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J-85 Model Development For Performance Optimization

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by

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J-85 MODEL DEVELOPMENT FOR PERFORMANCE OPTIMIZATION

A thesis by Austin Childers

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ABSTRACT

MODEL DEVELOPMENT FOR PERFORMANCE OPTIMIZATION

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Larsen Motorsports is a local jet racing facility in Melbourne, Florida. Larsen Motorsports is a key partner with Florida Tech. Larsen Motorsports has a highly skilled manufacturing team along with a robust manufacturing capability. Through their team's many years of racing Larsen Motorsports has tuned and developed engineering for both the J-60 and J-85 jet engines. These modifications vary from small design changes to production of components to entire system redesigns. One of the most extensive redesigns their team has developed is the afterburner section of the General Electric J-85 jet engine. Their team has designed and tuned the entire afterburner section, including tailpipe, fuel manifold, and flame holder. Larsen has tested many iterations of its flame holder to develop its current 3D octagonal design. These past tests have been primarily based on prior experiences working with these engines. The task for this thesis is to use the knowledge obtained from the Masters of Flight Test Engineering curriculum combined with my professional expertise and resources to optimize their design further. I will provide Larsen Motorsports the necessary CAD models that will allow fabrication consistency in their baseline design and offer the ability to conduct analyses design.

Establishing baseline performance data will be essential when assessing subsequent design changes. Using finite element analysis (FEA), and computational fluid dynamics (CFD) techniques, analytical performance data can be compared to instrumented data. Larsen Motorsports uses a General Electric J-85 jet engine to power all their current jet cars. This engine is chosen for its power to weight ratio and availability. Larsen takes many of the unusable accessories off the stock to reduce complexity as well as weight. Using the expertise of

Christopher Larsen, President of Larsen Motorsports, and knowledge gained from the Flight Test curriculum, I will develop CAD models, conduct analyses, and provide test procedures for future performance increases. Using the files and tools within this thesis I will provide Larsen Motorsports the information required to manage and maintain their platform. While this thesis's focus is primarily on the engine, specifically the afterburner, the utilization of these modern design practices has applications throughout their vehicle. I look forward to delivering these models to Larsen Motorsports and continue to work with them in their development of their racing team.

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FIGURES

TABLES

NOMENCLATURE

A/R – As Required
CG – Center of Gravity
dA – Mean Flame Area Element
x - Axial Coordinate
BR - Blockage Ratio
CONFIG – Configuration
δ – Displacement
f – Fuel Mixture Fraction
FADEC – Full Authority Digital Engine Control
FBW – Fly-by-wire
FF– fuel flow
Fwd- Forward
est – Estimated
EGT - Exhaust Gas Temperature
NHRA - National Hot Rod Association
ρ – Density
outbd- Outboard
inbd- Inboard
lb - Pound
R – Radius of Combustor
RF – Flame Radius of Curvature
sL - Laminar Flame Speed
T – Time
TRef - Reference Flame Temperature
u' - Turbulent Velocity Fluctuation
U - Reactants Inflow Velocity
USAF – United States Air Force
u - Velocity Vector
VGV - Variable Guide Veins
xF - Flameholder velocity
Δp - Pressure Drop Across Burner
τ - Flame Element Time Lag
ζ - Non-Dimensional Pressure Drop Across Burner
() u - Quantity in Reactants
SFC – Surface
W_f – Fuel Weight

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to Larsen Motorsports for the opportunity and their willingness to allow this once in a lifetime opportunity to Florida Tech students such as myself. I know I may never have another experience as rewarding as this in my professional and academic career. The Larsen team, specifically Chris Larsen, was an invaluable resource that provided a wealth of knowledge in the development of jet engine design. His willingness and enthusiasm with respect to this project was critical to the success of it. He and his team worked with me during very challenging times allowing students to enter their facility.

I would like to express a big thank you to Chelsea Reichard and Jacob Portugal for the coordination and support throughout this process. It is my hope that between our projects that Larsen Motorsports has been provided with quality data, tooling, and testing that they can use to achieve many more wins as a racing organization.

Lastly, I would like to thank Dr. Brian Kish, program chair of the FTE department, and my academic advisor, not only for his support throughout my thesis but the entirety of my master's studies. His willingness to answer questions and listen to students on course curriculum is the primary reason why I will never forget my Flight Test Engineering studies and will use what I have learned throughout my career.

CHAPTER 1: INTRODUCTION

BACKGROUND

1 Larsen Motorsports is a local jet racing facility in Melbourne, Florida. Larsen Motorsports is a key partner with Florida Tech. Larsen Motorsports has a highly skilled manufacturing team along with a robust manufacturing capability. There use of the General Electric J-85 helped propel their team into the winner circle on multiple occasions. They have selected the J-85 platform for its reliability, availability, and incredible thrust-to-weight ratio. The J-85 is one of the longest-running small jet engine platforms which dates to the 1960s. This history has allowed the public and private sectors to optimize and refine the J-85 to the platform it is today. To date, the J-85 has seen little development using modern practices such as Computer-Aided Design, Finite Element Analysis, and Computational Fluid Modeling, just to name a few. This is due to the bulk of its refinement taking place before the advent of these tools.

2 Through their teams many years of racing, Larsen Motorsports has tuned and developed engineering on a multiple of jet engines. These designs vary from small design changes to production components to entire system redesigns. One of the most significant redesigns their team has developed is the afterburner section of the General Electric J-85 jet engine. Their team has designed and tuned the entire afterburner section including, afterburner case and flame holder. Larsen has tested many iterations of its flame holder to develop its current octagon design. These past tests have been primarily based on experience working with jet engines.

PURPOSE

3 The thesis's task is to use the knowledge gained from the Master of Flight Test Engineering curriculum, combined with my professional experiences and resources, to optimize their design further. The contents of this thesis will provide Larsen Motorsports the necessary modeling and simulations that will allow a controlled and measured approach for future optimization of their baseline design. Establishing baseline performance data will be critical when assessing subsequent design changes Using finite element analysis and computational fluid dynamics techniques, I will identify areas in the design to focus on design changes. This will be the basis of all design change recommendations. Utilizing the expertise of Chris Larsen, along with knowledge gained from the Flight Test curriculum, I will develop an optimized design and test procedures. Larsen Motorsports uses a General Electric J-85 jet engine to power most of their jet cars. This intent of this thesis is to create a 3D model of the engine which accurately represents their current configuration of the engine to be used in all future cad models. Larsen Motor Sports also has come up with a custom designed afterburner through track testing. This afterburner will also be modeled as this will be the standard afterburner going on all future cars.

DESCRIPTION OF PLATFORM

4 The GE-J-85-13 is a small single-shaft afterburning turbojet engine developed from General electric. The GE-J-85 base of engines has been in use for over 50 years due to is reliability and excellent thrust to weight ratio. The engine specifications can be seen in Table 1: GE- J-85-13 Specification and the cross-section view can be seen in Figure 1: Cross-Section of GE-J-85-13.

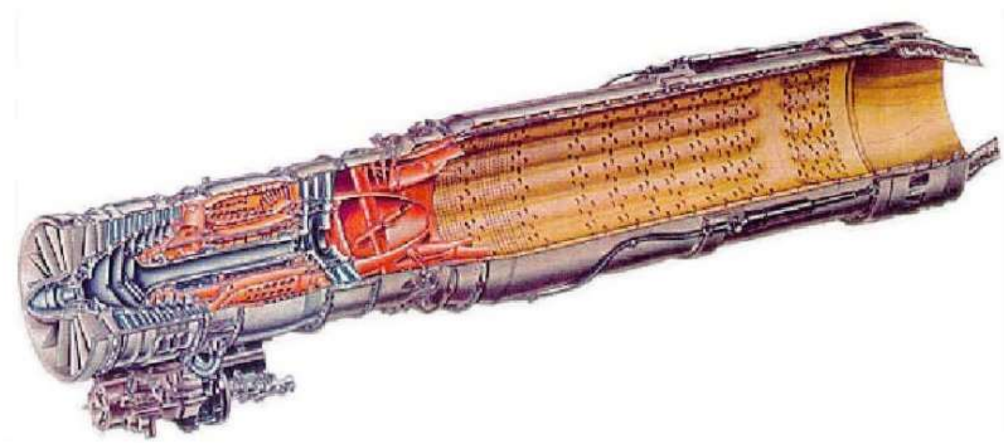

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Figure 1: Cross-Section of GE-J-85-13

BASIC JET ENGINE BACKGROUND

5 In general, a jet engine is composed of four sections, as seen in Figure 2: Jet Engine Cross-section. These sections are the intake, compressor, combustion chamber and exhaust. The intake section is where air is drawn into the engine. The compressor is where the inlet air is compressed and thus heated by an axial or centrifugal compressor. The compressor's turbines are a multi-stage

succession of rotors and stators that compresses the incoming air. Centrifugal compressors are comprised of a rotating impeller, followed by a diffuser that routes the air to the combustion chamber via a compressor manifold. It should be noted, not all inlet and compressed air goes to the combustion section. 50-90% of air is scavenged during compression for multiple purposes. Some of these are inlet particle separation, bleed air for pneumatic sources, bleed air for environmental control systems and engine cooling depending on the engine configuration. The combustions section, which is part of the hot section is where the air from the compressor section. is ignited within the combustion chamber which is sustained by a continuous flow of fuel from multiple fuel nozzles. Metered fuel sprayed into the combustion chamber results in the increase/decrease of power output of the engine. The exhaust section is where turbines are turned by the escaping combustion section air. The rotating power turbines are shafted to the output shaft back to the compressor section and accessory section which is how the engine remains operational.

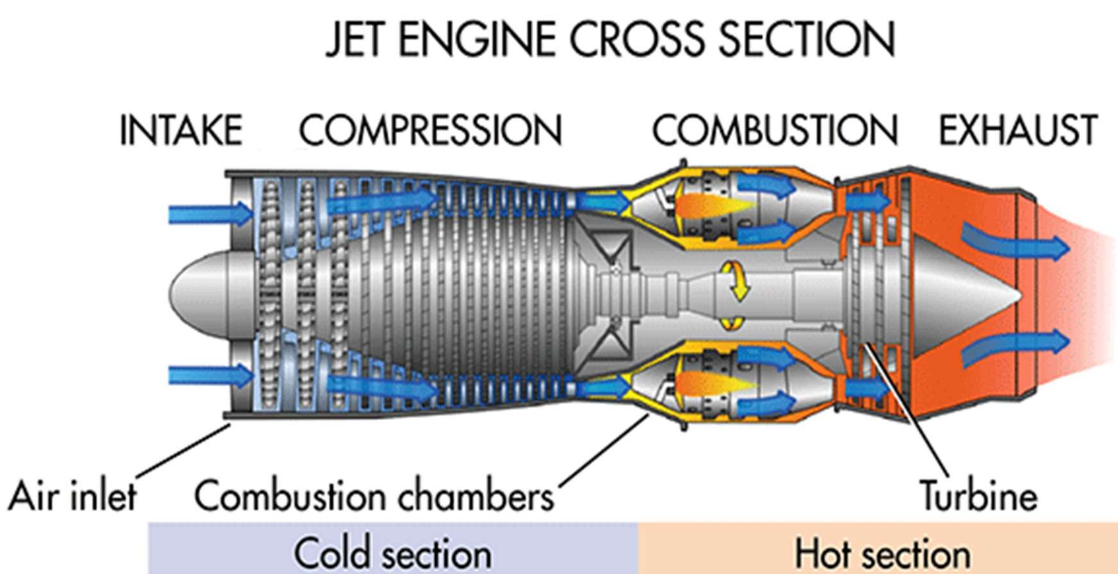


Figure 2: Jet Engine Cross-section

Table 1: GE- J-85-13 Specification

Model	GE-J-85-13	
Type of Motor	Afterburning Turbojet Engine	
Combustor	Simple Annular	
No. of Turbine Steps	2	
Length of Motor	23 ft	
Weight of Engine	400 lb	
Compression Ratio	6.8	
	Military	Maximum with Afterburner
Thrust	2720 lbs	4069 lbs
RPM	16542	16542
Consumption	2700 lbs/h	8800 lbs/h

J-85 HISTORY

6. Originally designed in 1954 for U.S. Air Force, Ed Wool designed the J-85 for use on the ADM-20 Quail. The J-85 soon after adopted in other light-jet applications including the supersonic Northrop F-5/T-38 family. Over 13,500 J-85s and 2,000 commercial CJ610s have been manufactured. Current plans for the U.S. Air Force (USAF) have applications for J-85-powered aircraft to be in service through 2040. A few of the reasons for this its reliability and its high

thrust-to-weight ratio. The General Electric J-85 turbine jet engine is used on the F-5 military fighter jet, the T-38 military trainer aircraft, the X-14 the vertical takeoff test aircraft and was used in the development of the prototype for the F-117 Stealth fighter. These are just a few of the many platforms that the J-85 was used on.

Figure 3: J-85 Cut-Away

J-85 CONFIGURATION

7. The J-85 is a small single-shaft turbojet engine produced by General Electric. Military versions produce up to 2,950 lbf of thrust; afterburning models can see thrust as high as 5,000 lbf. Depending upon equipment and type of model, the J-85 can weigh from 300 to 500 pounds. It is one of General Electric's most successful and longest in-service military jet engines. Commercial versions have seen over 16.5 million flight hours to date. The CJ610 which is the J-85's civilian

models, does not have an afterburner, and the CF700is built to improve fuel economy.

J-85 AFTERBURNER SECTION

8 The afterburner section of the J-85 adds an additional 1349 lbs. of thrust. The engine, while using the afterburner, can use up to four times the amount of fuel as compared to normal operations. An afterburner is an additional component present on some jet engines. Its purpose is to provide an increase in thrust by injecting additional fuel into the jet pipe downstream of the turbine. The primary benefit of afterburner is a significant increase in thrust; the disadvantage of an afterburner is the large amount of fuel it requires to operate, as an afterburner is highly fuel inefficient. For the purposed of drag racing this is acceptable for the short periods during which it is required to be used. When the afterburner is not in operation, this duct serves as the exhaust duct for the engine. Therefore, it should not interfere with the exhaust flow of the engine. If the afterburner is properly designed, the engine will not even notice the presence of the afterburner. In principle, the engine operates the same with or without an afterburner. Afterburner should be sized to provide stable combustion during operation. To do this, the cross-sectional area of the afterburner must be large enough so that the gas velocity does not exceed the flame blowout velocity. Otherwise, the combustion mixer is blown out of the exhaust nozzle, making it difficult to form a flame. The afterburner casing supports the exhaust nozzle and externally mounted nozzle operating components. Air flows into the combustion section through a hole in the periphery of the liner to prevent the occurrence of high noise or screech. The rear fan duct and turbine exhaust cone act as diffusers that reduce the speed of the fan exhaust and engine exhaust. Fuel is injected by a series of perforated spray bars located inside the front of the afterburner. The stock J-85 engine has seven fuel spray manifolds in the rear fan duct in front of the Afterburner. Some J-85s utilize a variable nozzle that adjusts the exhaust nozzle area of the J-85 engine. This is used to regulate the flow of air to maximize the

thrust output while also ensure the engine does not overheat and fail. The J-85 Afterburner & Variable Nozzle can be seen in Figure 4: J-85 Afterburner & Variable Nozzle.

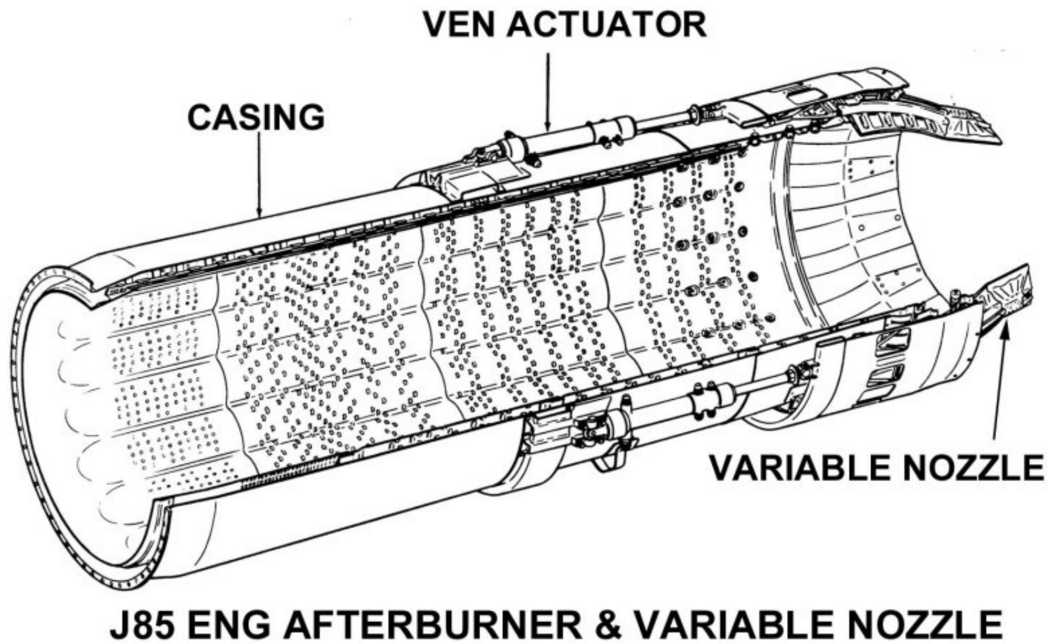


Figure 4: J-85 Afterburner & Variable Nozzle

J-85 FLAME HOLDER

9 The J-85 flame holder is mounted behind the fuel spray bar and forms a local vortex, reducing the gas velocity and stabilizing the flame when operating the Afterburner. The flame holder consists of an annular concentric ring with a V, C or U-shaped cross-section depending on the model. The J-85-13 flame holder can be seen in Figure 5: J-85 Stock Flame Holder.

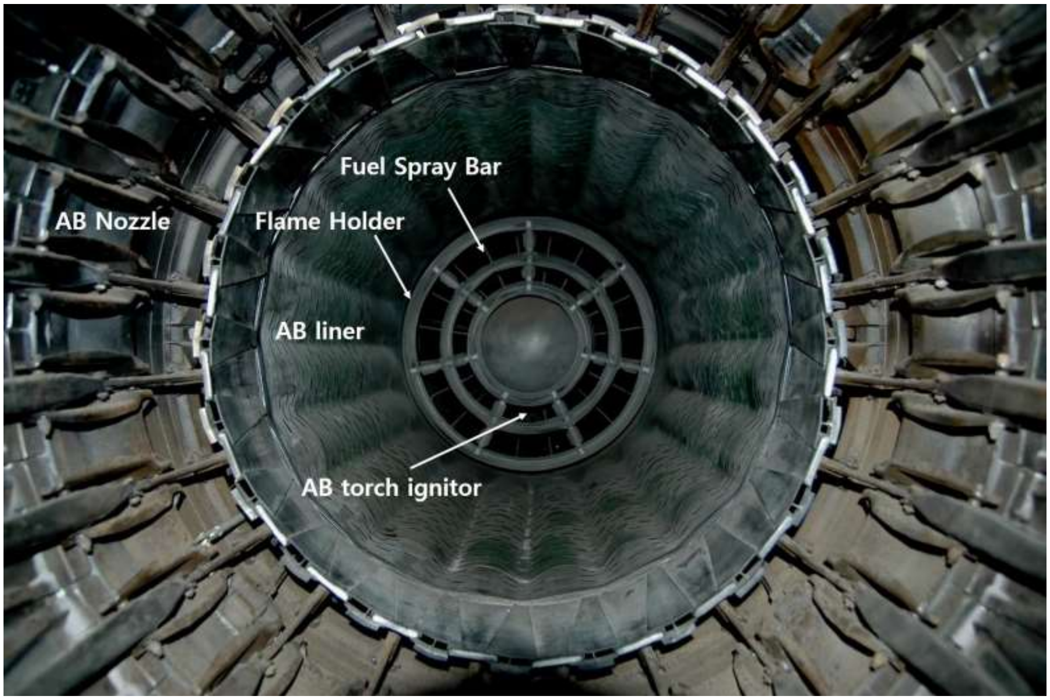


Figure 5: J-85 Stock Flame Holder

LARSEN MOTORSPORTS

<u>LARSEN MOTORSPORTS BACKGROUND’</u>

10 In the beginning of the Larsen Motorsports Jet Racing career, their first dragster, The Mista Fire, used a Pratt and Whitney J-60 Turbojet engine due to its incredible power. This engine produces 3,000 lbs. of force at 16,000 RPMs without the afterburner ignited. The fastest jet dragsters in the world use this engine to obtain speed of over 300 mph in the quarter mile. Although these engines seem like the obvious choice for power and performance, production of the J-60 was only live between the years of 1958 and 1977, with only 2,269 engines built. With numbers like these it is easy to conclude that maintenance and accessibility are limited, therefore expensive. Although the Larsen’s’ have manufactured more than just one J-60 cars in the past, many of their cars took advantage of the General Electric J-85 engine.

Figure 6: Elaine Larsen with her Jetcar with the J-85 installed

11 The General Electric J-85 engine has the highest power to weight ratio of its time, which is why it was used to replace the J-60 engine used in the famous dragsters. Although this engine does not produce 3,000 lbs. of thrust, it does produce 2,850lbs of thrust at 16,500 RPMs while weighing only 398 lbs. These numbers result in a 7.3:1 power to weight ratio. Another advantage of these engines is that GE built more than 12,000 engines before production ended in 1988. That is over five times the quantity of the J-60.

Figure 7: Larsen Motorsports inventory of J-85 engines

LARSEN MOTORSPORTS VEHICLE CONFIGURATION

12 These engines produce an enormous amount of power and give the vehicles enough thrust to reach 150mph in the quarter mile, over 60% of the air that goes through the engine, is unburned. This is where the afterburner takes part producing about 50% of the overall power of the engine and afterburner assembly. While the air coming out of the engine is thousands of degrees and has plenty of oxygen to burn, there is more fuel introduced into the tailpipe through a fuel

manifold. The fuel manifold is a hollow steel ring, with 36 holes drilled in that releases fuel. Once that fuel is introduced, the flame holder creates a low-pressure recirculation zone which holds that fuel and is why surface area of the flame holder is so important. The flame holder allows enough time to ignite the fuel and produce the additional thrust.

LARSEN MOTORSPORTS USE OF THE J-85

13 The afterburner assembly was designed based on the 1970s and 1980s factory design data. The design itself is custom, but the data acquired through years of use are the driving force behind the current configuration. The Larsen Motorsports team have used analytical data and testing to determine the best area to place the fuel manifold and flame holder in their design seen in Figure 8: View Looking Forward at Flame Holder. The way that these experiments were conducted was using a multitude of setups, they would arrange the flame holder, closer, and further, with occasional small tabs welded on to increase fuel grip. Using their test trailer seen in Figure 9: GE-J-85-13 with Larsen Equipment on Test Trailer, they were able to use analytical data to help guide the placement process. With many mistakes made, and many turbine nozzles burned up, they were finally able to finalize a proper distance from the turbine to create the maximum amount of power with little room for error.

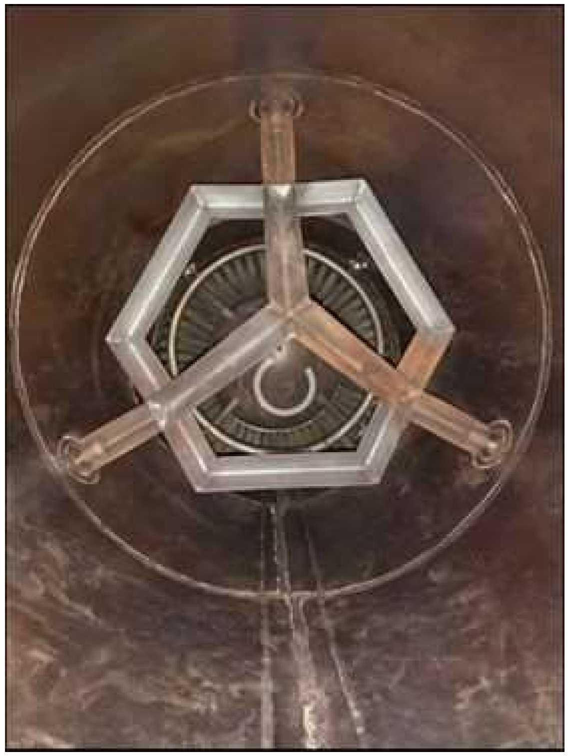


Figure 8: View Looking Forward at Flame Holder

Figure 9: GE-J-85-13 with Larsen Equipment on Test Trailer

CHAPTER 2: MODEL DEVELOPMENT

14 For the development of the master file, a few sources were utilized. Some models came from online model repositories, some models were delivered from Larsen Motorsports, and many were modeled from drawings or manual measurements. All modeling was done in Siemens NX and the master file will be delivered to Larsen Motorsports for further development and analysis. The full configuration can be seen in Figure 10: Model of GE-J-85-13 with Larsen Motorsports Equipment.

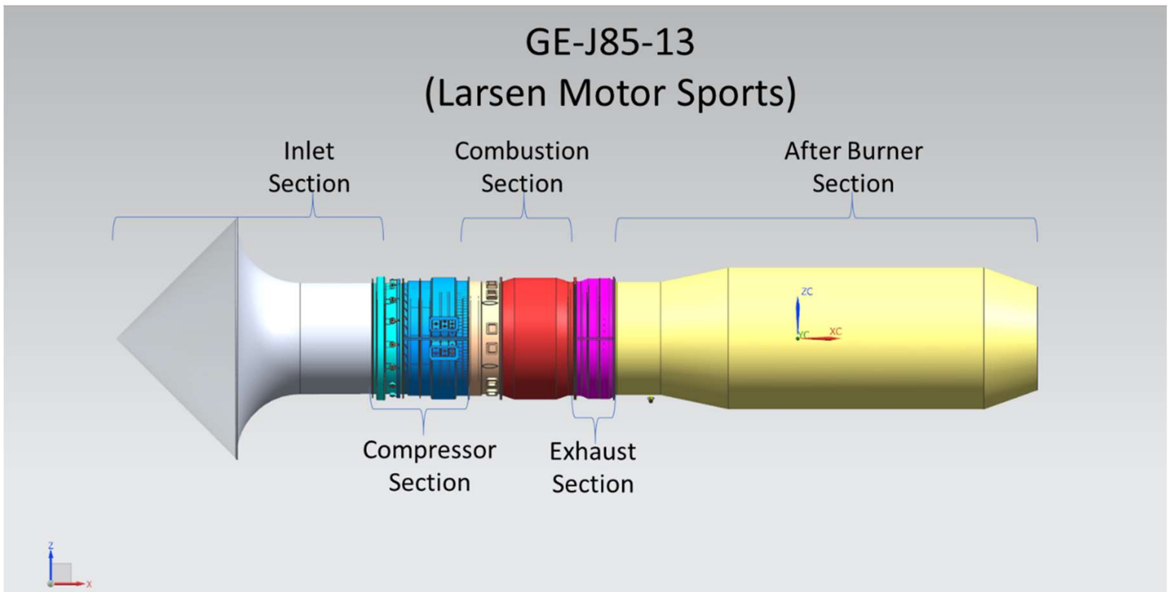


Figure 10: Model of GE-J-85-13 with Larsen Motorsports Equipment

15. While CAD modeling is an invaluable tool when it comes to design, new design is not the only thing that CAD modeling can assist with. When working with large complex files such as the J-85 model, configuration management becomes critical, especially if there are different applications or vehicle configurations. Establishing correct part numbers along with accurate part counts will deliver a quality bill of material or BOM, which will allow troubleshooting and part replacement for seamless configuration management and reduced errors.

16 A “best modeling” practice that was utilized in the master file was the use of layers. Layers allow the user to patrician the model, as shown in Figure 11: Layers Within Master File. This is useful when working on a specific section of the engine to eliminate unnecessary models. It also reduces load times and allow the user to quickly begin working within the file. The layer system can be arranged by section as shown or partitioned by system such as fuel, lubrication, casing, and other required sections.

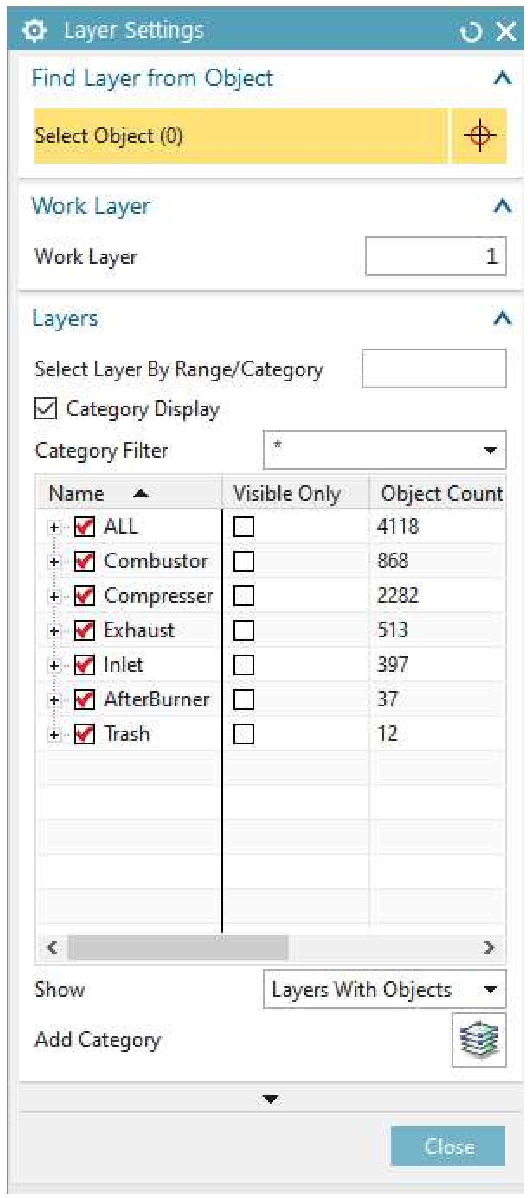


Figure 11: Layers Within Master File

INLET SECTION

17 The inlet section of the model was comprised of two major components the inlet and the variable guide vanes,, as seen in

18Figure 12: Inlet Model. The intake is composed of a standard inlet screen as regulated by the National Hot Rod Association or NHRA and bell mouth inlet.

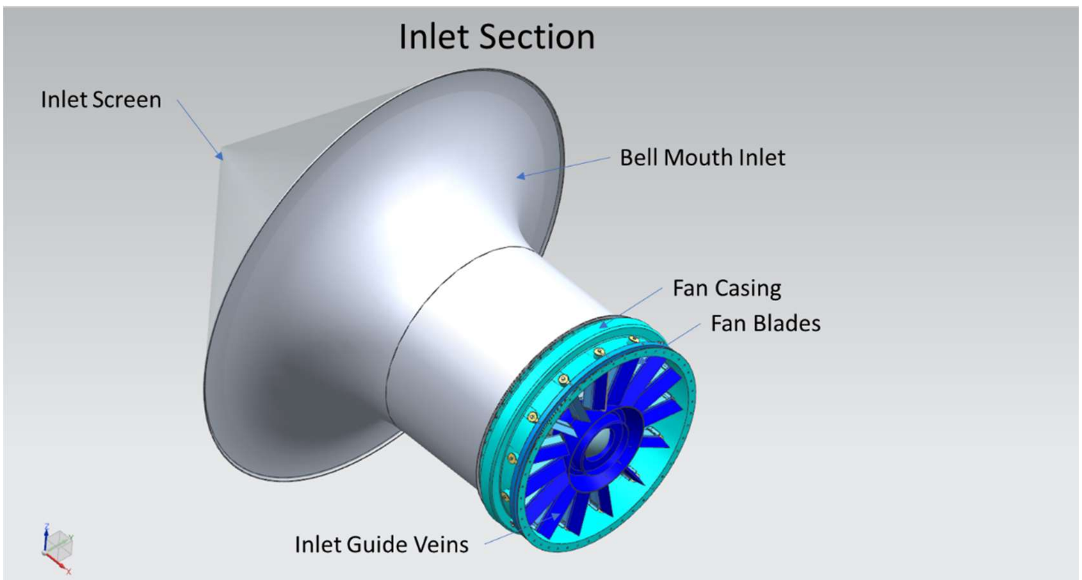


Figure 12: Inlet Model

19 It should be noted that there are two different types of inlets that Larson Motorsports utilizes. One that is outfitted for their test stand shown in Figure 9: GE-J-85-13 with Larsen Equipment on Test Trailer and another for their vehicle shown in. Figure 13: *Larsen Motorsports Vehicle Inlet*. In situations where there are multiple variants of the same component there are multiple ways to maintain a configuration. The simplest is to create multiple detail models, that tree into unique subassemblies, that tree up into unique master files. Depending on the amount of configuration this can become cumbersome. Another alternative is the use of reference sets as shown in Figure 14: Use of Reference Sets. Reference

sets allow different configurations to exist within the same file but only display one solid body at a time.

Figure 13: Larsen Motorsports Vehicle Inlet

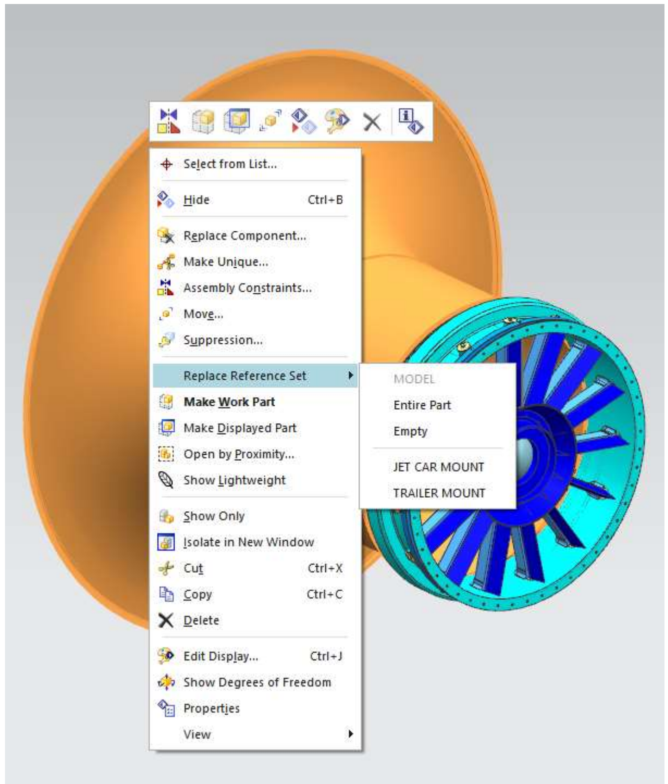


Figure 14: Use of Reference Sets

20 The other section if the inlet is the Variable Guide Veins or VGV section. On an aircraft the VGVs are present to maintain stable flow in the compressor at conditions away from the design condition. The design conditions for jet engines are typically high power during initial climb so the VGVs only start to close at reduced powers at different operating conditions. At high power, the vanes are pitched 90 degrees to maximize flow through the engine, minimizing drag and maximizing thrust. As they are gradually closed when power is reduced, they present more obstruction to the flow, acting as a variable throttle valve in the path of the flow being closed, so presenting an increased pressure ratio loss. A VGV can be used to maximizing pressure ratio per stage at the design condition but at the cost of the increased weight of the mechanisms to drive the VGVs.

21 Unlike aerospace, in the arena of jet-car racing, there are much fewer design conditions to contend with. For the most part, maximum thrust is the only condition that the engine is tuned to for these applications. The biggest condition

that engineers must contend with is temperature and air density gradient. Once a jet is tuned to the location and temperature, the VGV is set and locked into place. However, using constraints, the entire VGV system can be linked and controlled by a single variable as shown in Figure 15: Variable Guide Veins Constraint Arrangement. This allows for the rapid manipulation of the model and which can aid in the use of Computational Fluid Modeling or CFD simulations.

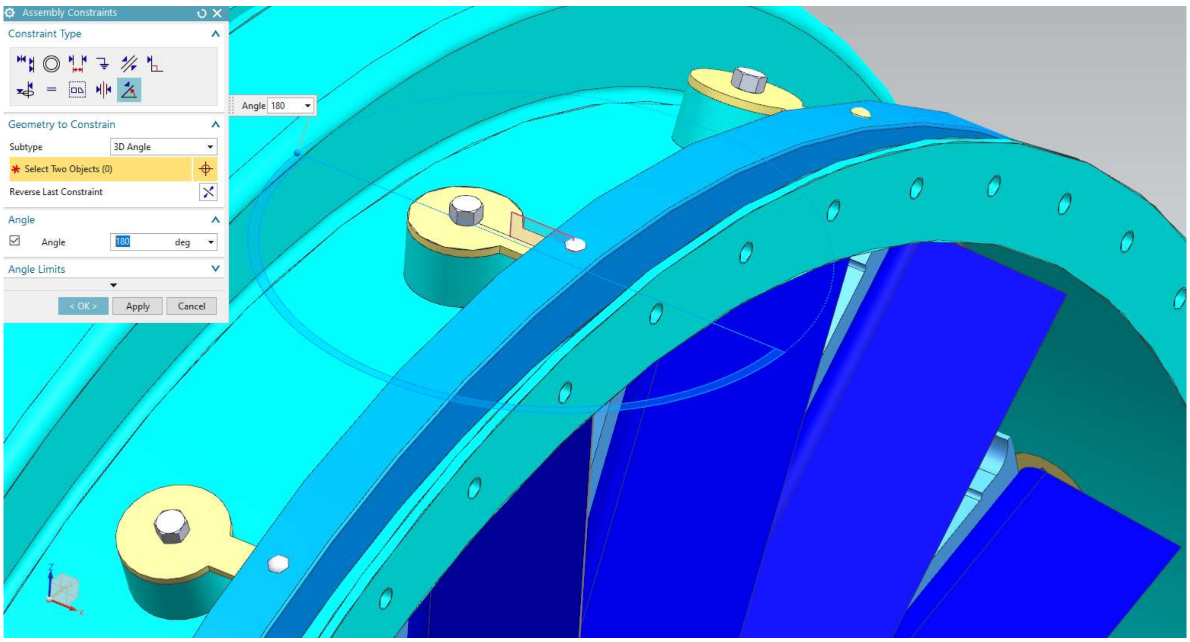


Figure 15: Variable Guide Veins Constraint Arrangement

<u>COMPRESSOR SECTION</u>

22 The compressor section of a jet engine is where the air that enters through the inlet is sent through a series of spinning blades to compress the incoming gases. The initial air that enters the engine is directed by the fan. The fan is an extremely well-designed component that sets the direction of the flow. For a General Electric J-85, there are 8 axial stages. This means that there are 8 layers of annular oriented blades; each layer is referred to as a stage. The first stage is the largest,

as the air moves through, the stage blades get smaller as well as the pitch. An important note to make is that after each stage, there is a set of stator blades. Stator blades are stationary blades that are attached to the outer casing of the compressor that helps direct air through the engine. If the blades spin too rapidly, there is a potential that the air stops compressing and begins to spin. These stationary blades prevent that from happening.

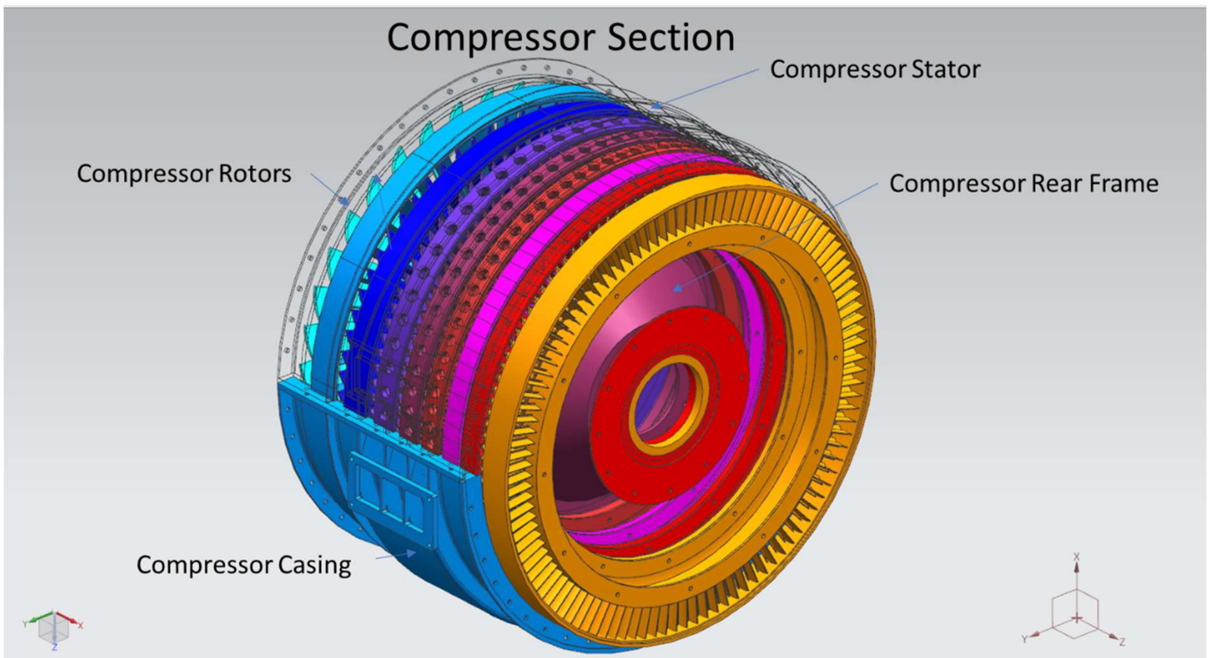


Figure 16: Compressor Model

COMBUSTION SECTION

23 After the compressor section is the Combustion Section. The first important component is the fuel injectors. Since the air already contains oxygen and is now compressed so much that it is now thousands of degrees, the last ingredient to combustion is fuel. Once the fuel is introduced combustion occurs and is ready to be directed out of the engine and make use of that energy. The air that enters the next section, the turbine, has an Exhaust Gas Temperature (EGT) of about 1,470 degrees Fahrenheit.

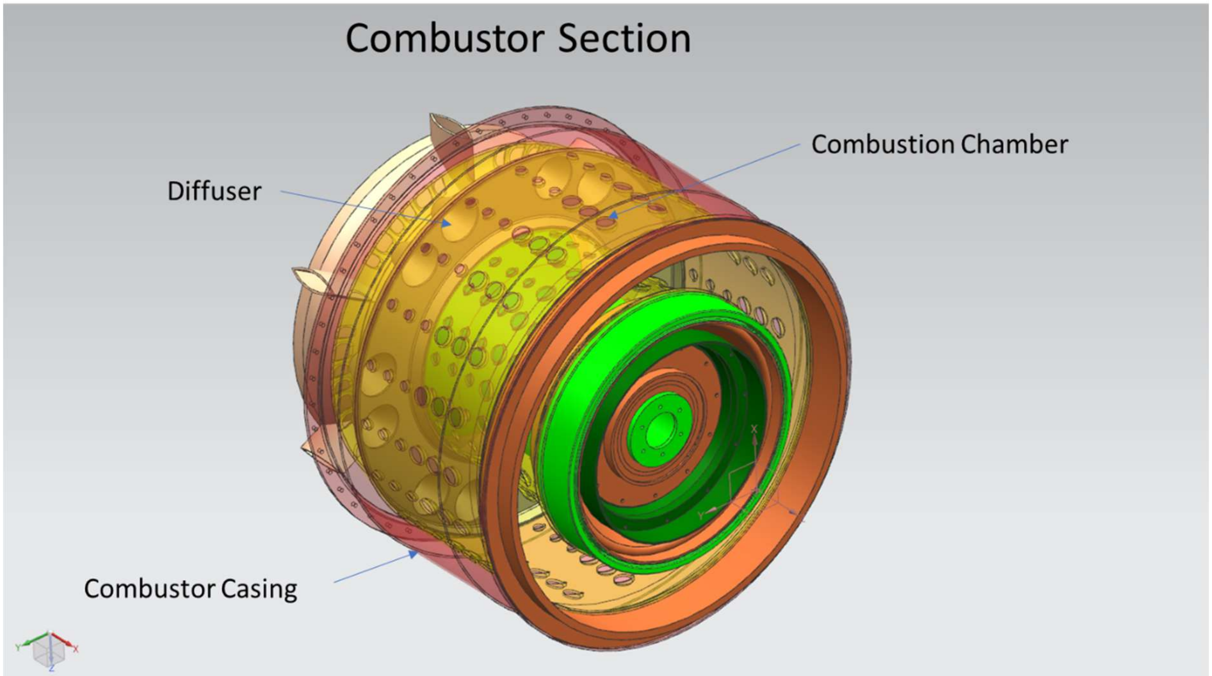


Figure 17: Combustor Model

EXHAUST SECTION

24 The exhaust or turbine section converts the high pressures from the air/burned fuel mixture out of the combustor into mechanical energy that drives the compressor. The turbine converts exhaust gas pressure into mechanical energy by expanding the hot, high-pressure gases to a lower temperature and pressure. The exhaust turbine is connected through a centrally located shaft which drives the inlet turbines. The model produces in this report is an important step in Jet Engine research for the Larsen Motorsports team. Using these models will allow them the ability to further support the students of Florida Tech. Masters and Doctorate students will now have the ability to complete CFD analysis on many components of this highly used engine and possibly innovate the engine to be more efficient and/or usable for other applications. This model will also support the undergraduate students in their studies to better understand what a jet engine is, how it works and the complex engineering work behind each component.

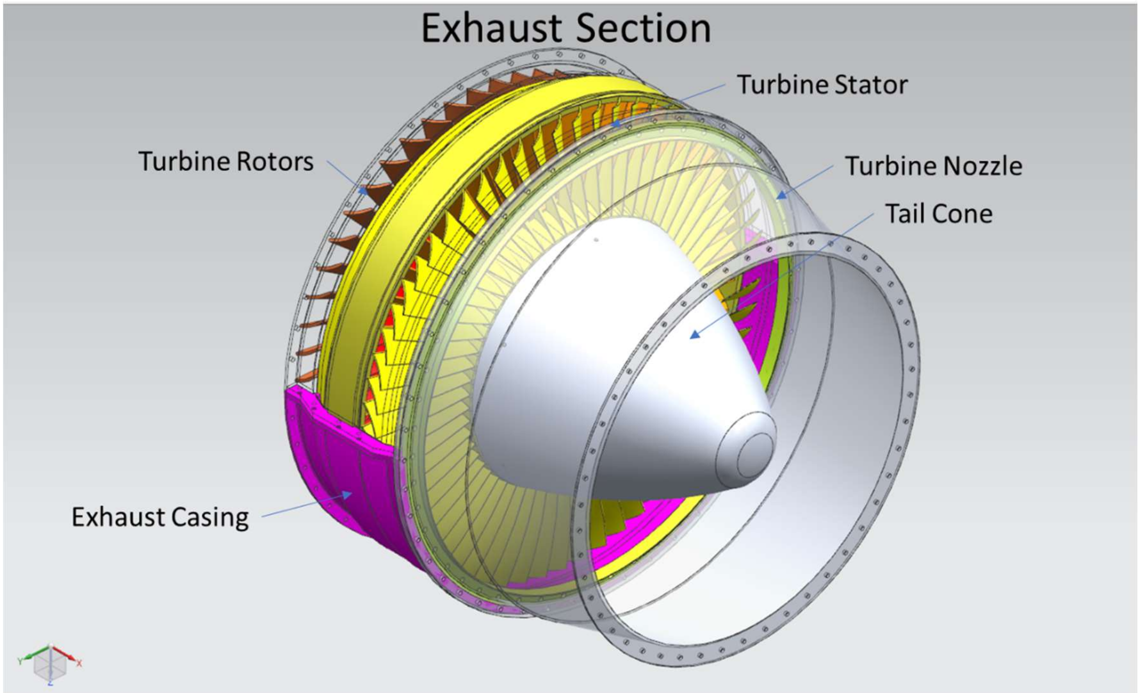


Figure 18: Exhaust Model

AFTERBURNER SECTION

25 The afterburner section is the only section that is comprised of all Larsen Motorsports equipment. There are three major components of this Afterburner: the casing, the flame holder, and the fuel manifold, as seen in Figure 19: Afterburner Model. As discussed previously, the afterburner provides an increase in thrust by injecting additional fuel into the afterburner, downstream of the turbine.

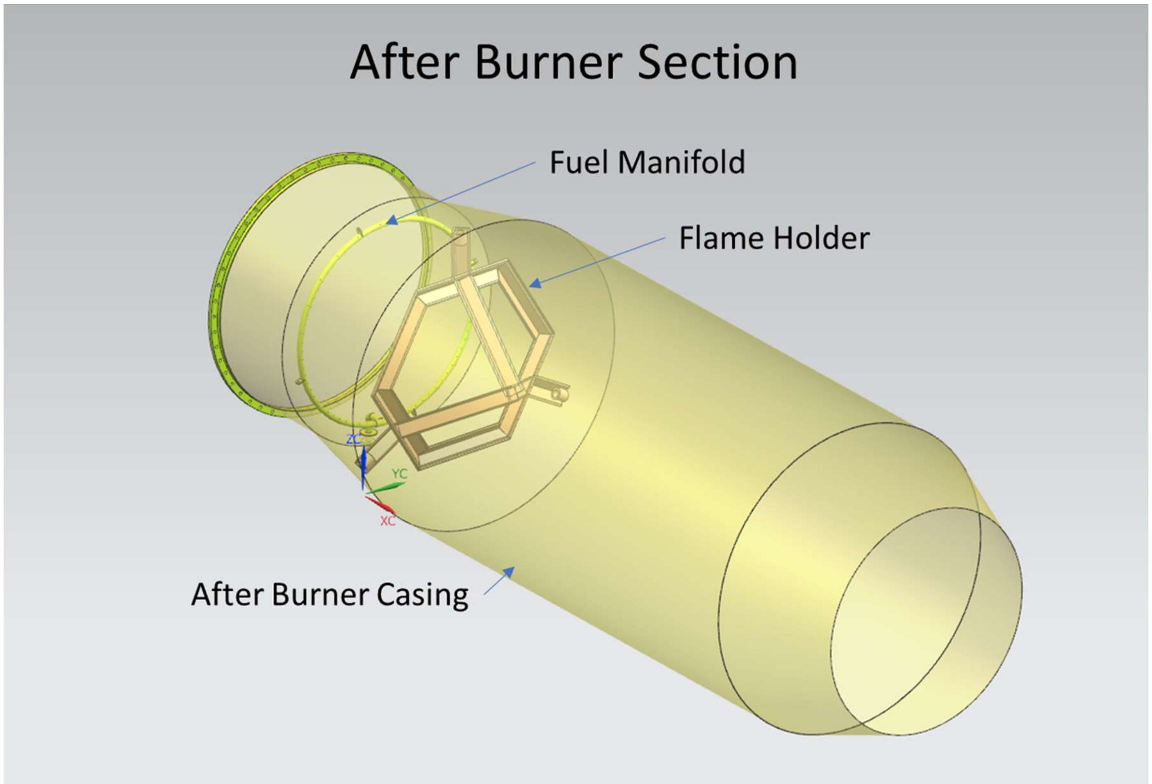


Figure 19: Afterburner Model

26 The bulk of the design changes for Larsen Motorsports occurs in the afterburner section. The goal of the afterburner for drag racing perspective is to maximize the amount of total thrust for a 5.5 to 6 sec duration while managing the engine temperature. The primary design components of the afterburner are the overall major diameter and length of Afterburner, the nozzle diameter, the placement of the fuel manifold, the placement of the flame holder, and the cross-sectional area of the flame arrestor.

27 Focusing on the afterburner casing geometry the model can simplify the major aspects to the Equation 1: General Thrust Equation. Where F is equal to the resultant force, $\dot{m}_{\boldsymbol{e}}$ mass flow at the exit, $\boldsymbol{V_e}$ is the velocity at the exit, $\dot{m}_{\boldsymbol{0}}$ is the mass flow at free stream condition, $\boldsymbol{V_0}$ is the velocity at the free stream condition.

$$F = \dot{m}_e * \boldsymbol{V_e} - \dot{m}_0 * \boldsymbol{V_0}$$

Equation 1: General Thrust Equation

28 There are multiple parameters that an Afterburner designer must consider that are not readily apparent from Equation 1: General Thrust Equation. First and foremost is exhaust temperature, steel begins to melt at 2500°F-2700°F and the GE-J-85-13 exhaust temperatures can reach up to 3200°F.[8] That means that prolonged use of the Afterburner can quickly damage equipment. Considering that most pulls in drag races last less than 6 seconds designers can use this information to base the dimensions on the Afterburner around these conditions. Pushing the maximum thrust but staying safely away from the melting temperature of engine components. The other parameter is gas velocity. As exhaust gas velocities increase the ability to maintain complete combustion becomes problematic. Flame stabilization which refers to the ability to establish and maintain continuous combustion, is a function of flow properties and velocity. This relationship can graphically be seen in Figure 20: Stability limit curves for circular cylinders [9]. The curves in this graph demonstrate where the velocity at which flame stabilization process fails which is called the blowoff velocity, is presented as a function of the fuel-air ratio. The fuel-air mixture produced by the injection process has a flame propagation velocity that is much lower than the gas speed in the combustion chamber. Thus, unless sources of continuous ignition are present in the chamber, the burning gas ignited by a temporary process will be blown out of the engine as soon as the ignition is stopped. In most afterburner systems, the continuous source of ignition is the wake of a flame holder held with its axis perpendicular to the flow.[9]

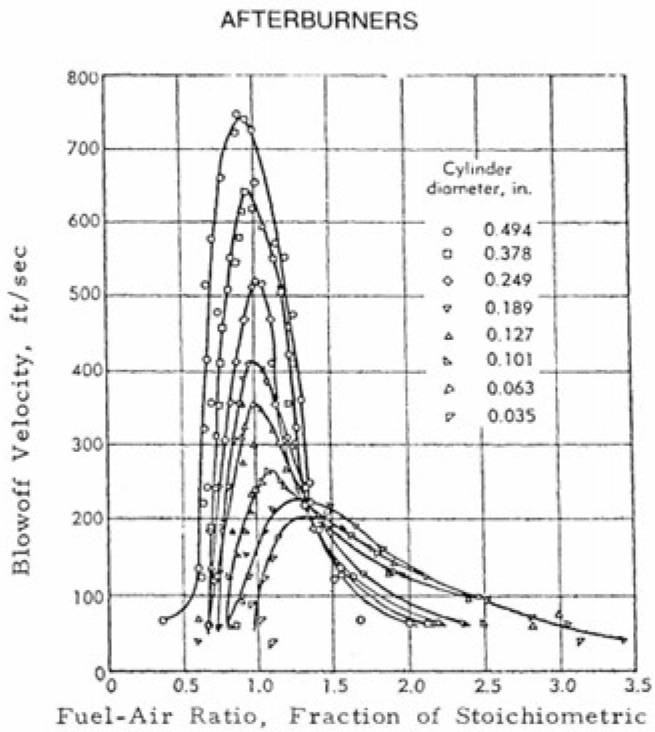


Figure 20: Stability limit curves for circular cylinders [9]

29 Another parameter to consider with the shape of the afterburner casing is the length. As mentioned previously the ability to maintain flame stabilization is critical to begin and maintain combustion, but the ability to maximize the total combustion is a function of time within the Afterburner. The length of the afterburner becomes a component of this combustion by virtue of dwell time. After the velocities of the Afterburner are understood, designers can adjust the length of the afterburner to maximize the amount of fuel that will be transferred into thrust. As the afterburner lengths increase, we will begin to see depreciating returns in timed runs as the weight of the vehicle will begin to increase. Designers of the Afterburner must consider this when sizing the afterburner for not only the engine but the vehicle itself.

30 Flame holders are used to stabilize flames in high velocity flow conditions. The wake behind the flame holder can be divided into the recirculation zone and

the mixing zone that keeps the recirculation zone away from the unburned reactants as shown in Figure 21: Flame Stabilization Zone Behind the Flame Holder. The mixing zone, characterized by turbulent shear layers with large temperature gradients and rigorous chemical reaction, is fed by turbulent mixing processes with cool combustible.

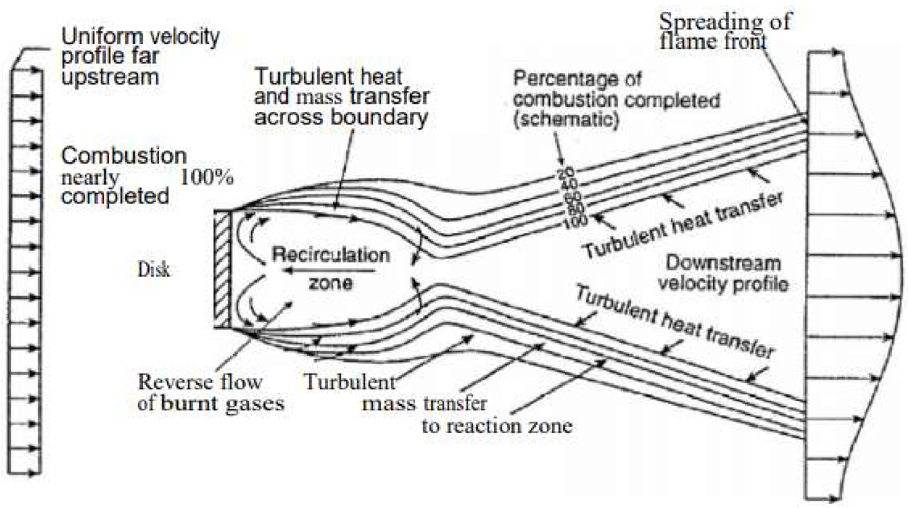


Figure 21: Flame Stabilization Zone Behind the Flame Holder [9]

31 There are multiple factors that have an impact on the stabilization of flames. These include: the blockage ratio (BR), the flame holder size and shape, the stream velocity and pressure. For flame holders that are mounted in stream, which is the case for the J-85, one of the biggest controlling parameters as the blockage ratio. Blockage is defined as the ratio of the area of projected flame holder to the cross-sectional area of the afterburner. An increase in flame holder size improves stability by extending the residence time of reaction in the recirculation zone. The shape of the flame holder affects its stability characteristics, which influence the size and shape of the wake region. As discussed previously an increase in stream

velocity has an adverse effect on flame stability as it nears the blow off velocity. Any increase in velocity reduces the range of mixtures strengths over which combustion is possible. The increase in fuel pressure typically results in improved flame stability. For the gas mixture, the increase in the pressure expands the stability loop by enhancing the blowout velocity, especially for a rich and near stoichiometric mixture.

32 The afterburner casing is not the only component that performance can be derived from. The fuel manifold and flame holder shape and placement play a critical role in the overall resultant thrust of the engine. Much like the diameter of the exhaust outlet, the placement forward and aft of the flame holder and fuel manifold have an inversely proportional relationship with exhaust temperatures and thrust, as seen in Figure 22: Thrust and Outlet Temperature vs Flame holder position. At the forward, most position exhaust velocities are much too high for flame stabilization to occur. As the flame holder position is moved aft, flame stabilization begins to increase and with that there is a dramatic increase in exhaust temperatures. Exhaust temperatures can reach undesirable levels and we will begin to see component failures. Depending on the use case of the afterburner a designer must place the flame holder far enough forward to maximize thrust, but far enough to minimize the risk of overheating components.

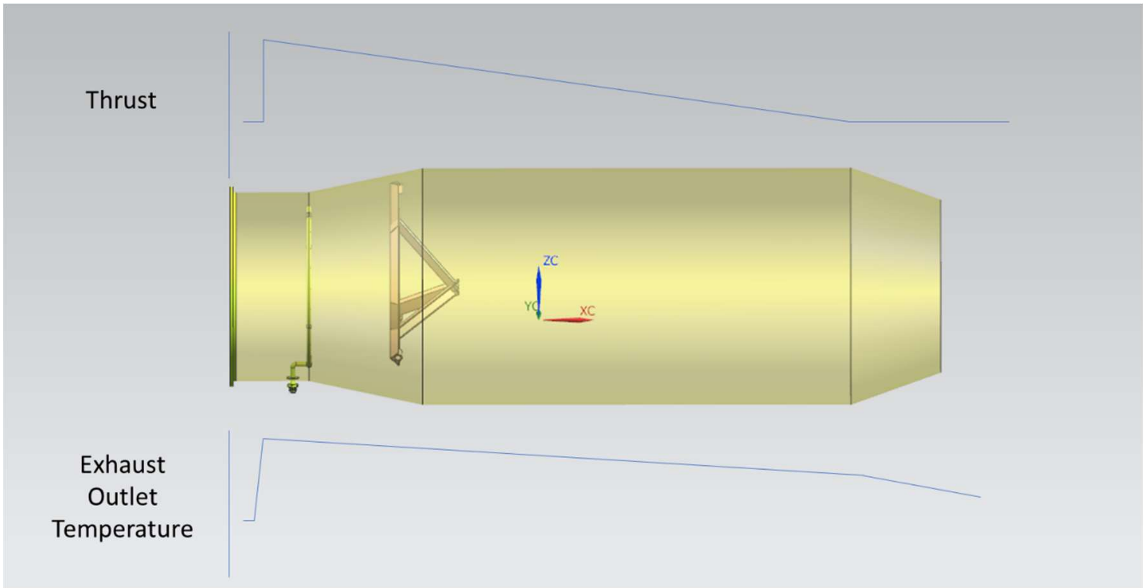


Figure 22: Thrust and Outlet Temperature vs Flame holder position

33 The forward and aft locations of the fuel manifold and flame holder are important, the other location that is critical is its position cross-sectionally to the afterburner casing. Flame size is directly related to thrust output, as the size of the flame increases the resultant thrust will increase; however, as seen previously, as flame size increases so does afterburner wall temperature which can cause failures. The location of the flame arrestor with respect to the fuel manifold is critical as well. If designed correctly the flame holder will create a low pressure zone that the fuel manifold will spray fuel into, as seen in Figure 23: Afterburner Cross-Section View. Note that the fuel manifold diameter and the flame holder octagon width are relatively the same size. Also, note the flame holder triangular portion that runs forward and aft this is to maintain flame stability deeper into the afterburner and helps center the flame to the center of the afterburner.

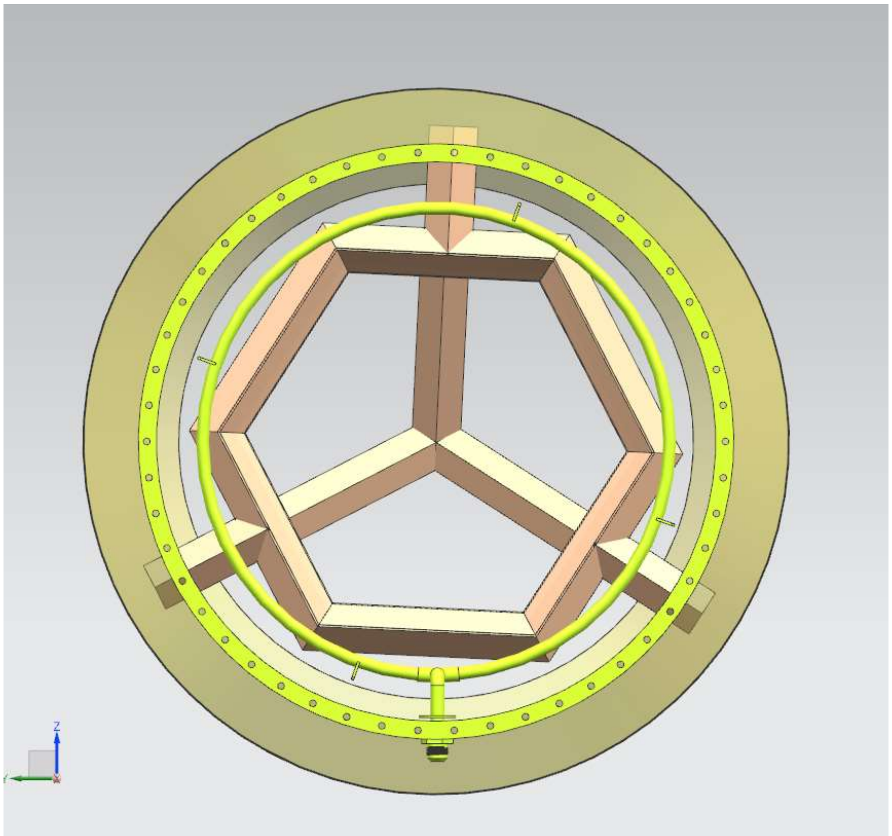


Figure 23: Afterburner Cross-Section View

MODEL MESHING

34 Model meshing is creating the subdivision of a continuous geometric space into discrete geometric and topological cells. Meshes are typically generated by computer algorithms, with human guidance, depending on the complexity and the type of results the designer is interested in. The goal is to create a mesh that accurately defines the component geometry, with high-quality cells, but without a mesh being so fine that it makes subsequent analysis overly cumbersome. Mesh concentrations should also be finer in areas where a more detailed analysis is required. Some of these areas are often areas of high stress concentrations or complex flow or thermal patterns.

35 Specific modeling practices are used in the precursory steps before meshing can begin. Figure 24: Afterburner Flow Model shows this simplification, what was a multi component assembly with welded sections and voids, can be modeled as one body to allow calculation to occur more seamlessly. This simplification can occur in this manner because the areas of concern for Figure 24: Afterburner Flow Model are not in the areas where the model simplifications were made. If the welded section were a concern, a detailed analysis in the area may be required.

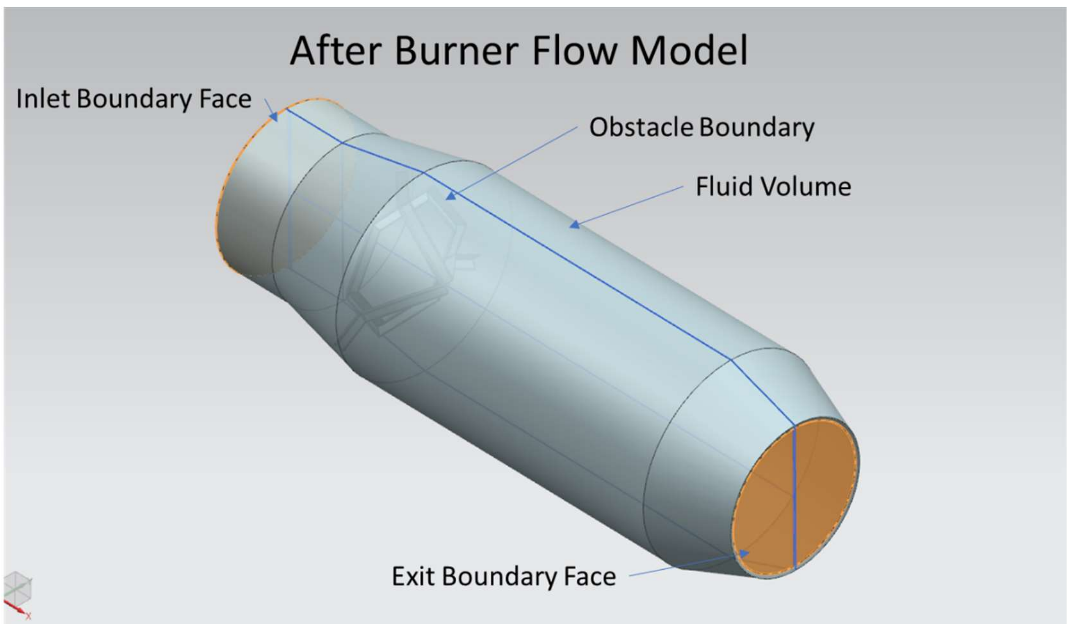


Figure 24: Afterburner Flow Model

36 In Figure 25: Afterburner Meshing the global meshing can be seen. This mesh can be used for Finite Element Analysis, Computational Fluid Analysis or Thermal Analysis. It should be noted that this specific mesh was tailored for a computational fluid analysis. Where the entire internal space of the afterburner is modeled solid and the obstacles, in this case the flame holder, are modeled as voids.

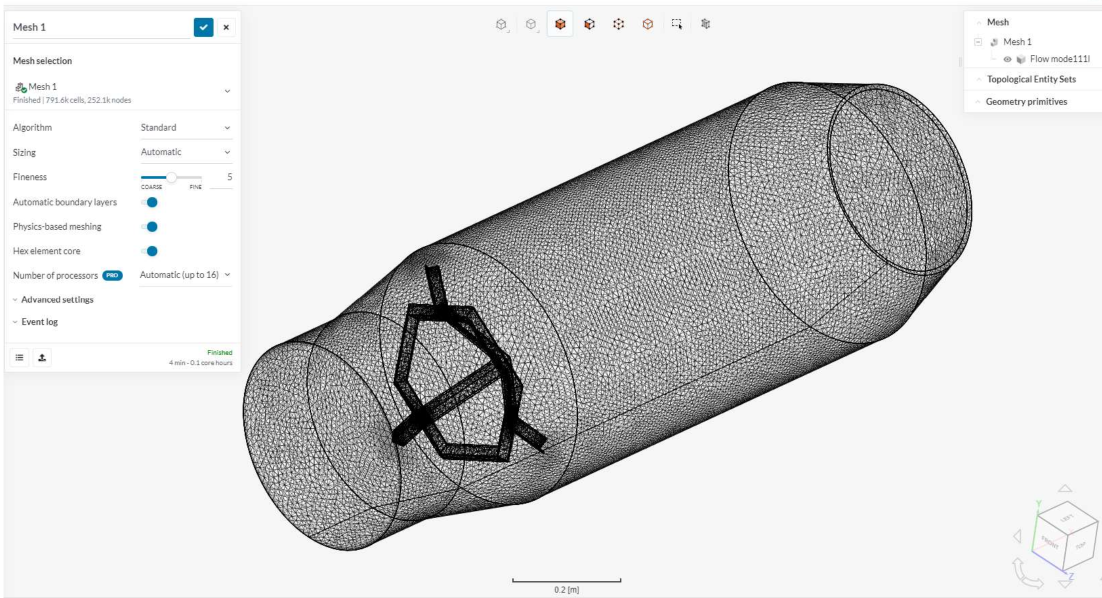


Figure 25: Afterburner Meshing

CHAPTER 3: RESULTS

FINITE ELEMENT ANALYSIS

37 Finite Element Analysis is a common practice in today's engineering community. Models are meshed into cells comprised of rods and nodes. There rods and nodes are given a specific resultant stiffness based on material properties and the nodes give the user locations to input forces. In Figure 26: Finite Element Analysis of the J-85 Flame Holder it is readily apparent where the highest stress concentrations occur on the J-85 flame holder. Designers can utilize this information to optimize the strength and performance of their designs. Reducing material in areas of low stress to save weight and increase material in areas of high stress.

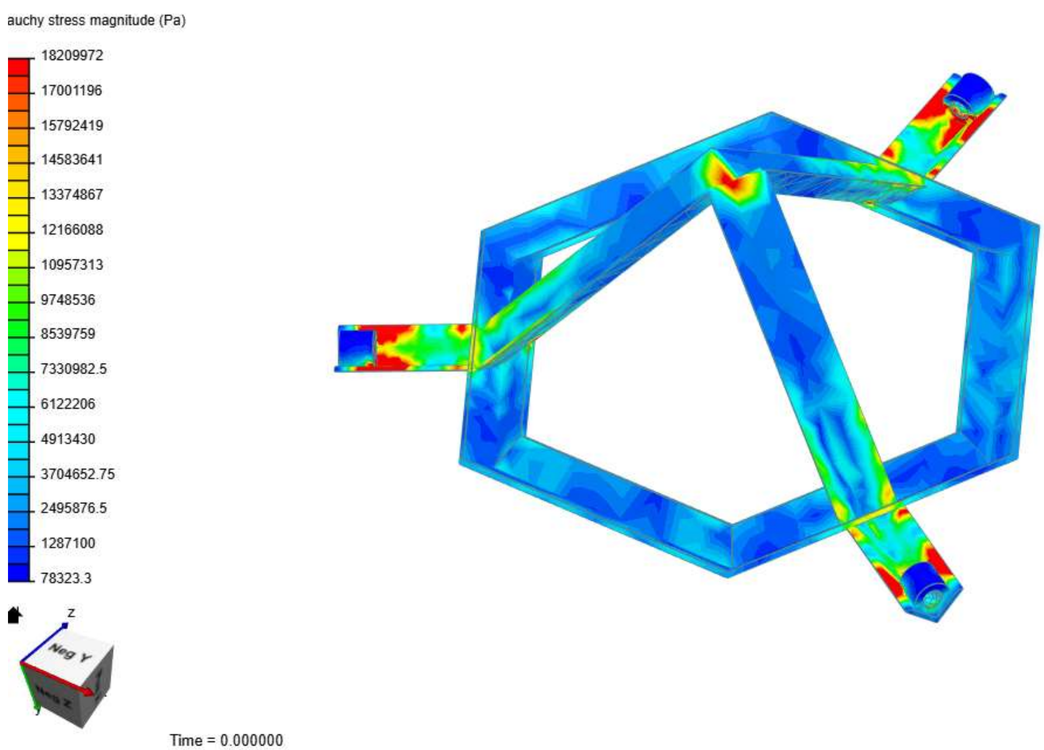


Figure 26: Finite Element Analysis of the J-85 Flame Holder

COMPUTATIONAL FLUID MODELING

38 Computational fluid dynamics (CFD) is a subdivision of fluid mechanics that utilizes numerical computations and geometric modeling to evaluate and resolve problems that involve fluid flows. Algorithms are used to calculate data and to simulate the free-stream flow of the fluid, and the interaction between the fluid and the surfaces defined by the user inputted boundary conditions. Figure 27: Pressure Profile of a Properly Machined Flame Holder shows the pressure profile J-85 afterburner. The results are as expected, where the highest pressures are forward of the flame holder and aft of the flame holder. The pressure is centered and tapers along the length of the afterburner.

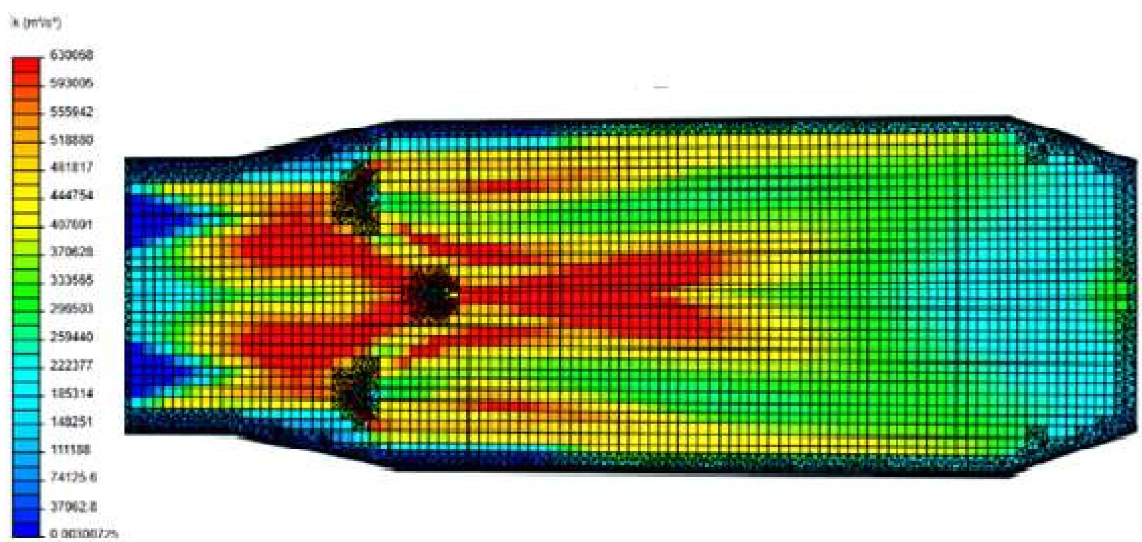


Figure 27: Pressure Profile of a Properly Machined Flame Holder

39 In Figure 28: Pressure Profile of an Out of Tolerance Flame Holder however, the flame holder model was purposely modeled incorrectly. The apex of the flame holder was modeled out of center by .050”. Even at the small tolerance offset the performance impacts are significant. Pressure profiles are shifted to one section of the Afterburner. This means that the flame stability will be more erratic and will not be centered in the Afterburner. This off centering of the flame will result in the afterburner casing heating up much sooner and will limit the amount of total thrust possible.

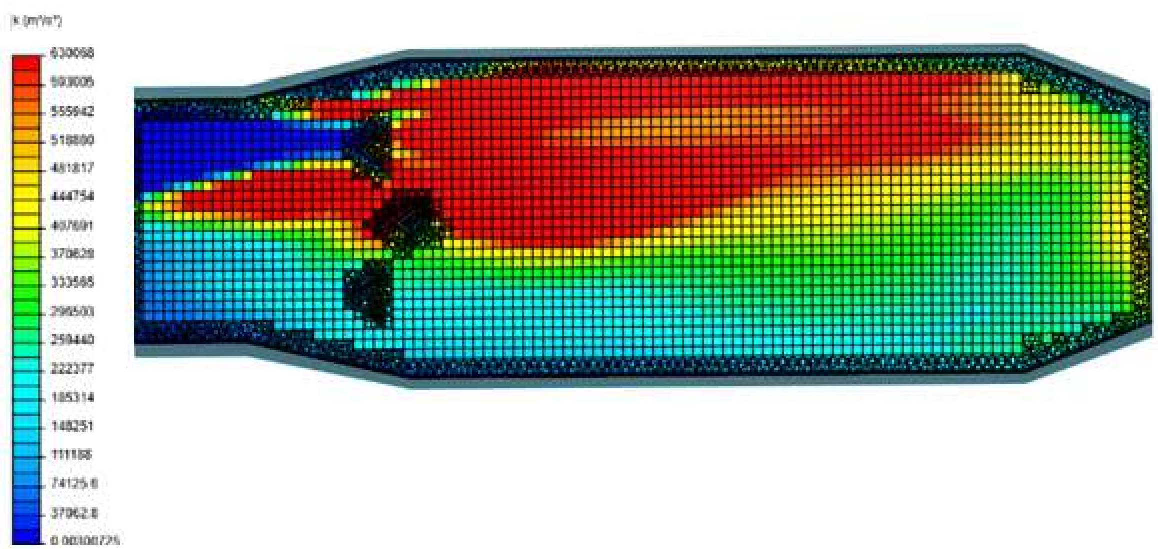


Figure 28: Pressure Profile of an Out of Tolerance Flame Holder

MANUFACTURING IMPLICATIONS

40 Through the results of the CFD analysis the importance of a properly machined flame holder is evident. Developing tooling for the assembly of the flame holder is critical to the performance of the J-85 flame holder. Jacob Portugal has taken

the information and has worked to develop such a tool which can be seen in his thesis *Larsen Motorsports Jet Car Flame Holder Tooling Fabrication* [10].

41 The tooling developed will provide Larsen Motorsports with the ability to consistently produce their flame holder at a tolerance within +/-.050”. The models created from this thesis were utilized in the design of the tooling jig, shown in Figure 29: Flame Holder Welding Jig CAD. The tool provides users the ability to weld the assembly together in a multitude of the required arrangements. As well as an ability to modify the design in a measurable and consistent way.

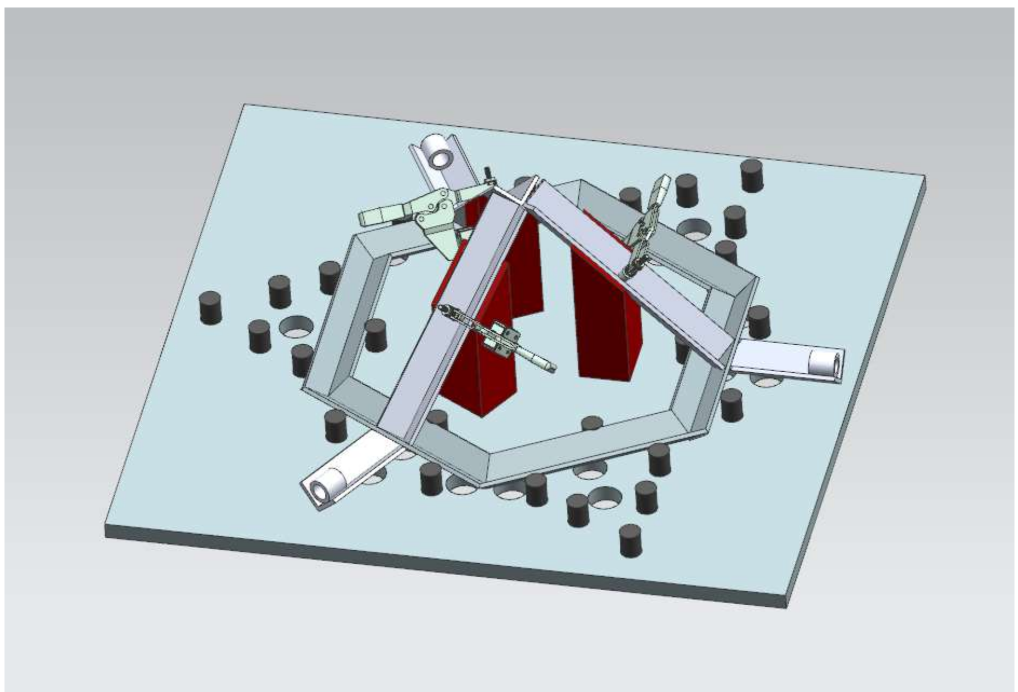


Figure 29: Flame Holder Welding Jig CAD

42 Tooling manufacturing and details of the development can be found in *Larsen Motorsports Jet Car Flame Holder Tooling Fabrication* [10]. The assembled tool, as seen in Figure 30: Flame Holder Welding Jig , along with the CAD files produced in this thesis will be provided to Chris Larsen of Larsen Motorsports for implementation and further development.

Figure 30: Flame Holder Welding Jig Assembly

REQUIRMENTS FOR FUTURE TESTING

43 The ability to produce a close tolerance part is only a portion of the tooling needs. The ability to produce a close tolerance part consistently is important for future performance increases. As discussed in the afterburner section of this thesis flame holder placement plays a huge part in the overall thrust output of the afterburner. The ability to produce a part consistently will allow Larsen Motorsports a consistent and measured approach to performance gains of there equipment. The area of focus for performance gains will be in the overall height of the apex of the flame holder. Adding shims to the underneath side of the keeper block, as seen in Figure 31: Keeper Block in the Un-Shimmed Configuration will allow for the apex of the flame arrestor to be lengthened or shortened for testing purposes. As discussed previously, the blockage ratio and the flame holder shape

have a tremendous impact to the flame stabilization zone. Through precise adjustments to these keepers an optimal flame holder shape can be identified for the maximum amount of performance gains.

Figure 31: Keeper Block in the Un-Shimmed Configuration

CHAPTER 4: CONCLUSION

44 The development of CAD models for J-85 and Larsen Motorsports equipment will provide their team with a consistent and measured approach to achieving performance gains for future modifications they will make to their platform. The models alone will allow an immediate impact to their team's ability to maintain configuration management, part control, and a consistent platform to train their engineering and technical staff. Using reference sets, managing multiple variants of the same component becomes trivial. The utilization of constraints allows their team an ability to moved linked components easily and seamlessly. Setting up a unified layer system allows faster computation times and enables multiple users to work within the same file without risk of saving over digital files. The model generated in this thesis is a critical component in jet engine research for the Larsen Motorsports team. Using these models will allow them the ability to further support the students of Florida Tech. This model will also support the Larsen Motorsports staff in their training to better understand what a jet engine is, how it works, and the complex engineering work behind each component.

45 The accurate and detailed models provided by this thesis will allow the Larsen Motorsports team to conduct advanced computer simulations to achieve performance gains. This approach will allow the team an ability to make design decisions without the need to conduct actual runs. This reduces the amount of cost that the Larsen Motorsports team will incur overtime as, track time is limited and often are very costly. It also reduces the risk of failures that would hazard to the driver or crew and could cause the risk of damage to equipment.

46 Finite element analysis can be used across their entire vehicle to determine where the highest stress concentration occurs and utilize this information to optimize the strength and performance of their designs. Reducing material in areas of low stress to save weight and increase material in areas of high stress

concentrations. While most of this thesis was centered on the engine itself the modeled based approach could be easily utilized on the dragsters frame to maximize the performance of the overall vehicle.

47 Computational fluid dynamics modeling, as seen in this thesis can showcase how small changes to design can have major impacts to the thrust and overall performance of the vehicle. Areas where drag and temperatures become critical should be highlighted in these analyses. Inlet, exhaust, and frame design are all areas where performance gains could occur if a rigorous CFD analysis were to occur.

48 Computer aided design can allow Larsen Motor Sports the ability to train, modify and test design changes in a safe and cost-effective manner. Using the files and tools that are contained within this thesis, will provide Larsen Motorsports the information required to manage and maintain their platform. Allowing them to continue to compete at a high level in their respective competitions. While the focus of this thesis was primarily J-85 specifically the afterburner, the utilization of these modern design practices has applications throughout their vehicle.

REFERENCES

[1] German, R. C., et al. *Measurement of Exhaust Emissions from a J-85-GE-5B Engine: at Simulated High-Altitude, Supersonic, Free-Stream Flight Conditions*. Dept. of Transportation, Federal Aviation Administration, Systems Research & Development Service, Available through the National Technical Information Service, Springfield, Va., 1973.

[2] Abernethy, Robert B. *Handbook, Uncertainty in Gas Turbine Measurements*. Arnold Engineering Development Center, 1980.

[3] Pizarro, Daniel Flórez. *Axial Compressor Analysis GE-J-85-13 Engine*. University Carlos III of Madrid, 2017.

[4] Yang, Gelan, et al. "A Numerical Study on Premixed Bluff Body Flame of Different Bluff Apex Angle." *Mathematical Problems in Engineering*, Hindawi, 31 Mar. 2013, www.hindawi.com/journals/mpe/2013/272567/.

[5] Gunston, Bill. *World Encyclopedia of Aero Engines: from the Pioneers to the Present Day*. Sutton, 2006.

[6] ANSYS, Inc. ANSYS, Inc., 2018, pp. 1–8, *Fluent Mosaic Technology Automatically Combines Disparate Meshes with Polyhedral Elements for Fast, Accurate Flow Resolution*.

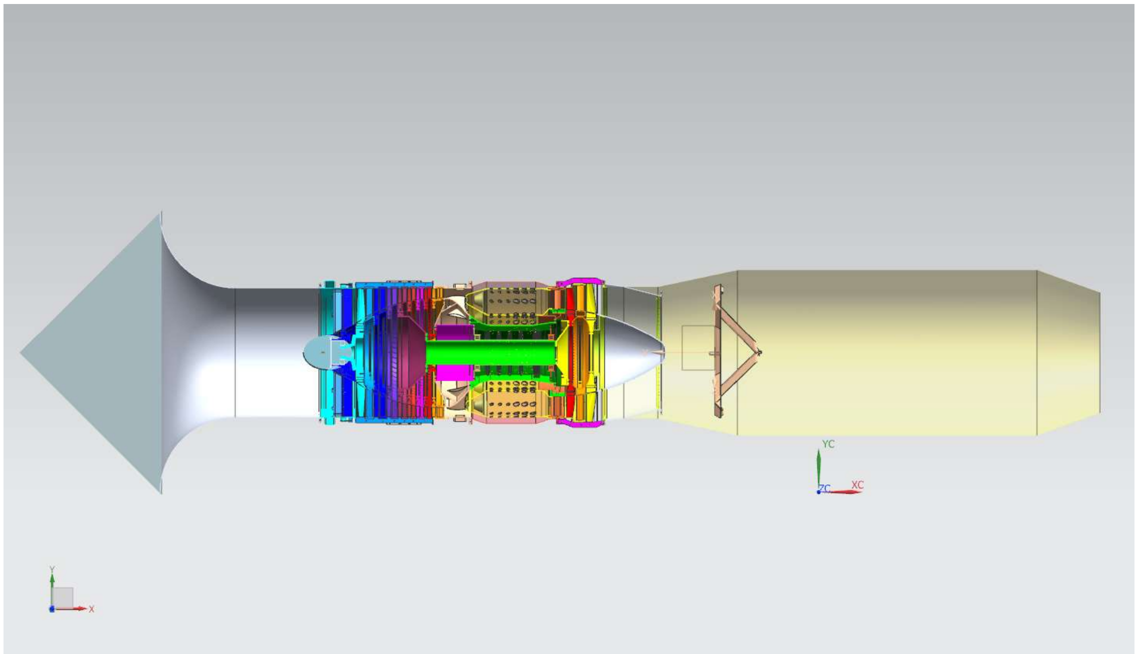
[7] "Afterburning Jet Thrust." *NASA*, NASA, www.grc.nasa.gov/WWW/K-12/airplane/turbab.html.

[8] Baltz, Robert, et al. "AEDC/UTSI J-85 Turbojet Test Stands." *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2012, doi:10.2514/6.2012-4284.

[9] Oates, Gordon C. "The Aerothermodynamics of Aircraft Gas Turbine Engines." *DTIC Online*, 1978, apps.dtic.mil/docs/citations/ADA059784.

[10] Portugal, Jacob. "Larsen Motorsports Jet Car Flame Holder Tooling Fabrication." *Florida Tech*, 2020.

APPENDIX A: CAD MODELING



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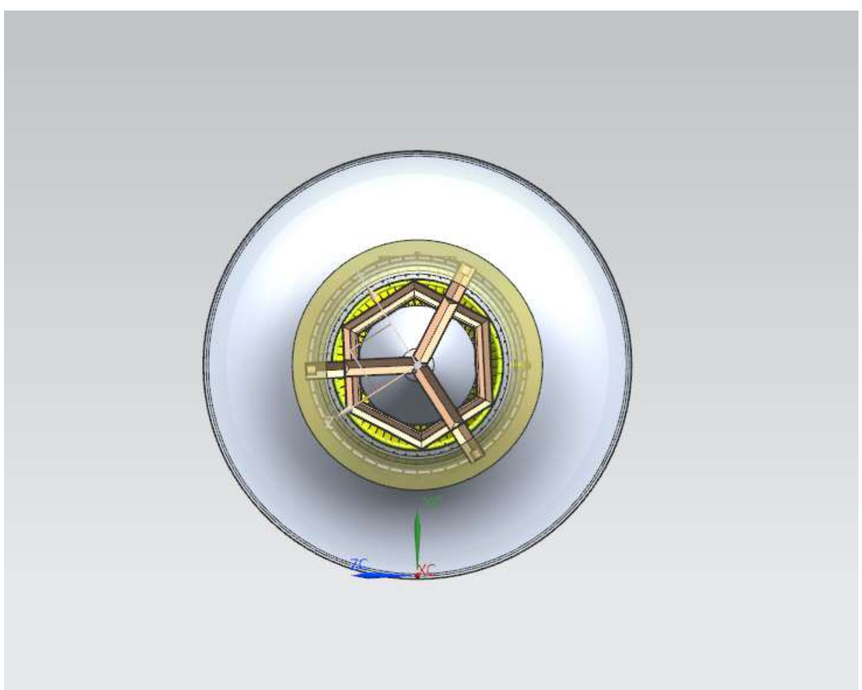
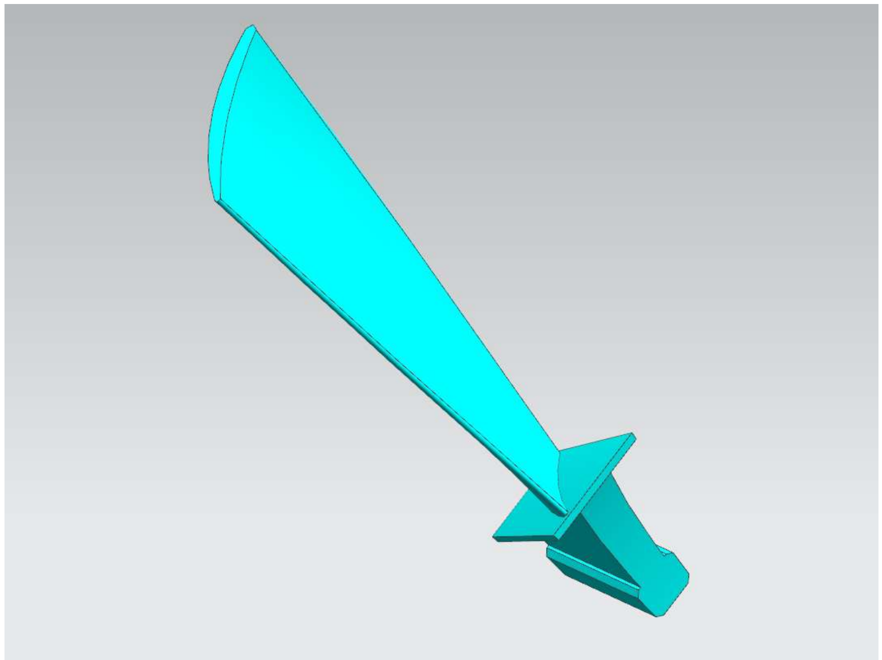
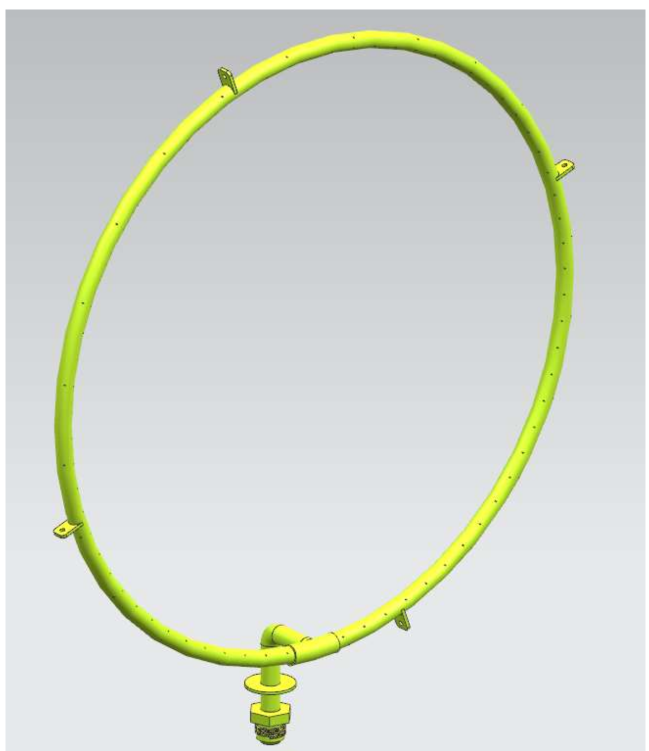


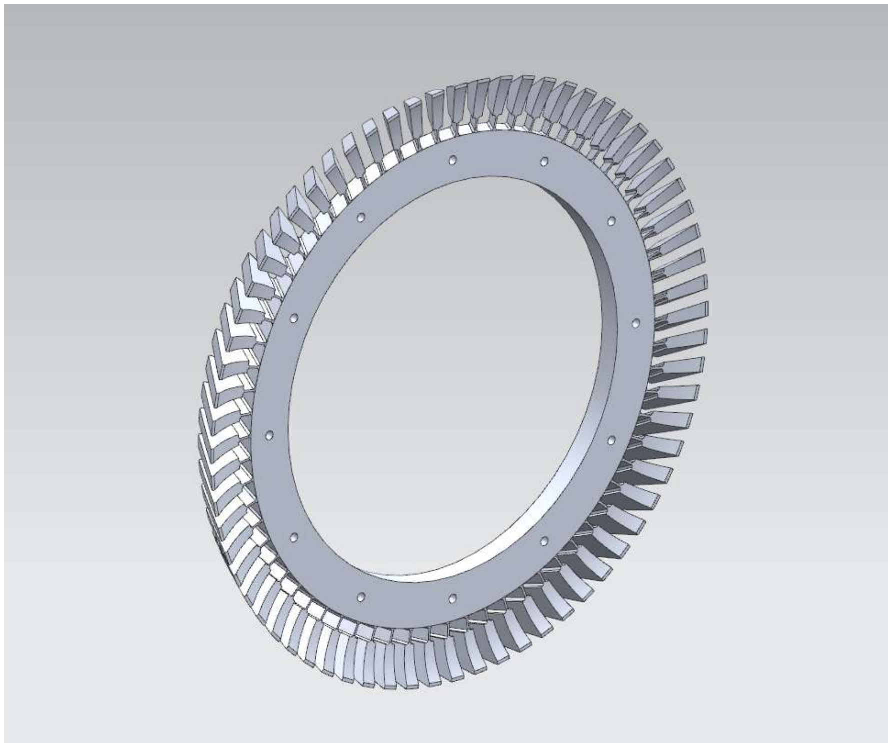
Item 2: J-85 View Looking FWD



Item 3: Individual Blade Model

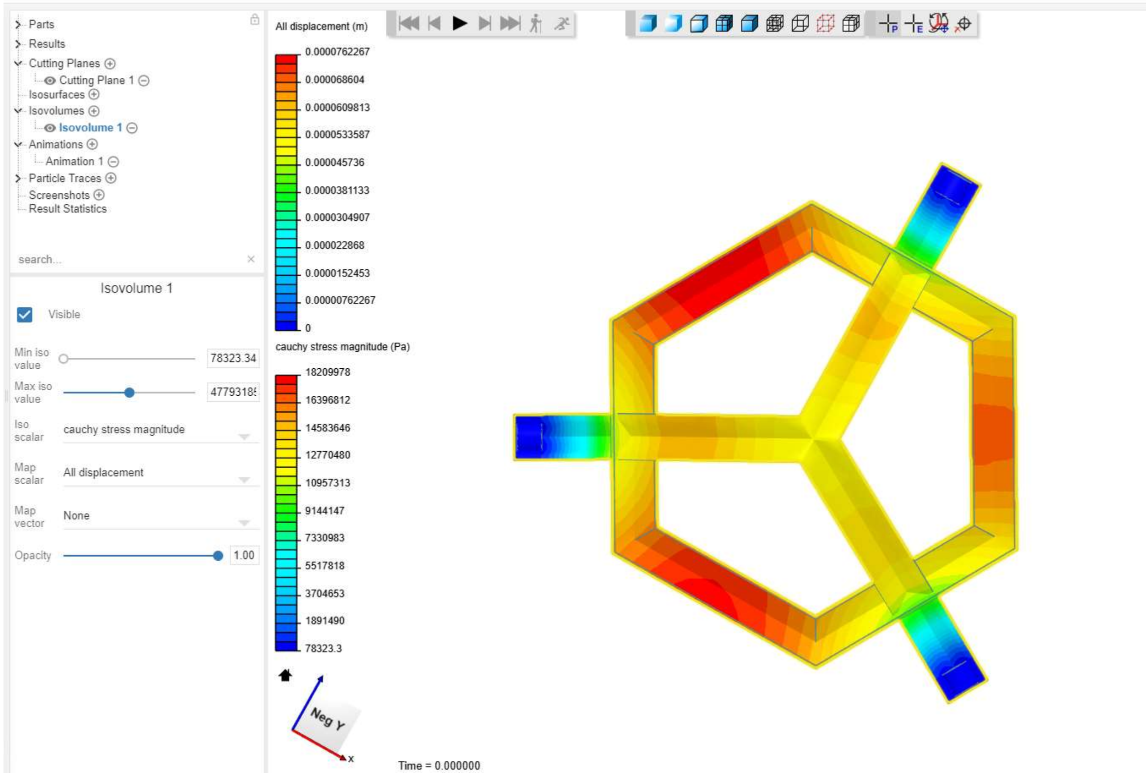


Item 4: Afterburner Fuel Manifold

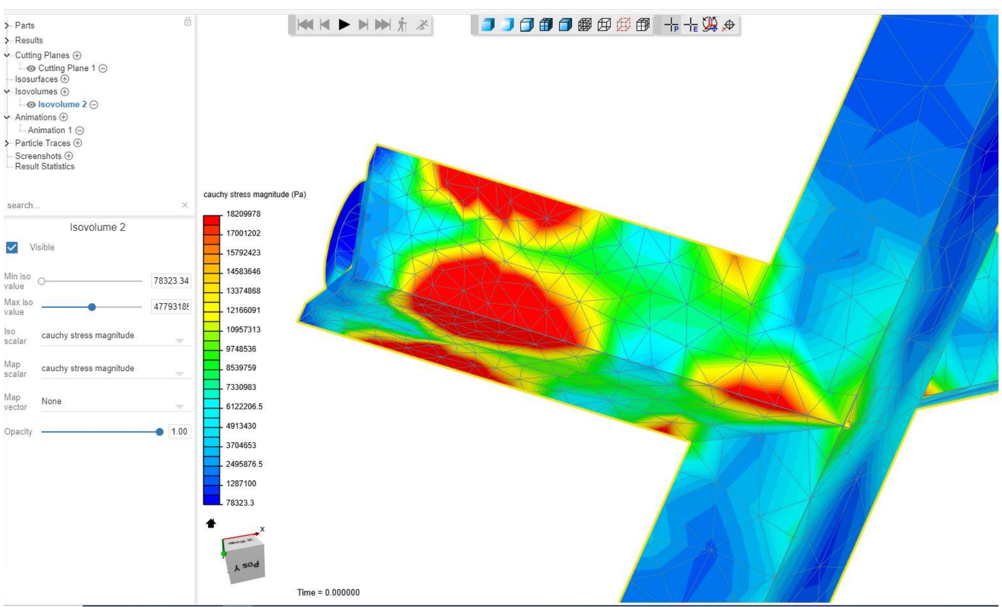


Item 5: Stator Model

APPENDIX B: FEM ANALYSIS

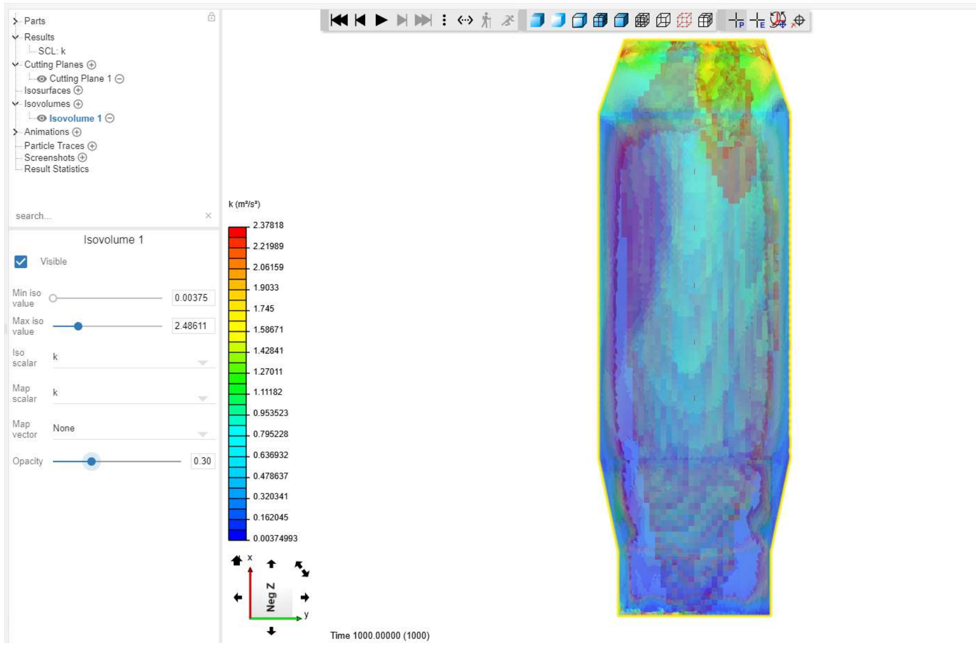


Item 6: Flame Holder Displacement

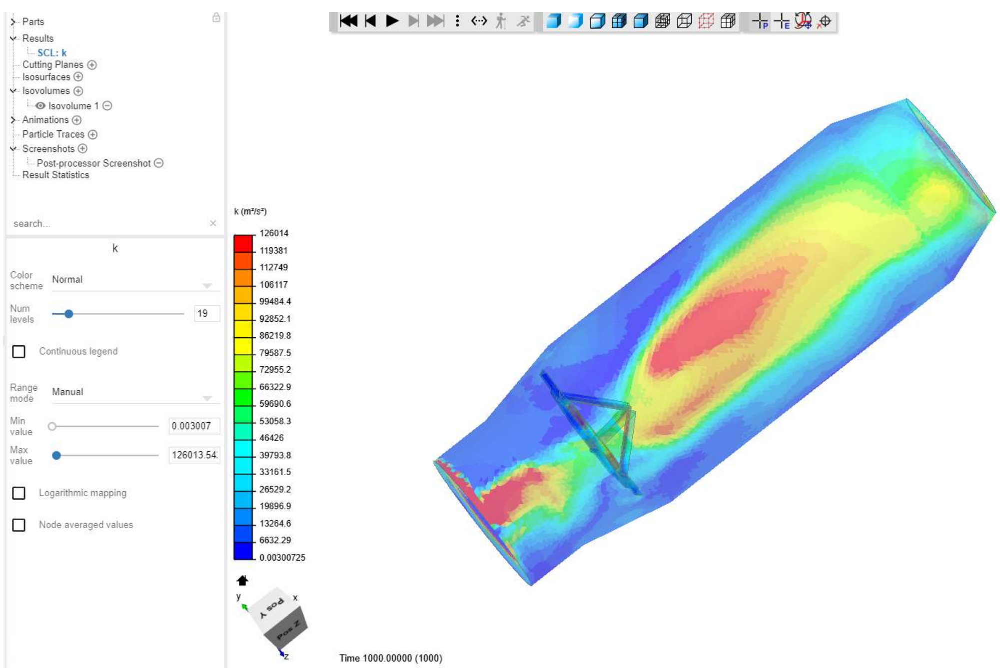


Item 7: FEM Flame Holder Detail View

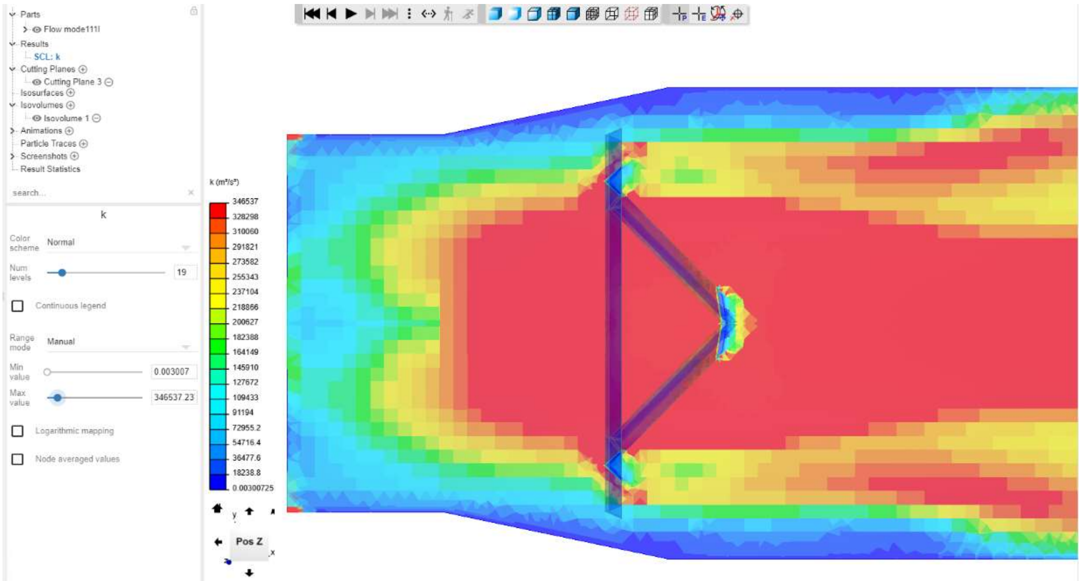
APPENDIX C: CFD ANALYSIS



Item 8: CFD Overview



Item 9: Afterburner Velocity Map

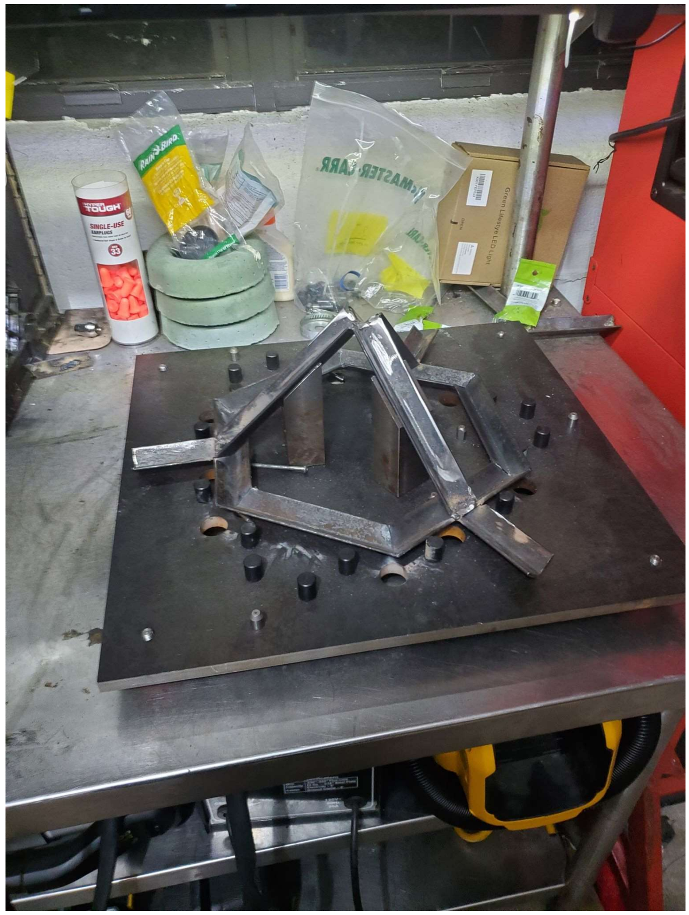


Item 10: CFD Detail Cross-Sectional Detail View

APPENDIX D: TOOL DEVELOPMENT

Item 11: Welding of Flame Holder

Item 12: Flame Holder Position 1



Item 13: Flame Holder Position 2

Item 14: Welded Flame Holder