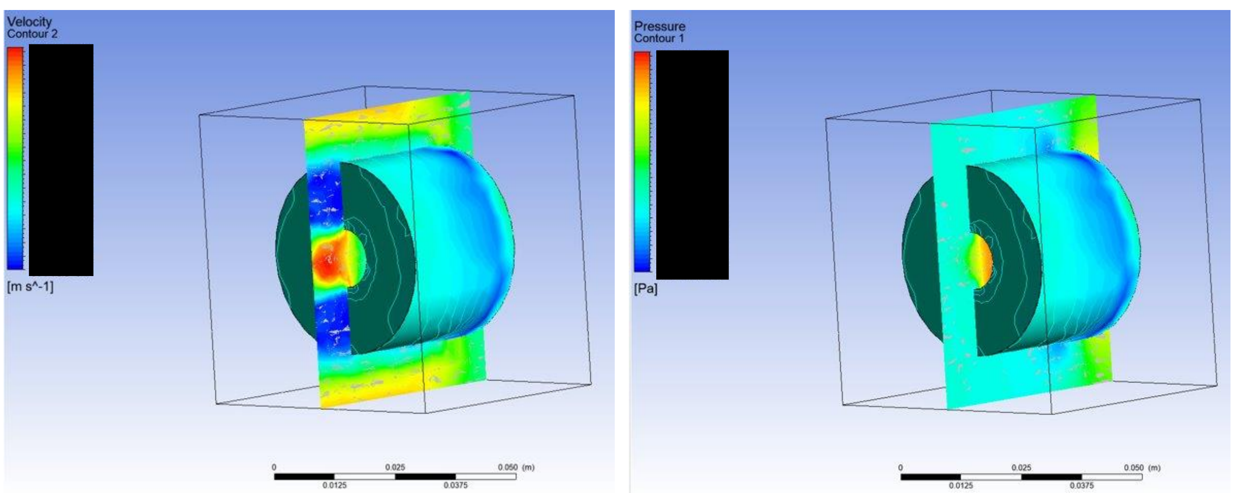


Figure 42: Pressure and Velocity analysis using Ansys Fluent

5.3.4 Computational Fluid Dynamics (CFD)- SolidWorks

Due to the complexity of simulation setup and validation using Ansys, and after recommendations from Dr. Shollenberger, the use of SolidWorks for our CFD analysis was pursued. The SolidWorks analysis includes both an external and internal flow simulation with the same boundary conditions found in Table 4. It is important to note that the initial SolidWorks results are inconclusive due to the steep learning curve with computational fluid dynamics (CFD). The team ran 85 different simulations trying to troubleshoot setting the proper boundary conditions. In section 5.3.5, the external flow simulation and contours provided a clear insight in the pressure, velocity, and temperature compared to this section.

The internal flow simulations required an enclosed volume, therefore, the “add caps” tool was used to enclose the volume. Two boundary conditions needed to be set where the initial velocity into the injector is 120 ft/s and needed a pressure constraint at the end of the injector tip. This pressure constraint led to some concerns due to the initial velocity and pressure values at the beginning of the simulation, but not the tip pressure value at the end of the CFD simulation, refer to figure 43. At this point, the velocity sources made sense, but the pressure values did not. Once the boundaries had been selected, the simulation ran up to 100 iterations and loaded the results. Figure 43 shows velocity profile of an internal flow simulation where the velocity matches the boundary condition given. Figure 44 shows the pressure profile where the numbers did not make sense and needed troubleshooting.

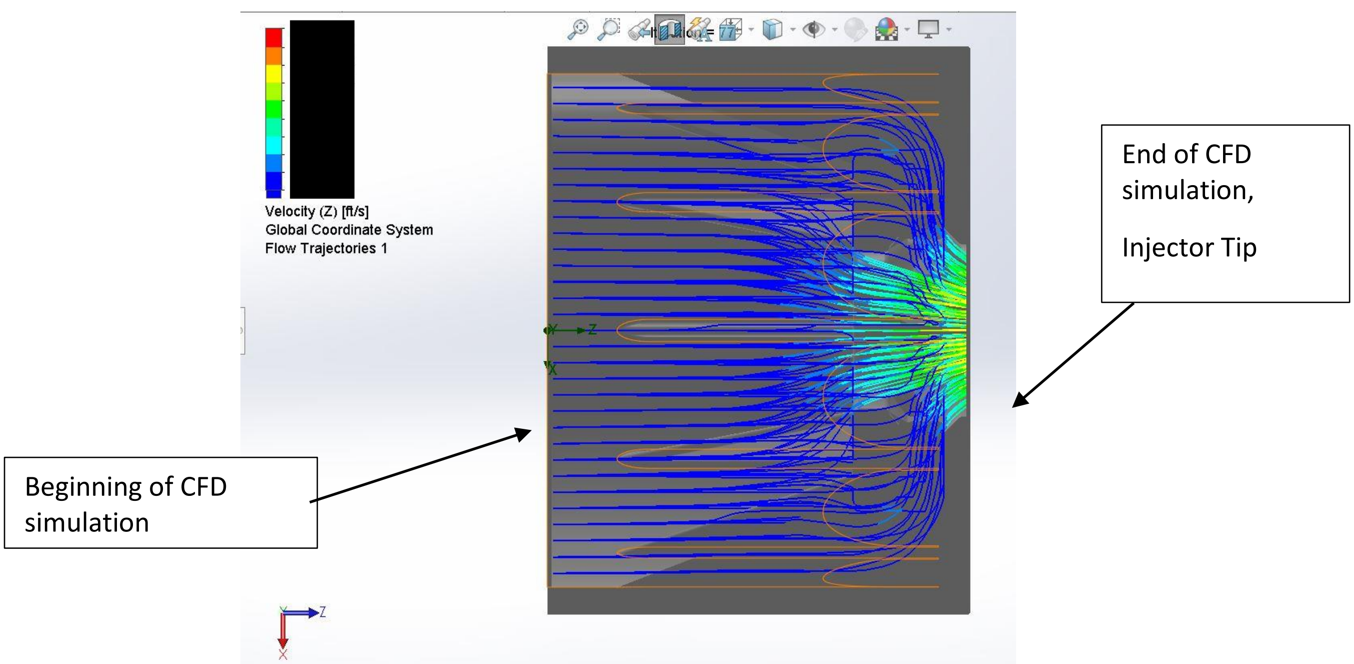


Figure 43. Velocity profile of Heat Fins injector tip using SolidWorks Internal Flow Simulation.

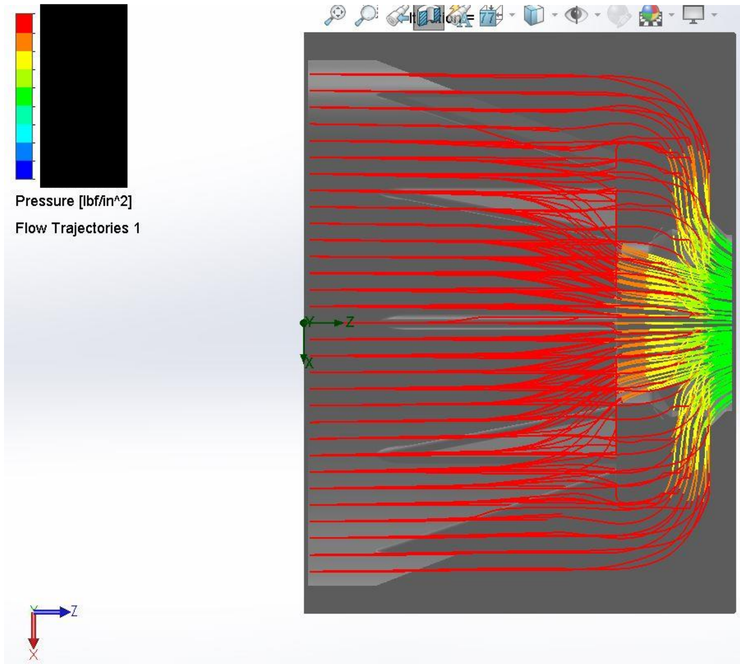


Figure 44. Pressure profile of Heat Fin injector tip using SolidWorks Internal Flow Simulation.

In addition, when running an internal flow simulation, the flow did not follow the design and exit accordingly, refer to figure 45. The external flow simulation showed the correct initial velocity of the air and pressure, but the flow converges to four different corners halfway through the simulation rather than exit at the injector tip. The constraint simulation box was modified to enclose the injector tip design with 0.005 in clearance all around. The edge of the pilot tube was selected as the plane with the sources of the air and there were about 200 points that represent the compressor air-flow sources, and it was constrained to only flow to the right. The following three figures are produced showcasing the changes in pressure, temperature, and the velocity of the fluid as it underwent different geometric shapes and an external flow simulation. The color gradient is shown on the top left corner along with the parameter being measured, the units are in parenthesis. The next three figures showcase the CFD for the Porous Prototype undergoing a SolidWorks external flow simulation. Figure 45 was the pressure profile, Figure 46 was the velocity profile, and Figure 47 was the temperature profile.

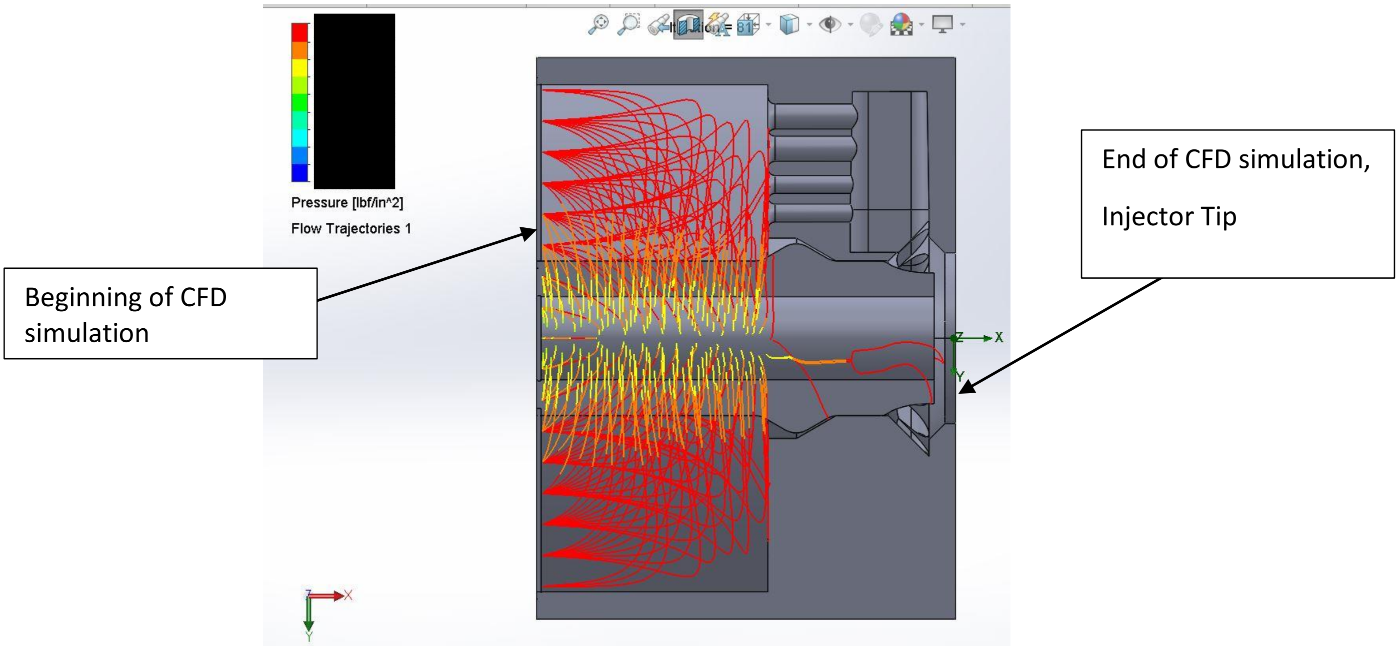


Figure 45. Pressure profile of Porous injector tip prototype #3 using SolidWorks External Flow Simulation.

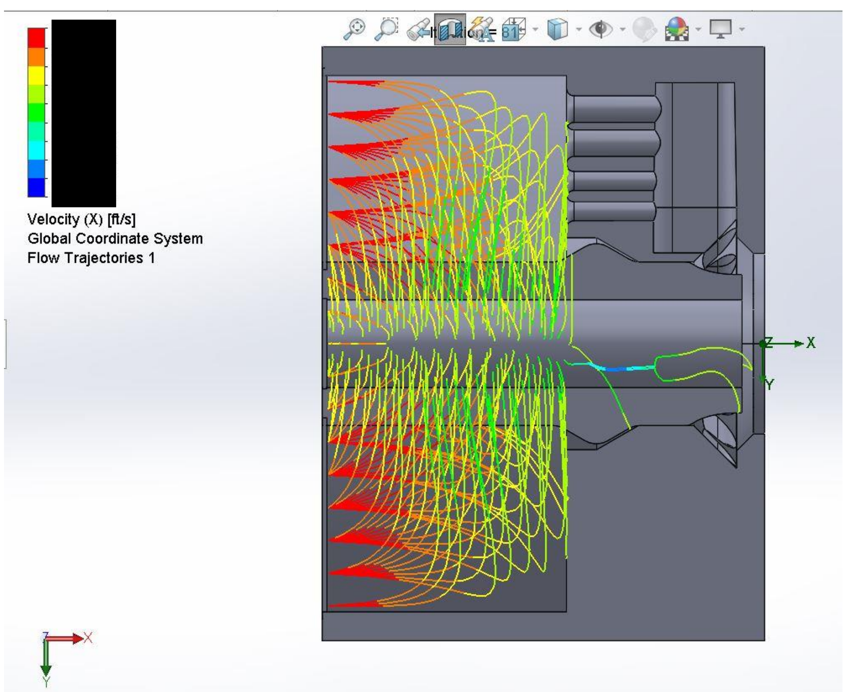


Figure 46. Velocity profile of Porous injector tip prototype #3 using SolidWorks External Flow Simulation.

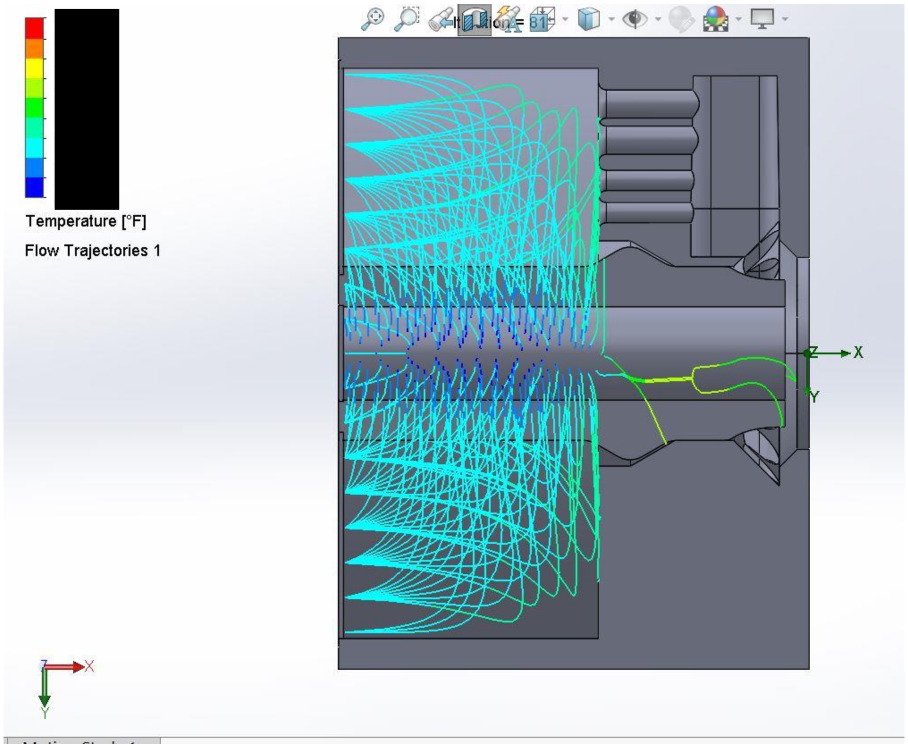


Figure 47. Temperature Profile of Porous Injector tip prototype #3 using SolidWorks External Flow Simulation.

5.3.4 CFD- SolidWorks Convection External Flowrate

Previous attempts shown in section 5.4.3 were unsuccessful but show the progress as the model was developed. Continuous research, trial and error, and a guest lecture from an engineer working in turbomachinery CFD yielded simulation conditions producing reasonable and comparable results to the simulation data provided by our sponsor. An external flow simulation modeled the internal airflow in the injector as a constant pressure source at the pressure value supplied by sponsor from the compressor discharge with a pressure drop supplied by sponsor at the injector tip outlet for the expansion and velocity causality. A flowrate, supplied by sponsor, at the same pressure for external air was modeled to approximate convection at the exterior of the injector tip. Material properties were taken directly from the Haynes International material catalog [10] to allow conduction in the material. Figure 48 depicts the temperature contour of the base model, simulating the current injector tip design. Temperatures experienced by injector tips were supplied by our sponsor for comparison. Fluid temperature and velocities were similar to CFD cross-section contours that had been used as reference, provided by Solar Turbines.

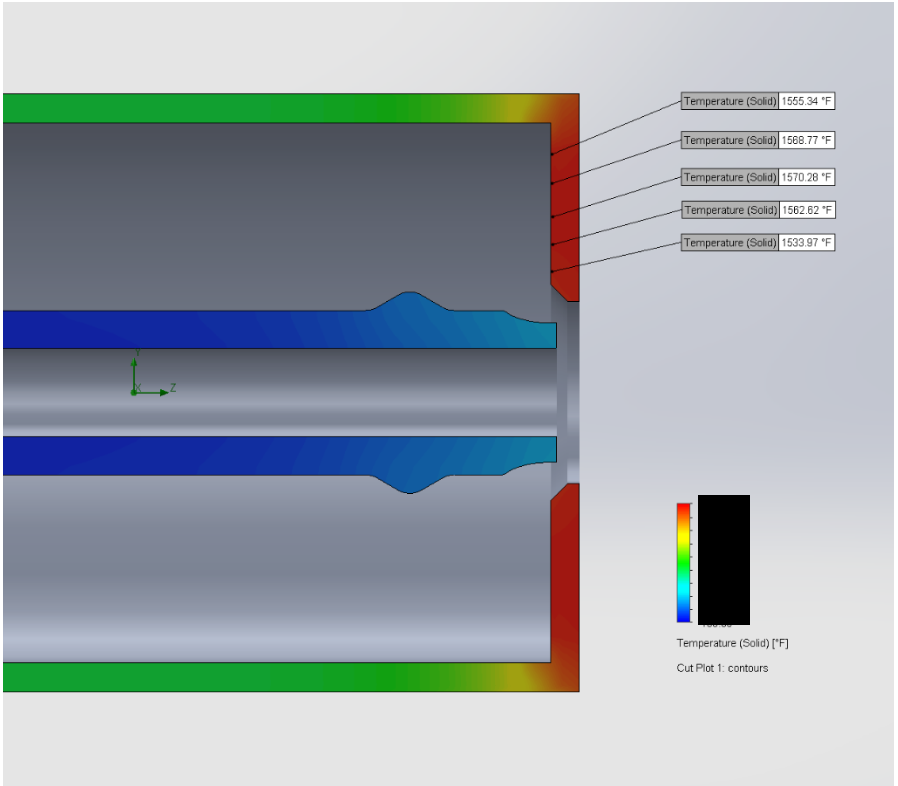


Figure 48. Base model CFD temperature contour.

A simulation with equal boundary conditions and flows was applied to the fin design model shown in Figure 49 portraying the pressure contour is shown.

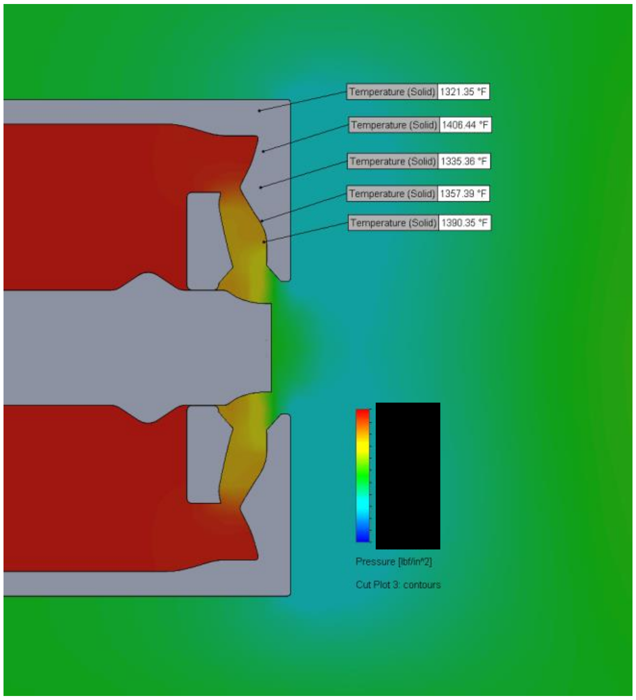


Figure 49. Pressure contour of CFD simulation on Fin Design.

Figure 50 shows the temperature contour in the material of the fin design model. From the probe values noted, a temperature around 1350 °F was found at the inner surface of the injector tip. In this case, a stark difference in internal temperatures is found compared to the base model. In contrast to the approximations for convection made in our FEA studies leading to lower performance differences between the two models, CFD using SolidWorks is more adept at correctly calculating the flow and convection relationship.

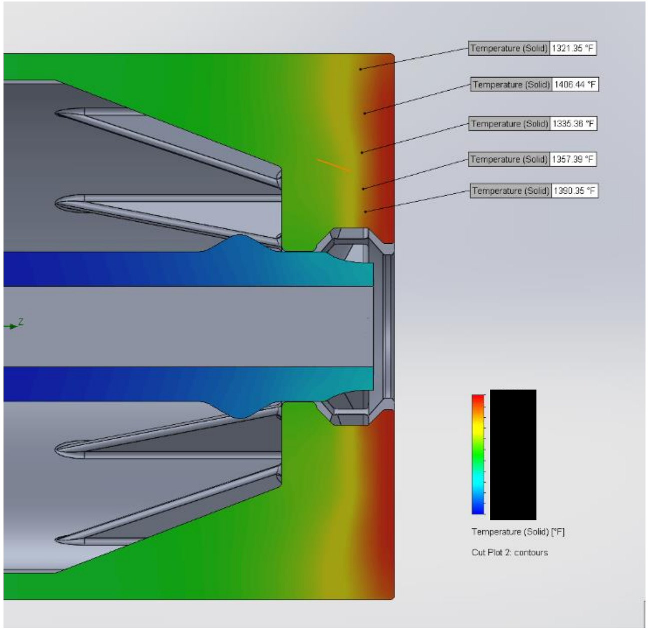


Figure 50. Temperature contour of CFD simulation on Fin Design.

The greatest concern as the accuracy of our CFD model is found when considering the velocity contour. Figure 51 reproduces the velocity distribution of our simulation with very low compressor discharge air flowrates found within the injector tip. From closer inspection of the velocity contours provided by our sponsor, expected values as low as 40-60 ft/s seemed reasonable but our simulation resulted in an average velocity around 12 ft/s from the discharge air used for the cooling structures (fins, porous structure). While this does bring up some concern, feedback from our sponsor concluded that this was a reasonable approach as we could not simulate the entirety of the turbine and flow.

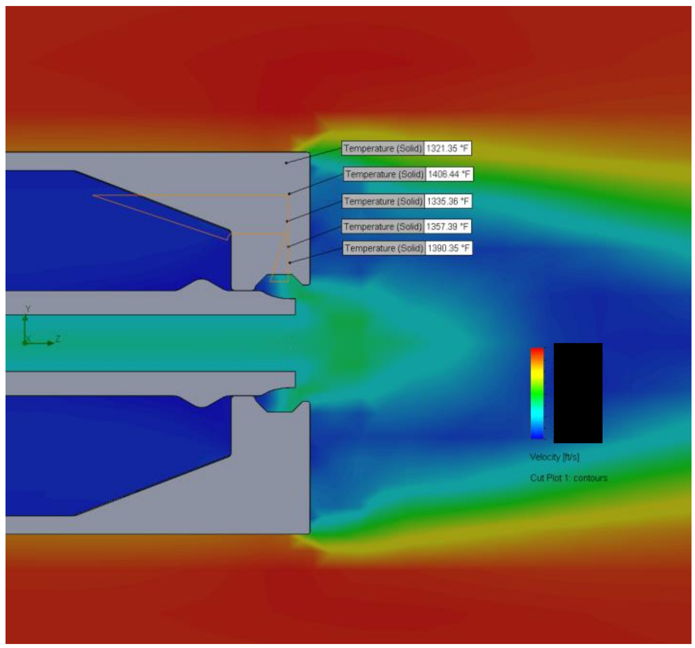


Figure 51. Velocity contour of CFD simulation on Fin Design.

The CFD model was applied to the porous structure model. An odd pressure distribution for this model resulted, shown in Figure 52. Additional pressure drop was found and may be the result of flow that is constricted which may lead to recirculation.

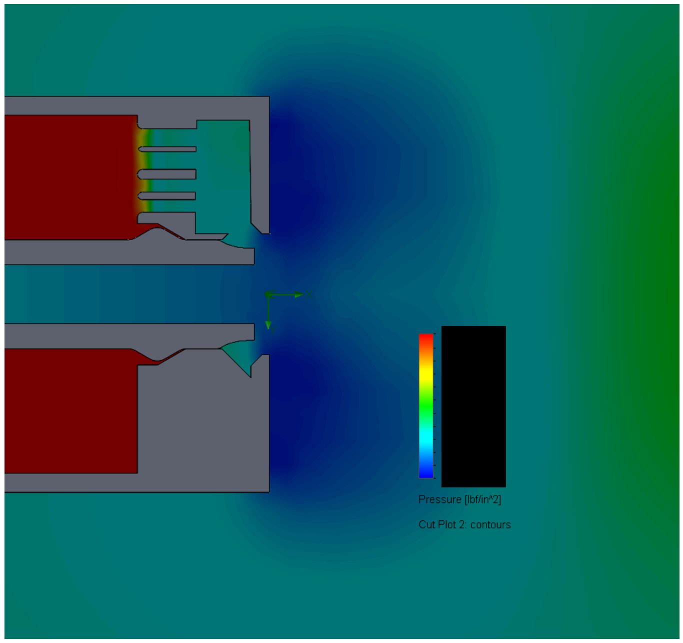


Figure 52. Pressure contour of CFD simulation on porous structure.

The temperature contour in Figure 53 displays a lower heat dissipation rate and higher inner surface temperature than expected. This again may be due to constricted flow or mesh refinement required for better fluid flow approximations. Structures with more aerodynamic properties may have been incorporated to decrease flow constriction.

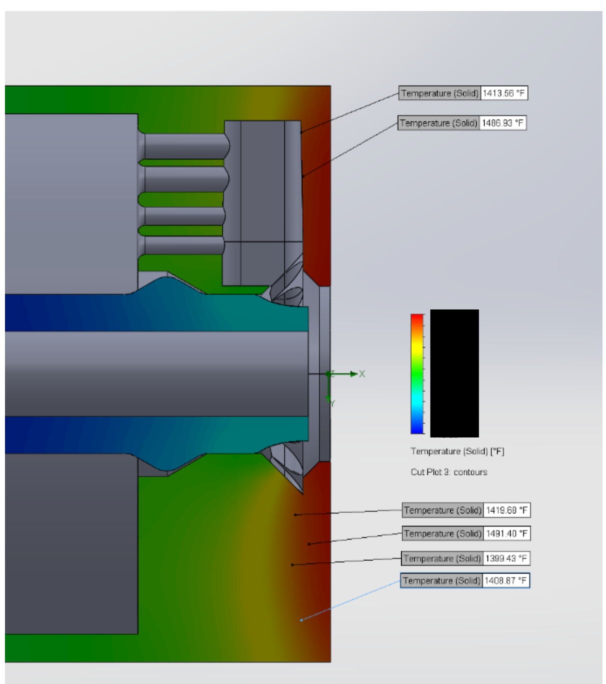


Figure 53. Temperature contour of CFD simulation on porous structure.

The velocity contour of the CFD simulation yielded similar results to previous application. The velocity field is of similar shape, shown in Figure 54, giving similar concerns as to the magnitude of velocity found within the injector tip. In this case, an average velocity of 9 ft/s was found internally. Further model validation may be necessary.

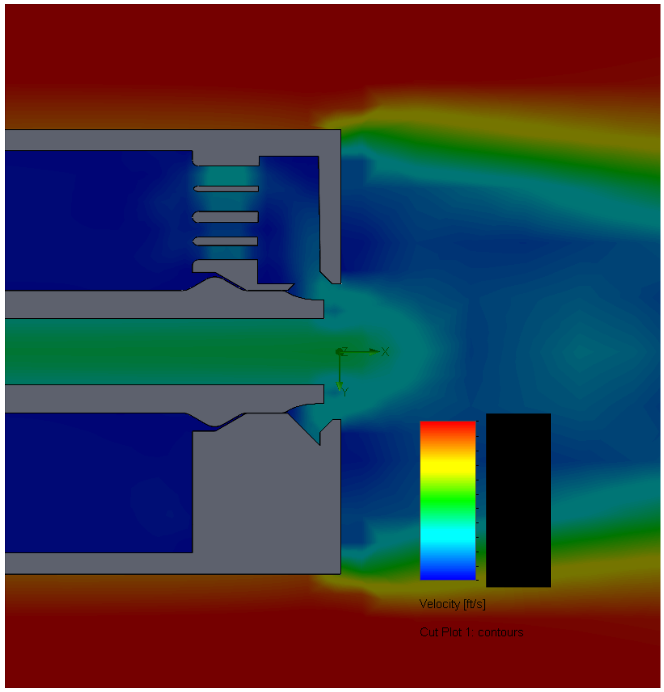


Figure 54. Velocity contour of CFD simulation on porous structure.

The development of the CFD model for injector tips in a gas-only power generation turbine has yielded results that validate our designs and note their areas where improvement is possible. The initial analysis using FEA led to this CFD development to more accurately model convection over the complex surfaces. It has been shown that there is serious potential for the designs to achieve the 1350 °F specification set forth by Solar Turbines. Analysis of the prototype using fuel tunnels was not pursued because of the hazards of pre-detonation.

The team selected the Fin Design as the official new design that would be prototyped and tested as it showed overall better heat dissipation compared to the Porous Structure and Fuel Tunnels using ABAQUS and SolidWorks CFD, and better flow characteristics.

5.4 Cost Analysis

The predicted cost to print an injector tip was $500.00 for the alloy x and $1000.00 for metal Additive Manufacturing Printing. The total cost per injector tip was $1500.00 to our sponsor. The team has a budget of only $1000.00 dollars, but the Additive Manufacturing Board at Cal Poly and the head of the board, Dr. Wang, had agreed to print a stainless-steel AM part free of cost for testing purposes. Due to unforeseen obstacles outlined in Chapter 6, the planned Verification Prototype was not produced in time for testing.

Table 6. Bill of Material Cost Breakdown

Component Name	Approximate Cost
Alloy X powder	$500.00
Metal AM printing	$1000.00

The material cost breakdown can also be found in the Indented Bill of Materials, Appendix XII.

Chapter 6: Manufacturing Plan

Our project was unique when it comes to manufacturing. Typical senior projects are large-scale and labor intensive with multiple subsystems, functions, and assemblies. However, since the purpose of our project is to lower the temperature of a small injector tip using a relatively new manufacturing process and validation was mostly analytical, our manufacturing plan greatly differed from the norm.

As the design relied heavily on boundary conditions, and other systems of the gas turbine rely on the design of the injector, computer analysis was required before any physical manufacturing and testing begins. The analyses previously mentioned (FEA and CFD) verified the possibility of the design meeting the specifications as found on the Specification Table, Table 2. Further investigation using structural and modal analysis is still needed to completely verify the injector design, to be done by Solar Turbines.

As additive manufacturing is a new process to each of the team members, a meeting was arranged with Cal Poly's professor responsible for the Additive Manufacturing Department on campus, Dr. Wang. The meeting shed light onto the project's timeline and gave crucial advice on the AM technique. Dr. Wang explained that AM printing is both expensive and time-consuming; hence, printing multiple design iterations is not an option. This caused a diversion from the team's original plan of printing multiple full-fledged models and testing each model. To accommodate for this challenge, Dr. Wang had suggested that we print each of our prototypes using a lower-cost additive manufacturing method such as plastic 3D printing to test the feasibility of the designs, shown in section 5.2.

3D printing holds a wealth of benefits over AM metal printing when it comes to initial prototyping. This method provides a low-cost solution with quick turnaround times and can be done on campus at no charge for students and shares similarities with AM printing. This means that the models will also verify certain aspects of our prototype's printing capabilities. Furthermore, some inspection and tests can be carried out such as checking self-supporting structures. Subsequently, multiple design iterations were 3D printed with PLA filament through Cal Poly's Innovation Sandbox. These 3D prints served as structural prototype models, refer to Section 5.2

Recommendations from the Additive Manufacturing Board lead to further optimizations of the final Fin Design. Fillets were increased with a common radius of 0.05". The final design is shown in Figures 55 and 56.

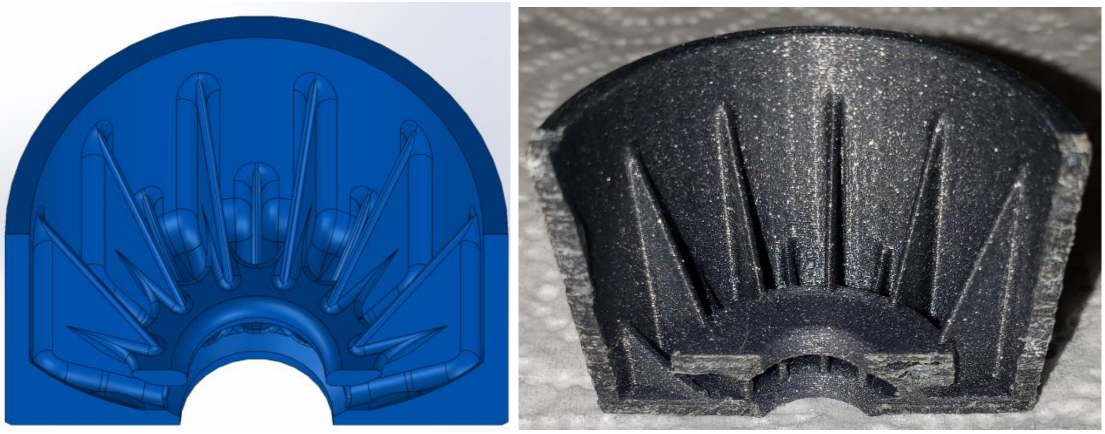


Figure 55. The Fin Design (left) and the structural prototype (right).

The horizontal support structure was made to have a gradual change in area to avoid failure due to thermal contraction when printing.

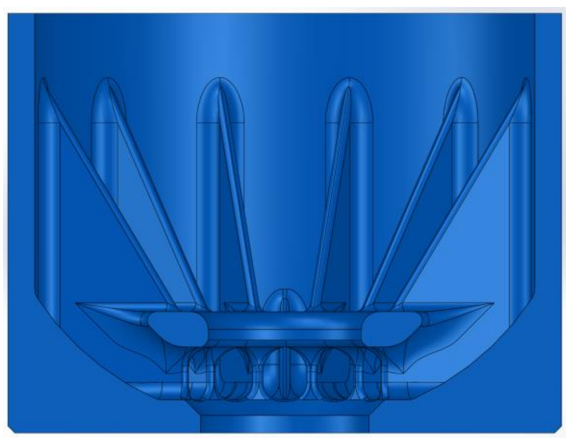


Figure 56. The Fin Design with gradual horizontal structure.

Once we narrowed our injector tip models and selected the Fin Design, Dr. Wang was willing to provide the stainless-steel powder and print a single example to allow further tests to be conducted on a full-scale prototype. One caveat is that the Cal Poly AM facility only used stainless steel for its prints. This model was to be as close to a production model as possible without the HIP treatment, however, stainless steel has different properties than the nickel-based superalloy Alloy X. Plans to print two prototypes, one of our Fin Design and one simulating the current design in use, meant that a heat dissipation test would be comparative between the two.

The team encountered unforeseen challenges when attempting to produce the Verification Prototype for testing purposes. Dr. Wang informed the team that the AM machine broke down, likely for the remainder of the quarter, on October 12, 2021. Due to our non-disclosure agreement, off-campus Additive Manufacturing was not pursued. Shortly after, the team member with machining certification contracted COVID-19, removing many possibilities of machining a simplified version of our Fin Design. We needed the AM print within a 3-week turnaround for testing purposes in November. All these unforeseen challenges led the team to manufacture a simplified model with conventional aluminum circular stock at the Cal Poly Machine Shop. The team purchased a flat aluminum sheet and cut out triangular fins. We then used metal conductive epoxy to add the aluminum fins to a circular flat-plate tube. The team added 8 fins to the Fin Design to have room for the thermocouples. Figure 57 shows the simplified models used for the heat dissipation test.

Figure 57. The simplified Fin Design (left) and the Flat-Plate (right) for a comparative heat test.

We informed Solar Turbines of the unforeseen challenges and they agreed to AM print the Fin Design using the correct material, Alloy X. These prints were done after the heat dissipation testing phase, but they prove that these parts can be made with Additive Manufacturing. Figure 58 displays the final Fin Design printed by Solar Turbines.

Figure 58. AM printed Alloy X Fin Design by Solar Turbines.

The comparison of the structural prototype, CAD model of the final Fin Design, and the AM part are shown in Figure 59.

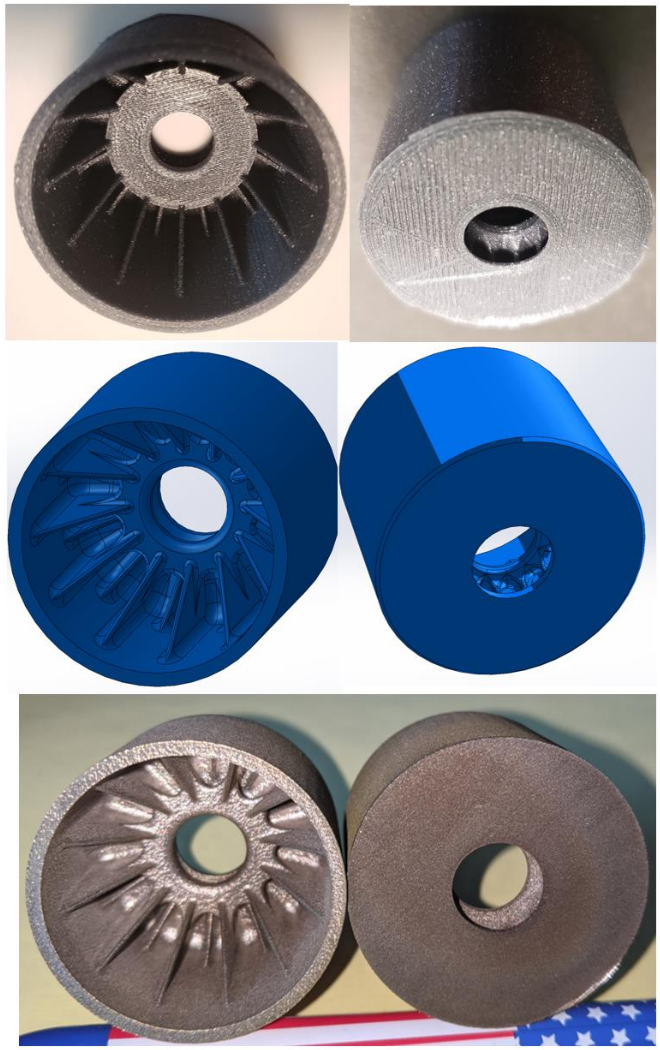


Figure 59. Plastic Fin Design Structural Prototype (top), final CAD model (middle), AM part.

Once the 3D prints and different iterations were successful and the AM printed prototype met our specifications, the prototype was sent to Solar Turbines to be evaluated by their staff. If the concept is validated, the full injector may be printed at Solar Turbines and subjected to a full-scale rig and full-scale engine test.

Chapter 7: Design Verification Plan

Verification of the success of our designs was greatly reliant on the use of simulation and computer software analysis, as mentioned. Due to the complexity of the conditions found within the Taurus T60 turbine, verification using these analytical methods must be convincing in its results to move forward to a physical rig test with a scale model manufactured from the desired Alloy X, carried out at Solar Turbines. This rig test and combustion test would serve to validate items such as pressure drop, heat transfer, and vibrations. The possibility of a rig test previously mentioned at Solar Turbines was cancelled due to Solar Turbines budget, time constraints, and relevance of this project. For this reason, only a heat dissipation test is conducted, outlined in the Design Verification Plan (Appendix XI) and in Table 7 below.

Table 7. Test Overview Table

Test	Test location	Desired Result	Test Purpose
Heat Dissipation	Mustang 60	Heat fin model yields lower temperatures than the finless model.	Show the effectiveness of fins for heat dissipation.

The tip heat dissipation test used the constructed aluminum parts manufactured in Mustang 60 along with a heat lamp as a radiation source and a voltage-controlled fan driving the convective heat dissipation. The goal of this test was to verify that our prototype injector tip dissipates more heat compared to the current design with no heat dissipation internal structures. Shown below in Figure 60 is the testing apparatus and Table 8 apparatus functions.

Figure 60: Heat Dissipation Test Diagram

Table 8. Test apparatus component descriptions

Test Component	Component Purpose	Simulation Property
Computer Fan	Forced Convection Source	Turbine Air Discharge
Reptile heat lamp	Radiation Heat Source	Fuel Combustion
Aluminum Fin model	Verification Prototype	Prototype Injector
Aluminum Flat Plate Model	Control Group	Existing Injector

In this test, a heat lamp was placed directly in front of the injector model at 4 cm while a voltage-controlled fan blew room temperature air through the inlet of the injector tip which mimicked the compressor air the injector tip received during real-life conditions. Thermocouples were placed in three different locations on the injector to obtain temperature readings: external surface, side wall, inner surface. The T-type thermocouples were validated before the heat dissipation test using boiling water and an ice-water mixture for reference temperatures. Both the Fin Design and Flat Plate models were tested with the same apparatus and test conditions then compared for model validity. The test is shown below in Figure 61.

Figure 61. Heat Dissipation Test performed in Mustang 60

First, the heat lamp in conjunction with the voltage-controlled fan were brought to steady-state with the Fin prototype inside the cardboard air concentrator. Once temperatures were stable, a 10-minute timer began. Once the time finished, a data point was collected. Another 5-minutes were given to verify steady-state conditions, adding another data point. Using the same conditions, the flat plate prototype underwent testing. The test was repeated on both the flat-plate and the fin design prototypes to confirm repeatability. Table 9 summarizes the results of the comparative test.

Table 9. Heat Dissipation Test Data and Results

Test 1				
	T_{out} (°F)	T_{inner}(°F)	$T_{sidewall}$ (°F)	**Pass/Fail**
Initial (room temp)	69.3	68.9	68.7	**PASS**
Current Design	89.9	83.7	79.5	
+5 mins	88.5	84.3	80	
Fin Model	85.5	82.4	78.2	
+5 mins	85.4	83.3	78.6	
Test 2				
Initial (room temp)	72.7	73.1	72.2	
Current Design	89.6	84.8	79.5	
+5 mins	90.3	84.6	79.6	
Fin Model	86.7	82.9	80.5	
+5 mins	85.4	82.3	80.2	

Figures 62 and 63 show the decrease in temperatures throughout the mock injector tip during the two test runs, confirming the effectiveness of fins for heat dissipation.

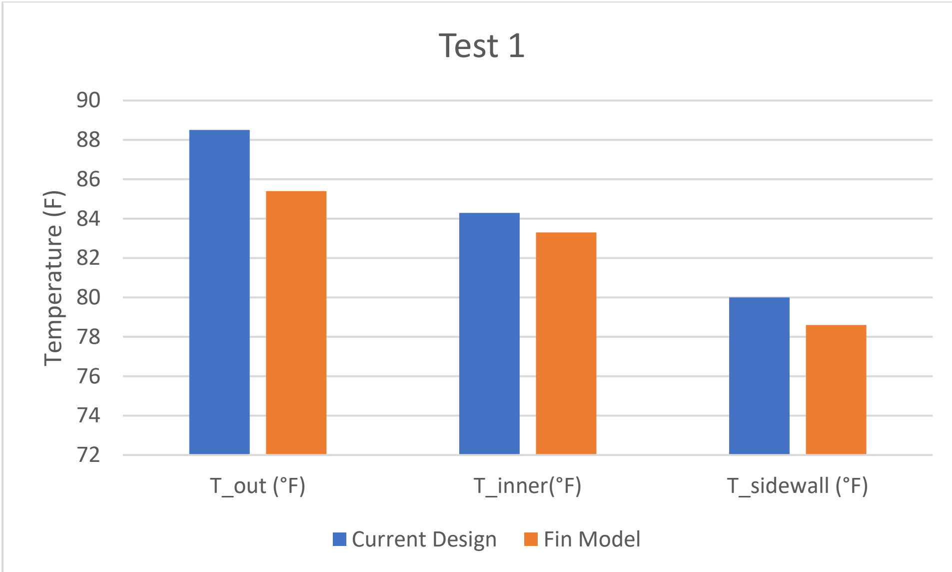


Figure 62. Heat Dissipation Test, run 1.

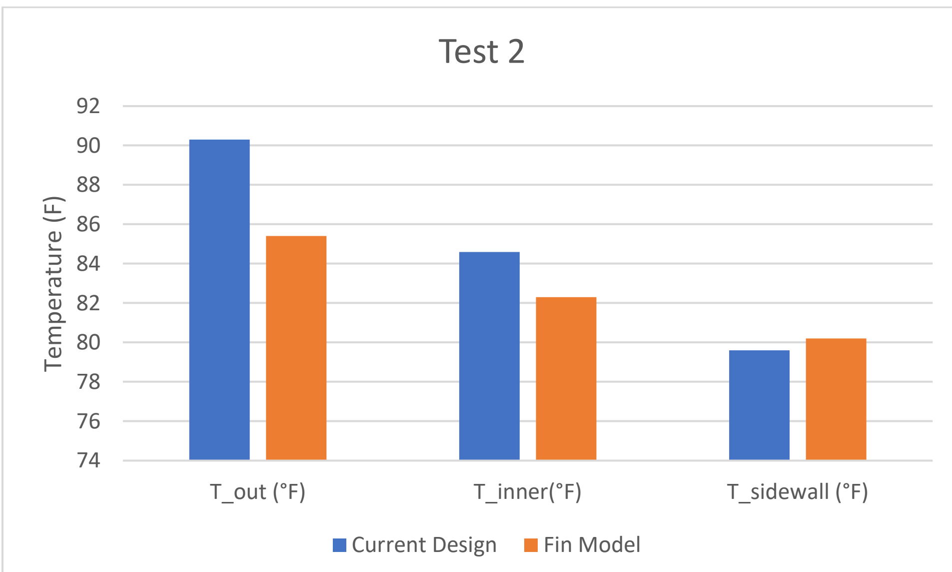


Figure 63. Heat Dissipation Test, run 2.

Table 10 summarizes the test and criteria for passing of the verification prototype. The test shows that additional heat dissipation and lower temperatures would be experienced with incorporation of fins into the injector tip.

Table 10. Final pass/fail result criteria

Test	Criteria	Pass/Fail
Heat Dissipation Test	Heat fins yield lower temperatures	**Pass**

Recommendations

The test carried out proven basic concepts of heat transfer regarding fins. Due to complications with a Covid-19 case within the team and the Cal Poly metal AM machine break-down, additional tests with representative conditions were not achievable. Although crude representations of the actual injector tips, these mock-up heat sink parts were used to perform a version of our planned heat dissipation test. Assuming a safe apparatus, the ideal test should involve a high temperature combustion heat source to simulate actual conditions within the gas turbine. This will yield larger temperature differences between the flat plate and fin prototypes, therefore a more thorough validation. Moreover, using an AM printed part with real combustion conditions such as a rig test will yield more realistic heat dissipation to validate this Fin Design. A recommendation of using an accurate Alloy X part for testing is necessary. Testing of actual pressure drops, fuel and air flowrates, vibrations, and service life were out of scope for our testing and should be investigated with rig and engine tests.

Chapter 8: Project Management

The timeline of the project encompasses one academic year consisting of three quarters. Key deliverables and deadlines are described for each quarter and step of the design process, with detailed tasks and dates leading up to the Final Design Review (FDR) shown in the Gantt chart (Appendix XI). The design, build, and test process were iterated on as analytical results guide our design. The ideation stage led to some rough CAD models, shown in section 4.4. These CAD models led some preliminary analysis where we proved that fins are an effective way to dissipate heat, shown in Figure 21 (Appendix VIII). The team continued iterating the top three CAD models and started using analytical programs such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) to validate one design over others. The Fin Design CAD model was chosen to be AM stainless steel printed on campus, but due to machine damage, the model was printed on-site at Solar Turbines. The AM Fin Design printed at Solar Turbines did not alight with the heat dissipation test schedule; hence, the team made some simplified aluminum models at the Cal Poly Machine Shop, refer to Figure 57. The simplified aluminum Fin Design and current design prototypes were used in the heat dissipation test. This test is previously described and uses a heat lamp to mimic combustion and thermocouples to obtain data regarding the design’s ability to dissipate heat. To finally validate the success of our design project, a potential rig test will physically simulate performance in a turbine with lower risk of failure. The physical test depends on Solar Turbines team analyzing the chosen design and approving it.

<u>Winter Quarter</u>

Initial sponsor meetings discussing the requirements of the design, background research into the turbine and injector field, and clear definition of the objectives in the project were accomplished. The Scope of Work (SOW) was developed, forming an agreement between our sponsor and our team on the work to be performed. Initial presentation resulted in approval of our understanding of the tasks.

After the Scope of Work was completed, the team created a function decomposition model with three main functions: comply with AM, increase heat dissipation, and increase durability (Appendix III). After the main function decomposition model, the team members individually built ideation models using paper, tape, play- Sponsor: Rick Rogers, Solar Turbines

doh, foam board, hot glue, and paper (Appendix IV). These ideation models underwent a concept selection using Pugh Matrices, weighted decision matrix, and preliminary analysis (Appendix VII). The team created a Preliminary analysis using heat transfer equations and thermal contours to show that heat fins improve heat dissipation. The three top ideas derived by the weighted matrix were created using SolidWorks and some rough CAD models were made. These rough CAD models are found in section 4.4. The summation of these efforts resulted in the present Preliminary Design Review (PDR), describing the direction of design for the Team to be approved by our Sponsor. After being approved, the team had various meeting where the Sponsor provided very specific boundary conditions created by their analysis team.

<u>Spring Quarter</u>

After the Preliminary Analysis was approved by our sponsor, the team had various meetings where the Sponsor provided specific boundary conditions as seen in tests. The provided boundary conditions help shape the Finite Element Analysis (FEA) approach and calculations, found in 5.3.2. The team also met with CFD faculty on campus, Dr. Shollenberger, where she advised us to use SolidWorks for the CFD simulation after warning us about the steep learning curve associated with Ansys. The top three prototypes underwent the same Finite Element Analysis (FEA) and used the base model results as a reference. During the winter quarter, the FEA results have shown that the current prototypes are successful in dissipating heat and potentially reaching all specifications set forth. The Computational Fluid Dynamics (CFD) external flow has shown some success ensuring that the prototypes are under the threshold provided of less than 1350 F. The internal flow boundary conditions and analysis were inconclusive until a guest lecture in the turbomachinery course shed new light on turbine simulations for SolidWorks. Here, the team finally gained clarity and reasonable simulation results. The simulation gained validity when a pressure-driven flow was used rather than a velocity-driven simulation.

After continued design and analysis, a Critical Design Review (CDR) included the FEA results and some CFD results. The team selected the Fin Design based on its heat dissipation ability. This project's timeline is displayed in Table 11 including the deliverables, description, and dates.

<u>Fall Quarter</u>

After the Critical Design Review and the Manufacturing Test Review had been submitted in the spring quarter, the team created the Final Design Report (FDR) which showcases the final prototype and final design decisions. This final report includes the prototype built on campus and the heat dissipation test conducted in the Mustang 60 Workshop. Delays in manufacturing and due to a Covid-19 case in the team lead to a rough verification prototype and testing. Even so, this combined with the previous analytical results gave reasonable confidence that the Fin Design would meet our sponsors specifications. This final design and all documentation will be given to Solar Turbines.

Table 11: Project Timeline

Deliverable	Description	Due Date
Scope of Work (SOW)	Document outlines our problem definition and entire project.	02/04/21
Preliminary Design Review (PDR)	First initial team review of ideation, model ideation, and prototypes.	03/ 04/21
Interim Design Review	Team design progress check.	04/08/21
Critical Design Review (CDR)	Detailed review of all components, costs, and analysis.	05/04/21
Manufacturing and Test Review	Showcase solution and required analytic testing such as FEA and thermal analysis.	06/03/21
Final Design Report (FDR)	Final prototype and final design report.	11/16/21
Submit FDR to Solar Turbines	Submit final design and all documents to Solar Turbines.	12/02/21

Chapter 9: Conclusion

Solar Turbines, a leader in gas turbine designs and manufacturing, needs to reduce maintenance costs regarding their injector tips for the Taurus-60 engine. Richard Rogers, a fuel injector design engineer at Solar Turbines, needs the team to redesign an injector tip using additive manufacturing to decrease injector tip temperatures in the Taurus-60 engine below 1,350 degrees Fahrenheit. Some of the design challenges include the boundary limitations of our design as the team is restricted to modifying only the injector tip interior design. Overall engine design and functions are already established; hence, the design is restricted to the injector tip to dissipate heat using its geometry. Furthermore, while the team was encouraged to be as creative as possible, there are some geometric freedoms and limitations caused by Additive Manufacturing (AM). The purpose of this Final Design Review is to demonstrate our solution to the problem statement originally proposed by our sponsor. The FDR highlights the team's ideation and design process, computer simulation results, and final product verification. Recommendations on interpreting our results and further validation were given. The final Fin Design showed promising results and achieved a temperature differential of over 150 °F compared to the current design based on simulation results. A breakdown of the Cal Poly metal AM machine and a Covid-19 case within our team delayed the production of a Verification Prototype and testing of the prototype greatly. A simplified Verification Prototype was finally manufactured, and a comparative heat dissipation test was conducted between it and a similar mockup of the current design in use. Improvement in thermals experienced throughout the Verification Prototype shows that fins aid in heat dissipation. The results of the project yielded a Fin Design that can reasonably be expected to meet the specifications set by our sponsor. We would like to express our gratitude to Rick Rogers and Solar Turbines for all their mentorship and constructive criticism in this project.

References

[1] Bloch, H. and Soares, "Process Plant Machinery," 2nd edition, Butterworth Heinemann, Rolls Royce,1998.

[2] Muktinutalapati, "Materials for Gas Turbines-An Overview," VIT University, India.

[3] Price, "Advanced Materials For Mercury 50 Gas Turbine Combustion System," San Diego, CA, Solar Turbines, 2009.

[4] S. Dryepondt, D. Ryan, and M. Kirka, "Comparison of Electron Beam and Laser Beam Powder Bed Fusion Additive Manufacturing Process for High Temperature Turbine Component Materials, Phase II," 2019. Accessed: Jan. 17, 2021. [Online]. Available: http://www.osti.gov/scitech/.

[5] Esmaeilizadeh, Ali, and Marzbanrad, "On the effect of spatter particles distribution on the quality of Hastelloy X parts made by laser powder-bed fusion additive manufacturing," University of Waterloo, Waterloo, ON, Canada, 2019

[6] Sampath, "Combustion Technology Challenges for Small Aviation Gas Turbines," Pratt and Whitney, 2002.

[7] "Alternative Control Techniques Document— Nox Emissions from Stationary Gas Turbines," Environmental Protection Agency, Research Triangle Park, North Carolina, EPA-453/R-93-007,1993

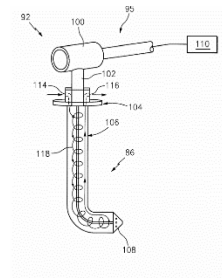
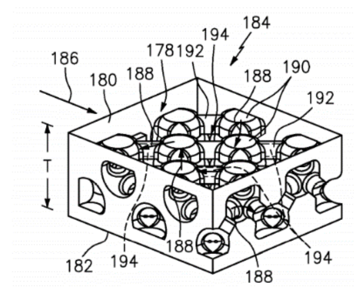
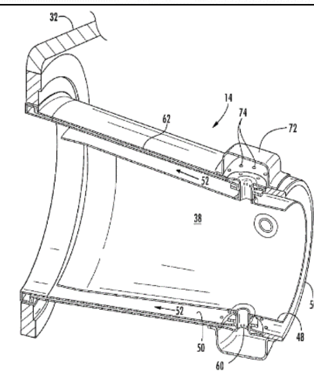
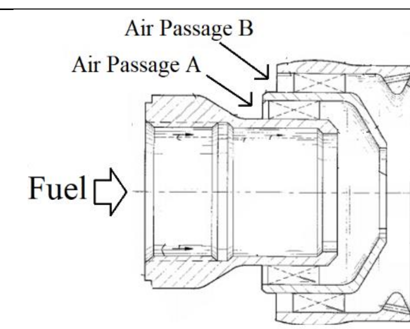
[8] Goldmeer, "Gas turbine fuel evaluation process: A case study on the application of Arabian Super Light Crude Oil for use in GE 7F-class Dry Low Nox (DLN) combustion systems," General Electric, Schenectady, GEA31424A, NY

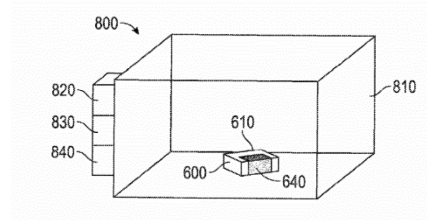
[9] A. Sadek, G. Ritter, C. Drews and D. Ryan, "Additive Manufacturing of Fuel Injectors", Solar Turbines, Columbus, OH, United States, Oct. 2017, Accessed on: April 14, 2021. [Online]. Available: https://www.osti.gov/servlets/purl/1406179

[10] Haynes, "*HASTELLOY® X alloy"*, Haynes, Kokomo, IN, United States, Accessed on: April 17, 2021. [Online]. Available: http://haynesintl.com/docs/default-source/pdfs/new-alloy-brochures/high-temperature-alloys/brochures/x-brochure.pdf?sfvrsn=15b829d4_40

Appendix I

Patent References

Patent Number	Title	Patent Description	Picture
US 2016/0201917 A1	COOLED FUEL NUECTOR SYSTEM FOR A GASTURBINE ENGINE	Compressor discharge air takes a helical shape as it provides convective cooling for the injector arm and assembly.	 FIG. 4
US 2020/0018234	COOLED FUEL INJECTOR SYSTEM FOR A GAS TURBINE ENGINE AND A METHOD FOR OPERATING THE SAME	Additive manufacturing provides means of almost microscopic manufacturing. This patent utilizes small vessel like structures to provide cooling.	 FIG. 9
US 8,863,523	SYSTEM FOR SUPPLYING A WORKING FLUID TO A COMBUSTOR	A fluid liner surrounds the combustion chamber. Fuel is used as a working fluid to provide convective cooling for the combustion chamber.	 FIG. 2
US 6,560,964	FUEL NOZZLE FOR TURBINE COMBUSTION ENGINES HAVING AERODYNAMIC TURNING VANES	Aerodynamics vanes form helical air shapes that intersect each other thereby increasing atomization of fuel.	

US 9,808,865	METHOD FOR MANUFACTURING A METALLIC COMPONENT	Combustion is used to remove burrs and dust from small complex printed shapes.	

Appendix II

QFD-Quality Function Deployment House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

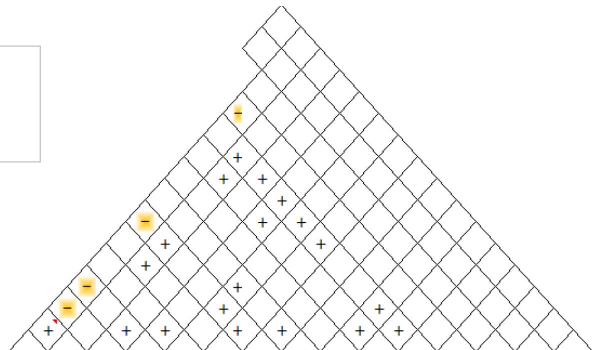
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Optimized Tip Cooling Using AM Process

Revision Date: 3/2/21

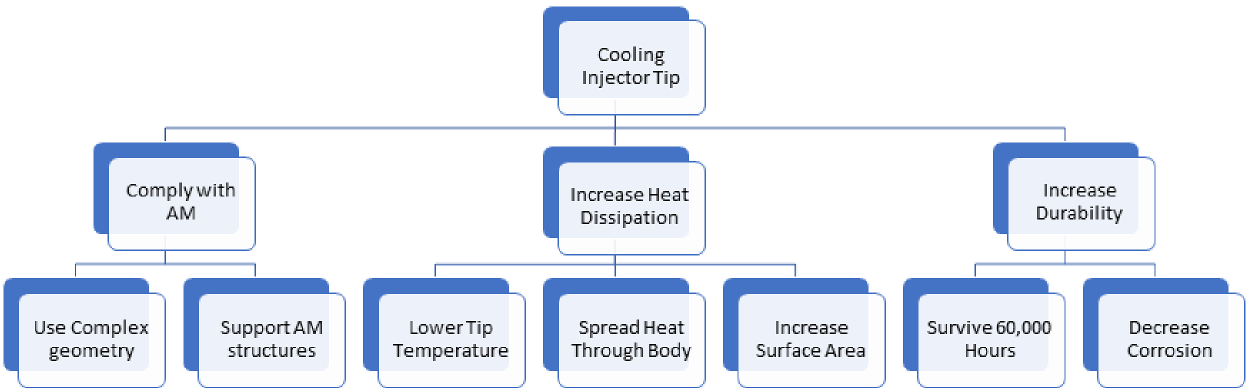


Row #	Weight Chart	Relative Weight	Solar Turbines	Manufacturers	Maximum Relationship	WHO: Customers / WHAT: Customer Requirements (Needs/Wants) \ HOW: Engineering Specifications (Tests)	Service Life	Cost	Fuel Temperature	Tip Temp	AM Angle Compliant Geometry	Size	AM Hole Linearity (angled)	AM Compliant Slot Geometry to	Outer Diameter of Injector Tip	Inner Diameter of Pilot hole	Combustion Vibrations					Fluid Liner	Air Swirler	Air Lattice	Existing Solar Injector		Row #
						Column #	1	2	3	4	5	6		9	10	11	12	13	14	15	16	NOW: Curr. Products					
						Direction of Improvement	▲	▼	▼	▼	▲	◇	◇	◇	◇	◇	▼										
1		25%	10	5	9	Use of Alloy X	●	○		●	●	▽	●	●			●					1	5	5	1		1
2		20%	10	5	9	AM Compliant Structure		○			●		●	●	●	●	○					1	5	5	3		2
3		20%	8	8	9	Avoid Premature Combustion			●								●					5	3	3	5		3
4		10%	6	5	9	No Modifications Outside Boundary						●			●	●	○					0	4	0	5		4
5		15%	9	10	9	Time Before Overhaul (TBO)	●		○	●												4	3	3	2		5
6		5%	5	10	9	Repairable			●	○		○										1	1	1	1		6
7		5%	8	5	9	Scalability		●			○											2	2	4	5		7
8																											8
9																											9
10																											10
11																											11
12																											12
13																											13
14																											14
15																											15
16																											16

	HOW MUCH: Target Values	60000 hours	1500 per tip	750°F	1350°F	>45° angles	Within injector scope	> 20 degrees	.001 in	1.57 in	0.232 in	.1 psi				
	Max Relationship	9	9	9	9	9	9		9	9	9	9				
	Technical Importance Rating	360	180	270	375	420	130		405	270	270	495	0	0	0	0
	Relative Weight	10%	5%	8%	10%	12%	4%		11%	8%	8%	14%	0%	0%	0%	0%
Curr. Products	Fluid Liner	4	3	4	2	0	0		0	0	0	3				
	Air Swirler	4	3	5	1	2	2		0	0	0	1				
	Air Lattice	4	0	4	5	5	5		1	1	1	1				
	Existing Solar Injector	2	1	5	4	3	5		4	3	3	3				
	0															
	Column #	1	2	3	4	5	6	8	9	10	11	12	13	14	15	16

Appendix III

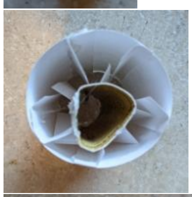
Functional Decomposition



Appendix IV

Tip Cooling Ideation List

1. 

2. 

3. 

4. 

5. 

6. 

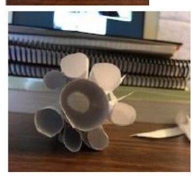
7. 

8. 

9. 

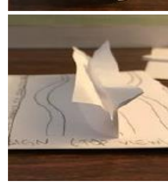
10. 

11. 

12. 

13. 

14. 

15. 

Appendix V

Pugh Matrices

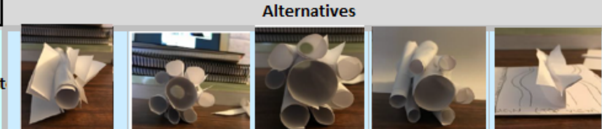
Pugh Matrix - A Decision Matrix

Problem/Situation: Comply with Additive Manufacturing

	Criteria	Baseline: Current Injector Tip	Alternatives 1	2	3	4	5	Totals	Rank
1	Use of Alloy X	0	+	+	+	+	+	5	1
2	AM compliant structure	0	+	+	–	+	+	3	5
3	Avoid premature combustion	0	0	0	0	0	0	0	
4	No modifications outisde boundary	0	0	0	0	0	0	0	
5	Time Before Overhaul	0	+	+	+	+	+	5	1
6	Repairable	0	+	+	+	+	+	5	1
7	Scalability	0	+	+	+	+	+	5	1
8		0						0	
9		0						0	
		Totals	5	5	3	5	5		
		Rank	1	1	5	1	1		

Pugh Matrix - A Decision Matrix

Problem/Situation: Increase Heat Dissipation



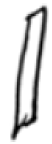
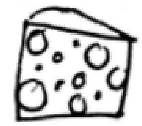
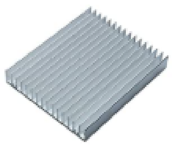
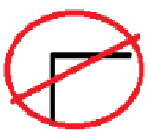
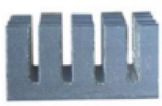
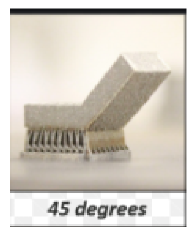
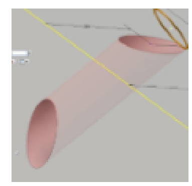
	Criteria	ne Current Inject	Alternatives 1	2	3	4	5	Totals	Rank
1	Use of Alloy X	0	+	+	+	+	+	5	1
2	AM compliant structure	0	+	+	+	+	+	5	1
3	Avoid premature combustion	0	0	0	0	0	0	0	
4	No modifications outside boundary	0	0	0	0	0	0	0	
5	Time Before Overhaul (TBO)	0	+	+	+	+	+	5	1
6	Repairable	0	+	+	+	+	+	5	1
7	Scalability	0	+	+	+	+	+	5	1
8		0						0	
9		0						0	
		Totals	5	5	5	5	5		
		Rank	1	1	1	1	1		

Problem/Situation: Feasibility

	Criteria	Baseline	Double Verical fins	Double Spiral fins	Lots of holes	Fin-hole-lattice combo	Fuel thru passage	Totals	Rank
			1	2	3	4	5		
1	Service life	0	+	+	+	+	+	5	1
2	Fuel temp	0	0	0	0	0	–	-1	7
3	tip temp	0	+	+	+	+	+	5	1
4	AM Geometry	0	0	+	+	+	+	4	5
5	Cost	0	0	–	+	–	–	-2	9
6	Modifications outside boundary	0	0	0	0	0	–	-1	7
7	Repairability	0	+	+	+	+	+	5	1
8	scalibility	0	+	+	+	+	+	5	1
9		0						0	
		Totals	4	4	6	4	2		
		Rank	2	3	1	3	5		

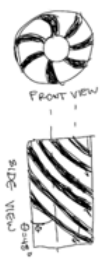
Appendix VI

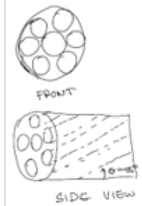
Morphological Matrix

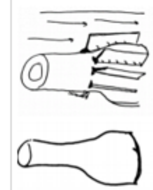
Functions					
Comply with AM	Short vertical structures 	helical like form 	tall vertical structure 	Change AM dimensions along pilot tube 	Porous structure 
Increase Heat Dissipation	fins 	Holes 	Fuel tunnel 	Turbulent flow 	Laminar flow 
Increase Durability	no sharp edges 	Thick rounded stem to withstand wear and tear 	Thin rounded stem due to AM process feasibility 	45-degree angle limit 	Angled Holes 

Appendix VII

Weighted Matrix







		Helical fins (thin stems)		Helical fins at 45°		Porous structure fuel tunnels at 45°		Porous structure holes at 45°		Tall Vertical fins		Porous structure for Turbulent flow with angled holes		Tube profile Change AM dimenisons with fins and thin rounded stems	
Team W14: Injector Tip Cooling	**Weight(1-5)**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Criteria															
Service Life	0.14	3	0.43	3	0.43	5	0.71	3	0.43	3	0.43	3	0.43	3	0.43
Fuel Temp	0.14	5	0.71	5	0.71	2	0.29	4	0.57	5	0.71	5	0.71	5	0.71
Tip Temp	0.14	4	0.57	4	0.57	5	0.71	3	0.43	2	0.29	3	0.43	4	0.57
AM Compliant Geometry	0.14	4	0.57	4	0.57	4	0.57	4	0.57	5	0.71	2	0.29	3	0.43
AM Hole Linearity	0.11	3	0.34	3	0.34	4	0.46	4	0.46	3	0.34	5	0.57	3	0.34
AM Slot Geometry for Thermal Expansion	0.03	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09
Cost	0.09	2	0.17	2	0.17	4	0.34	5	0.43	5	0.43	4	0.34	4	0.34
Outer Diameter	0.06	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17
Inner Diameter	0.06	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17	3	0.17
Combustion Vibration	0.09	3	0.26	3	0.26	3	0.26	3	0.26	3	0.26	3	0.26	3	0.26
Total	**1.00**		**3.48571**		**3.48571**		**3.77143**		**3.57143**		**3.6**		**3.45714**		**3.51429**
Rank			**5**		**5**		**1**		**3**		**2**		**6**		**4**

Appendix VIII

Preliminary Calculations:

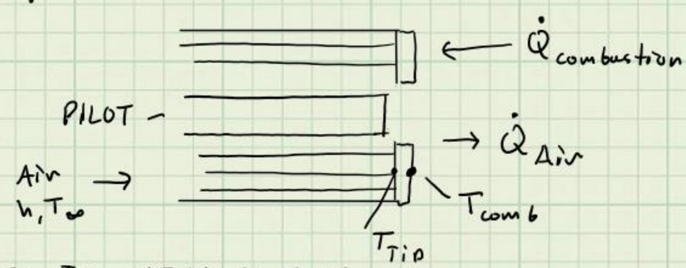
GIVEN: $T_{tip} = 1350°F$, $T_{flame} = 3500°F$, $d_o = 1.57$ in

$d_i \cong 0.48$ in, $K = 13.2\ (Btu/hr)/(ft \cdot °F)$

$T_\infty = 77°F$, $h = 17.6\ (Btu/hr)/(ft^2 \cdot °F)$

FIND: HEAT TRANSFER RATES FOR FINS AND INTO TIP

SCHEMATIC:



ASSUMPTIONS: ISOTHERMAL FINS
TIP TEMP. CONSTANT
CONSTANT PROPERTIES
INFINITE LENGTH FINS
OUTTER $T = T_{flame}$

INNER $T = 1350°F$

ANALYSIS: AREA OF INJECTOR TIP

$$A = \pi(r_o^2 - r_i^2)$$

$$= \frac{\pi}{4}(1.57\ in)^2 - \frac{\pi}{4}(0.48\ in)^2$$

$$A = 1.755\ in^2$$

$$\dot{Q}_{comb} = KA(T_{flame} - T_{tip})/L$$

$$= \left(3.2\ \frac{Btu/hr}{ft \cdot °F}\right)\left(1.755\ in^2 \cdot \frac{1\ ft^2}{(12\ in)^2}\right)\left(\frac{3500 - 1350}{\left(1.755\ in^2 \cdot \frac{1\ ft^2}{(12\ in)^2}\right)^{0.5}}\right)$$

$$\dot{Q}_{comb} = 760\ Btu/hr$$

$$\dot{Q}_{Fins} = \sqrt{h P k A_c}\ \theta_b$$

$P = 2w + 2t$

$w = 0.0877 \text{ in}$

$t = 0.0229 \text{ in}$

$P = 0.221 \text{ in}$

$A_c = wt$

$= 0.002 \text{ in}^2$

$\theta_b = 1350°F - 77°F$

$= 1273 °F$

$$\dot{Q}_{Fin} = \left(17.6 \frac{Btu/hr}{ft^2 \cdot °F} \cdot \frac{1 ft^2}{144 in^2} \cdot 0.221 in \cdot 13.2 \frac{Btu/hr}{ft \cdot °F} \cdot \frac{1 ft}{12 in} \cdot 0.002 in^2\right)^{0.5} 1273°F$$

$= 9.79 \text{ Btu/hr}$ FOR EACH FIN

$\# \text{ Fins} = 96$

$96 \cdot \dot{Q}_{Fin} = 939 \frac{Btu}{hr}$

$\dot{Q}_{Fins} > \dot{Q}_{combustion}$

Convection coefficient calculations:

ASSUMPTIONS: CONSTANT PROPERTIES
2 psi DROP
FULLY DEVELOPED FLOW

DISCHARGE AIR PROPERTIES:

$P_{cd} = 240$ psi

$T_{air} = 825°F$

$\rho = 0.5012$ lbm/ft^3

$\mu = 2.335 \times 10^{-5}$ lbm·ft/s

$Pr = 0.7126$

$k = 0.03046$ BTU/hr ft °F

INJECTOR FLOW CONDITIONS

$V_{in} = 120$ ft/s

$V_{ext} = 300$ ft/s

$$Re_{in} = \frac{\rho V D}{\mu}$$

$$= \frac{(0.5012 \text{ lbm/ft}^3)(120 \text{ ft/s})(1.42/12)\text{ft}}{2.335 \times 10^{-5} \text{ lbm·ft/s}}$$

$Re_{in} = 3.049 \times 10^5$

$Re_{out} = 6.278 \times 10^5$ (USING $L = 3.0$ in)

INTERIOR FLOW COEFFICIENT

GNIELINSKI CORRELATION

$$\overline{Nu}_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

$\varepsilon \simeq 18\ \mu m = 3.28 \times 10^{-6}$ ft

FROM MOODY DIAGRAM AND HALLAN-COLBROOK CORR.

$f = 0.0143$

$$\overline{Nu}_o = \frac{(0.0143/8)(3.09\times10^5 - 1000)(0.7126)}{1 + 12.7(0.0143/8)^{1/2}(0.7126^{2/3} - 1)}$$

$$= 434.4$$

$$= \frac{\bar{h}L}{k}$$

$$\bar{h} = \frac{(434.4)(0.03096\ Btu/hr\ ft\ {}^\circ F)}{(1.42/12)\ ft}$$

$$\bar{h}_{in} = 111.8 \quad Btu/hr\ {}^\circ F\ ft^2$$

EXTERIOR CONVECTION COEFF.

$$\overline{Nu}_L = (0.037\ Re_L^{4/5} - 871)\ Pr^{1/3}$$

$$= 658.9$$

$$= \frac{\bar{h}L}{k} \qquad (L = 1.17 in)$$

$$\bar{h} = 205.8\ \frac{Btu}{hr\ ft^2\ {}^\circ F}$$

Appendix IX

Design Hazards Checklist

DESIGN HAZARD CHECKLIST

Team: W14 - Injector Tip Cooling Faculty Coach: Eileen Rossman

Y	N	
☐	☒	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☐	☒	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will you have any non-grounded electrical systems?
☐	☒	9. Will there be any large batteries or electrical voltage (above 40 V) in the system?
☐	☒	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☒	☐	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Could the system generate high levels of noise?
☒	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?
☐	☒	16. Is it possible for the system to be used in an unsafe manner?
☒	☐	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, complete a row in your Design Hazard Plan including (a) a description of the hazard, (b) a list of corrective actions to be taken, and (c) the date you plan to complete the actions.

Appendix X

Failure Modes and Analysis

												Action Results			
System / Function	**Potential Failure Mode**	**Potential Effects of the Failure Mode**	**Severity**	**Potential Causes of the Failure Mode**	**Current Preventative Activities**	**Occurence**	**Current Detection Activities**	**Detection**	**Priority**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Severity**	**Occurence**	**Criticality**
Structural system	angles too great	internal collapse	9	additive manufacturing limitations	check angles	2	Observation	1	18	inspection, CAD Models	April 2021 before Critical Design Review -Lourdes				
	broken fillets	structure failure	6	structure too thin	CAD	2	FEA	3	36	inspection, CAD models	April 2021 before Critical Design Review -Lourdes				
	porous structures- not large enough to let air through	injector tip does not dissipate adequate heat	6	air passages too small	dimention constraints that prevent small porous structures	7	CFD	2	84		June 2021 before Critical Design Review-Andy				
	clearance slots- not large enough to allow thermal expansion	injector tip does not dissipate heat	5	slots not large enough to allow thermal expansion, interference	minimum slot dimension	3	FEA	4	60	CAD inspection	April 2021 before Critical Design Review -Andy				
	excessive vibrations	total turbine failure	8	structure causes wave propogation	limiting constrained flow	7	Modal Analysis	8	448	vibration simulation	fall 2021- Andy, Alberto, Lourdes				
Cooling System	excessive pressure loss	stagnent air = no cooling	6	air passages too small	make passages large	7	CFD	6	252	inspection by sponsor	June 2021 before Critical Design Review -Andy				
	excessive heat	increased failure rate	6	not enough heat dissipation	heat transfer analysis	7	FEA/CFD	4	168	computational fluid dynamics and thermal heat dissipation	June 2021 before Critical Design Review -Lourdes				
Fuel Delivery system	precombustion	catastrophic detonation	10	fuel temperature too high	increase surface area of tunnels	2	FEA	4	80	thermal heat dissipation test to check fuel temp	April 2021 before Critical Design Review -Alberto				
	excessive pressure loss	main fuel supply off target	8	tunnels too small	CAD	3	CFD	3	72		June 2021 before Critical Design Review -Andy				
	fuel leaks	catastrophic detonation	10	cracks or holes in structure	wall thickness inspection	3	FEA	7	210	inspection, test print, fuel pressure test	April 2021 before Critical Design Review -Alberto				
Material property system	corrosion	decrease the life span of injector tip	6	typical AM process, heat	heat treatment for AM printed part (HIP)	6	FEA	3	108	thermal dissipation analytical testing, sponsor approval	April 2021 before Critical Design Review -Alberto				
	surface flaws	different properties at each location	4	laser process	heat treatment for AM printed part (HIP)	3	FEA	8	96	test print and inspection	April 2021 before Critical Design Review -Alberto				

Appendix XI

DVP&R

DVP&R - Design Verification Plan (& Report)											
Project:	W14 Injector Tip AM Design		Sponsor:	Solar Turbines, Rick Rogers						Edit Date:	11/15/2021
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Tip Temperature	Comparitive test using high temp Sauna bulb to mimic radiation source and thermocouples to measure temps. Simulated airflow with small computer fan.	Temparture at tip	Our design must yield lower temps than existing design,	Mustang 60	Radiation bulb, voltage-controlled fan, thermocouples, Aluminum mock-up prototypes	Team	11/9/2021	11/11/2021	Each thermocouple showed a difference of approximately 2 degrees Fahrenheit	Fin prototype dissipates more heat than the simple flat plate model.

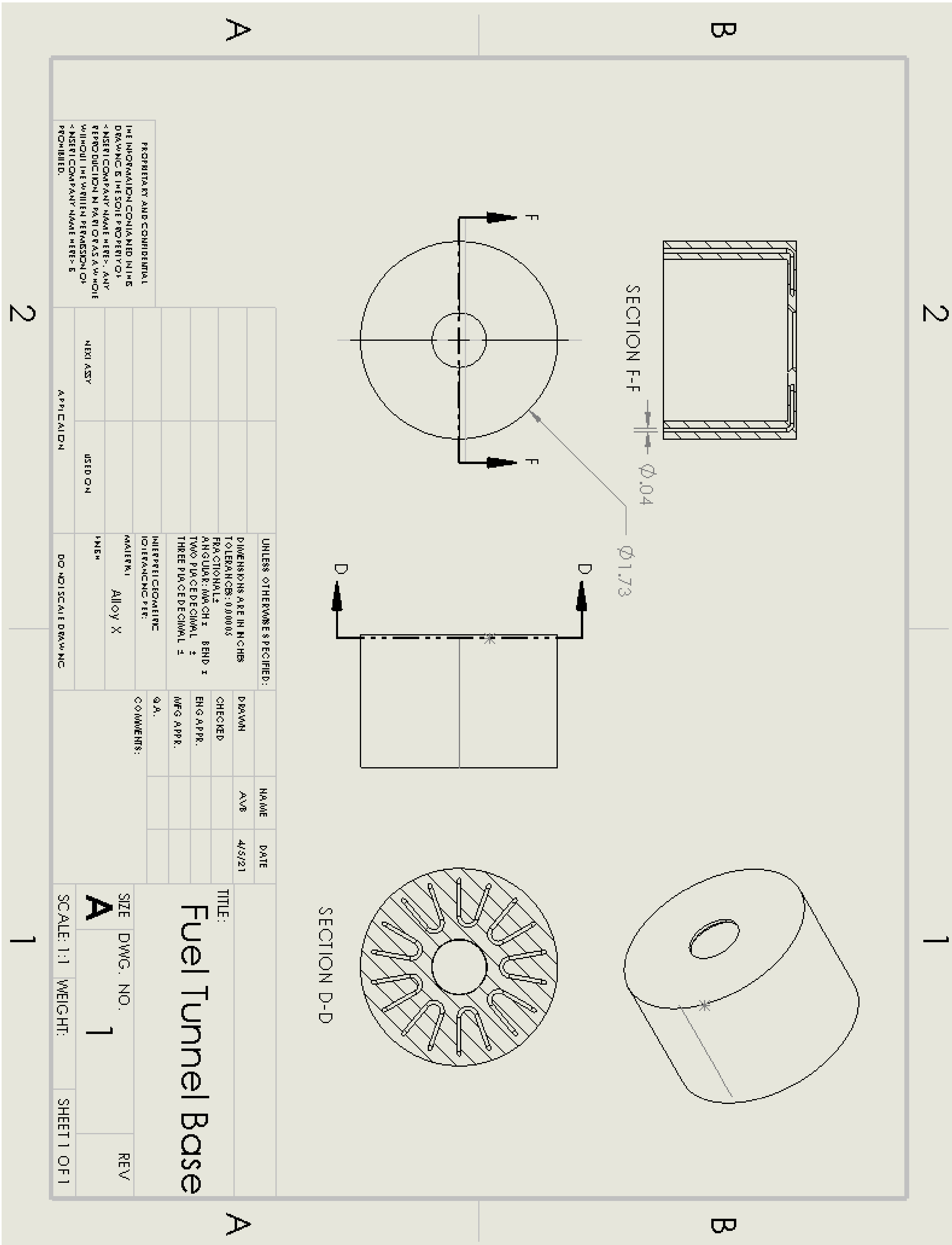
Appendix XII

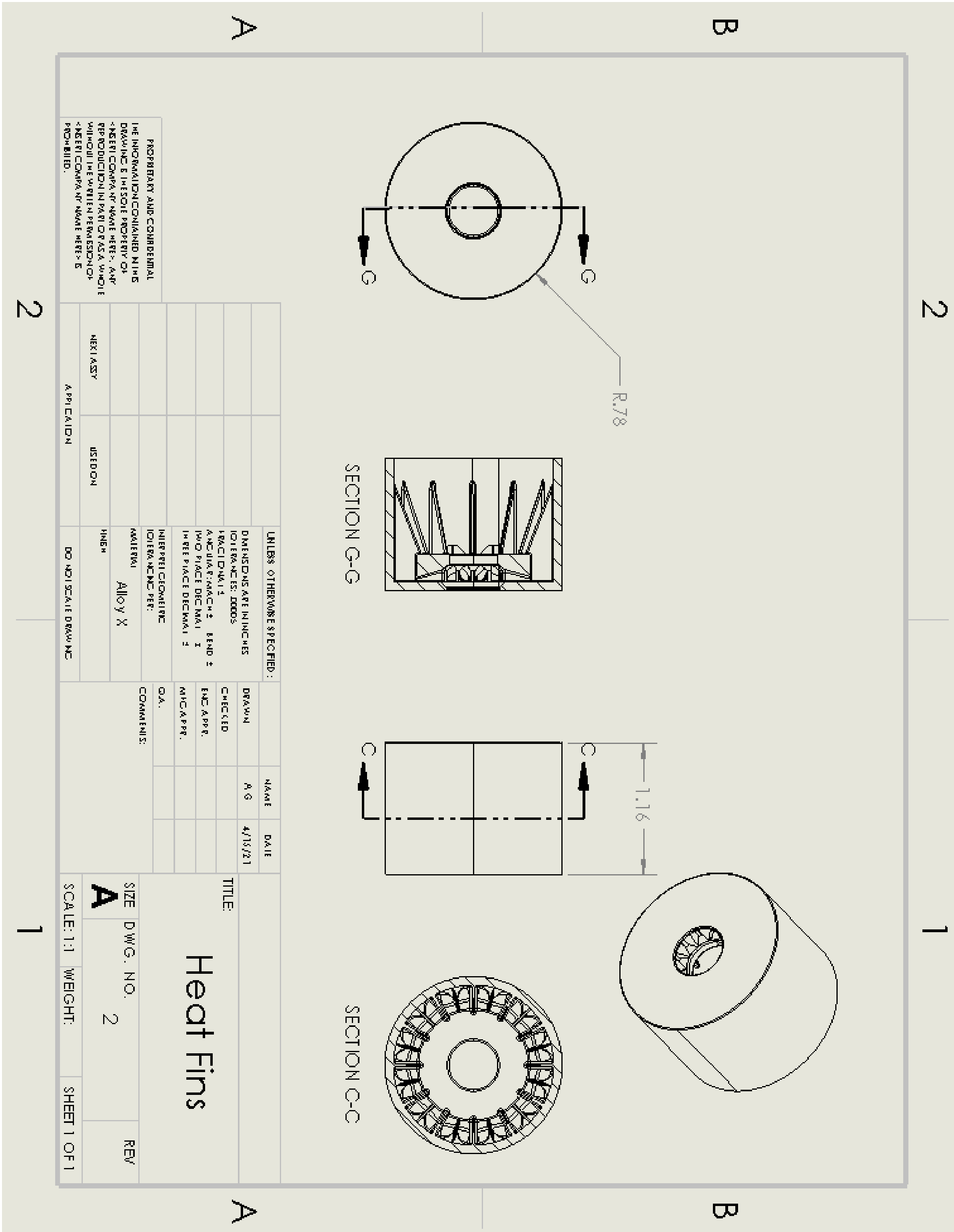
Indented Bill of Materials

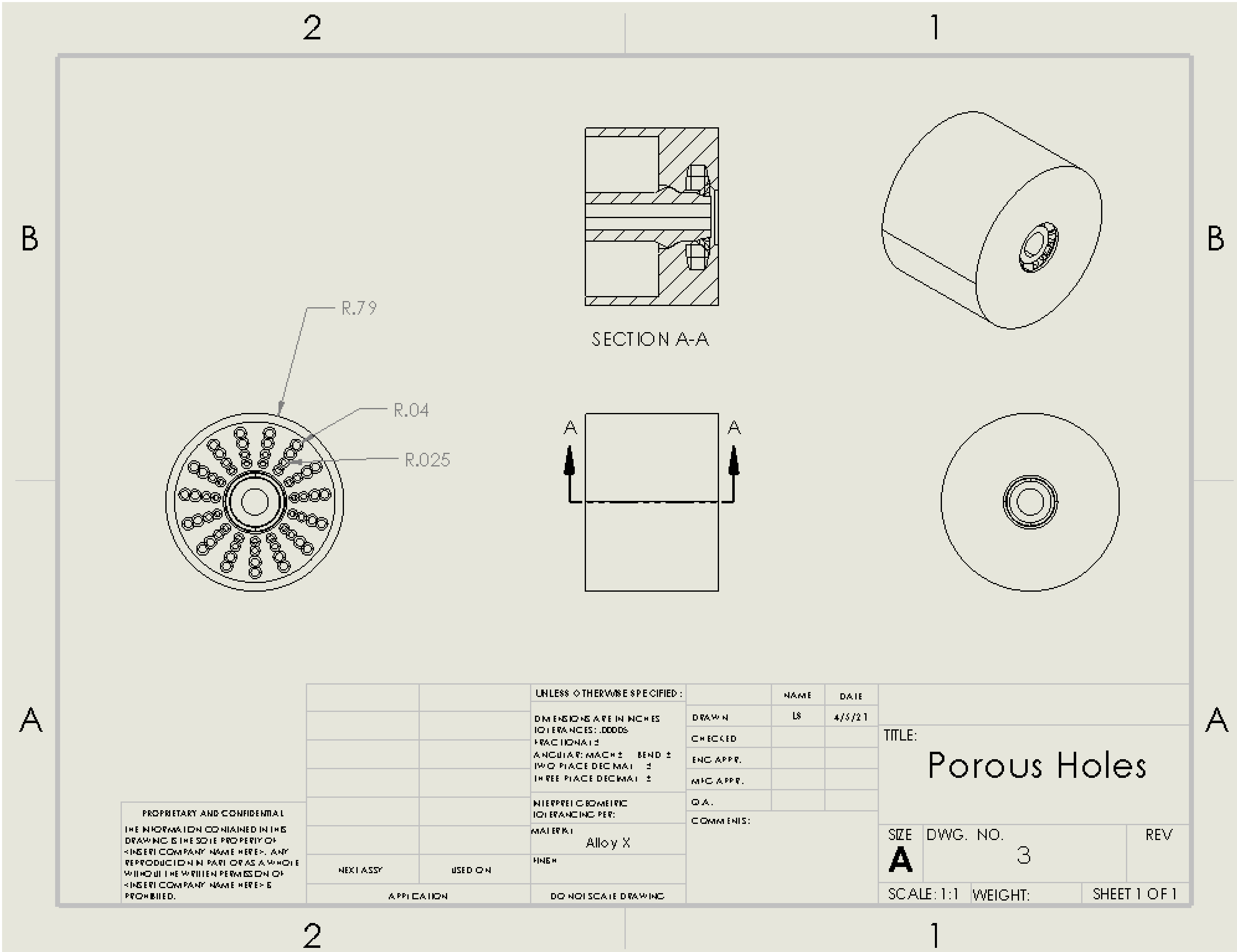
Assy Level	Part Number	Descriptive Part Name					Qty	Mat'l Cost	Production Cost	Total Cost	Part Source	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*						
0	100000	Top Assembly									------	
1	110000		Injector Tip				1	$500.00	$ 1,000.00	$ 1,500.00	custom	AM using Alloy X
	Total Parts						**1**			**$ 1,500.00**		

Appendix XIII

Drawing Package



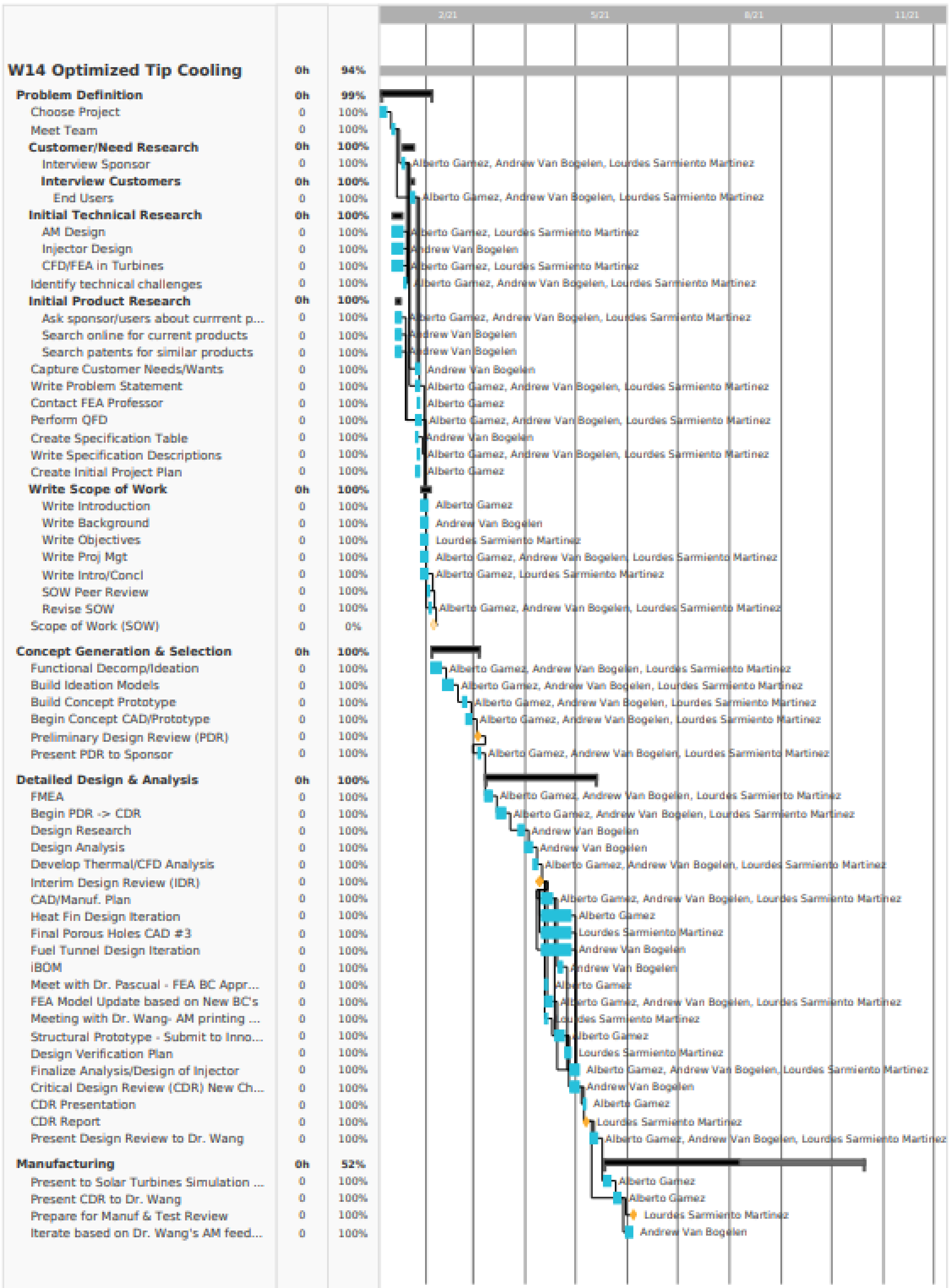

SECTION G-G
SECTION C-C
R.78
1.16
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
A.G
MATERIAL
Alloy X
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
TITLE:
Heat Fins
SIZE
A
DWG. NO.
2
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL



R.79
R.04
R.025
SECTION A-A
A
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: .00005
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Alloy X
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
LS
4/5/21
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Porous Holes
SIZE
A
DWG. NO.
3
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

Appendix XIV

Gantt Chart



Engineering Ethics Debate	0	100%
Adjust design if needed for AM	0	100%
Meet with Dr. Wang- present final C...	0	100%
Submit part to be AM printed	0	50%
Wait for part to get printed- 2 weeks	0	0%
AM compliant test - inspection test	0	0%
Verification Prototype Sign-Off	0	0%
Testing	**0h**	**97%**
start brainstorming heat dissipation ...	0	75%
email Dr. Pascual or Dr. Lemiuex to ...	0	100%
submit heat dissipation procedure to...	0	100%
check in with Rick (sponsor) -updates	0	100%
meet w/ Dr. Pascual or Dr. Lemieux	0	100%
Iterate test procedure based on class...	0	75%
email the correct people to reserve l...	0	100%
Team decided to not reserve a lab ti...	0	100%
order necessary testing instruments -...	0	100%
Received- heat lamp and the fan	0	100%
Heat dissipation test	0	100%
Examine Prototype after Testing	0	100%
Rig Test at Solar Turbines	0	100%
DVPR Sign-Off	0	100%
Test results chapter	0	100%
email Dr. Wang about AM part timeli...	0	100%
email Dr. Want to confirm AM machi...	0	100%
Email Rick to see if Solar Turbines co...	0	100%
update team-Rick confirmed we coul...	0	100%
Contact Protolabs to see off campus...	0	100%
Email Rick regarding NDA and off ca...	0	100%
update team-Rick said we cannot AM...	0	100%
Emailed shop Tech to CNC simplified...	0	100%
update team-top 2 shop tech are bu...	0	100%
make solid works modifications- incr...	0	100%
Team decided to not hire shop tech- ...	0	100%
Order and solder T thermocouples	0	100%
Update Thorncroft on latest manufac...	0	100%
buy aluminum sheet from Home Dep...	0	100%
start manufacturing prototype	0	100%
Heat Dissipation Test	0	100%
Project Wrap-up	**0h**	**100%**
Address Feedback from Solar Turbin...	0	100%
Operating Manual Chapter	0	100%
Manufacturing Chapter	0	100%
Create Expo Poster	0	100%
Present Expo Poster	0	100%
Add DR chapters	0	100%
Write FDR Report	0	100%
Clean out workspaces	0	100%
Final Design Review (FDR)	0	100%
Present Final Results to Solar Tubines	0	100%