GENERAL ELECTRIC J85 ENGINE FLAME HOLDER TOOLING

by

Jacob Portugal

A thesis submitted to the College of Engineering and Science of Florida Institute of Technology in partial fulfillment of the requirements for the degree of

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General Electric J85 Engine Flame Holder Tooling

A thesis by Jacob Portugal

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ABSTRACT

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Larsen Motorsports competes in drag racing events all over the country using their jet power drag cars. These competitions are focused on getting the most performance out of the engine as possible by shaving weight off the vehicle and increasing the amount of power produced. One of the many factors in the amount of power produced by the car is the afterburner. Afterburners can increase thrust from ~3,000lb to ~5,000lb in a standard J85 engine. Due to this there is a good deal of attention paid to the efficiency and performance of the afterburner. The specific portion this thesis focused on, was the flame holder design and tooling for fabrication.

The flame holder slows the stream of air coming out of the engine down to allow for proper flame development in the afterburner. Too slow and the backpressure will have negative effects on the engine, and not slow enough results in poor flame development and a lack of power. The flame holder must also be modifiable to allow for tuning to the environment. Fabricating consistency has a direct influence on the flame holders performance. Due to this I have developed tooling to allow for the flame holder to be fabricated consistently time after time. This specialty tooling considers manufacturing tolerances, not only for the flame holder, but also for the tool. My experience as a mechanical engineer allowed me to bring knowledge of standard manufacturing processes to this specific task.
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ACRONYMS AND ABBREVIATION

ID – Inner Diameter
DOF – Degree(s) Of Freedom
CAD – Computer Aided Design
CFD – Computational Fluid Dynamics
FEA – Finite Element Analysis
CNC – Computer Numerical Control
PSI – Pounds Per Square Inch
KSI – Kilo Pounds Per Square Inch
MIG – Metal Inert Gas
FWD – Forward
BOM – Bill of Materials
ACKNOWLEDGEMENT

Everyone at Larsen Motorsports was incredibly helpful in teaching me about what they do and how they do it. Their facility allows for a very hands-on approach to learning. This style of teaching is very effective in teaching the theory behind jet engines. Chris Larsen was instrumental in this learning and the experience overall. Every meeting with Chris taught me something new.

I would like to say thank you to Florida Institute of Technology for hosting such an incredible program. This flight test program has taught me a great deal, and the experiences were both informative and enjoyable. Finally, I would like to acknowledge the program chair of the Flight Test Engineering department, Dr. Brian Kish. Dr. Kish used his experience in the field to give us the opportunity to learn about how flight test engineering should be done.
CHAPTER 1
INTRODUCTION

BACKGROUND

1. Larsen Motorsports Background: Larsen Motorsport’s mission statement is to give young engineers opportunities to drive, design, build and maintain jet drag cars. They bring their cars all over the country to different tracks for national competitions on the quarter mile. Chris and Elaine Larsen own Larsen Motorsports. Chris has a careers worth of experience being an aircraft mechanic, giving him the skills needed to keep costs at Larsen down. Elaine has been drag racing for over 20 years and brings the skills needed to race and train new drivers. Chris teaches all the crew how to build, maintain, diagnose, tune, etc. the engines. This pairing is perfect for teaching young people all the aspects that exist in the drag racing world.

2. A typical J85-AB modified engine taken off an aircraft will have all the accessories installed which would be needed for flight. At Larsen they know exactly which accessories can be removed to reduce weight and complexity. A custom fuel manifold, flame holder and afterburner have been designed by Larsen to support their unique requirements. A bell-mouth inlet is used to give maximum air flow into the engine. A wire mesh is used to prevent debris from getting into the engine. In 2015 Larsen worked on a Finite Element Analysis to determine the optimal flame holder design for the drag strip. This resulted in a flame holder which was not better than the design used at the time. Testing is done on the drag strip by timing the off the line speeds. This will be discussed later in greater detail.

3. Turboshift jet engines are comprised of a compressor, combustion, and a turbine. Air flows into the inlet, where it is then compressed by the compressor blades. The compressor section takes air from ambient pressure with a relative velocity to the aircraft and pressurizes it so that combustion is possible. There are typically two stages to the compressor section, but in some cases, it is simply a
gradual increase in compression throughout the entire section. The J85 is one such example of an engine with a gradual increasing of blade density. Each assembly compressing the air by 1.3. This compression is powered by the turbine section of the jet. After the air is compressed it runs through the combustion stage. During the combustion stage the air is mixed with fuel. When the engine is turned on a spark is provided to start the flame, but while running no additional flame needs to be added. This is due to two inputs, there are diffusers in the combustion chamber meant to keep the flame alive, and the flow of air is not so fast that it blows out the flame. After the combustion stage the air moves to the turbine. As mentioned before the turbine is meant to power the compression section. This is effectively taking some of the power created by the engine to compress the air coming into the inlet. The compressor blades and turbine blades will be linked through a gearbox to allow the sets of blades to operate at different speeds.

4. In aviation afterburners are helped to push planes through the sound barrier. This is done at the expense of fuel efficiency though and is only seen in military applications. There are two commonly known commercial examples which had afterburners, the Concorde SST and Soviet Tu-144. Since for this application I am only focusing on an afterburner used on a drag strip there is not a focus on the fuel efficiency of the car. An afterburner works by taking the already hot high velocity air coming out of the exhaust and adding fuel through the injectors to it to create an increase in thrust. This increase in thrust can be up to 50% of the original engine thrust. This incredible increase in power comes with relatively little build complexity as there are no moving parts, but there does exist a design complexity. Ensuring the engine continues operating as if there is no difference with the afterburner on and off is a difficult task that involves tuning the backpressure created by the flame holder and geometry of the exhaust. The amount of fuel being dumped into the afterburner will also influence this balance. The reason the afterburner can create so much additional power with the exhaust coming out of the engine is the average jet engine only burns near half of the total oxygen that comes
in the intake. This leaves more than enough oxygen to create a significant increase in thrust. The amount of boost can be tailored through careful design of the flame holder, the amount of fuel and the shape of the exhaust. This is important for aviation as not all systems are going to require extra thrust. One example of such an aircraft is the Concorde. The Concorde’s afterburners only added around 17% to the overall thrust (1). This is due to the Concorde not needing a huge jolt of thrust, but just enough to push past the sound barrier. The fuel air mixture is typically ignited though the use of electric sparking devices. In Figure 1: J79 Flame Holder and Igniter, a flame igniter is shown for demonstration purposes (2). This figure also shows the 3-tiered flame holder being used in this afterburner.

If there were no flame holder the stream of air would exit the afterburner before fully igniting the fuel. For this reason, flame holders are used to slow the stream of air exiting the engine. As the flow is slowed the backpressure into the exhaust increases. If too much backpressure exists, the results can be catastrophic failure in the form of hammershock. Hammershock can cause the engine to stall resulting in loss of engine power. Since the stakes are so high with this design it is important to perform rigorous testing before putting major assets or a person’s life at risk due to an engine failure. Larsen does this by making incremental changes in the flame holder design to ensure an engine does not experience a stall. Conversely if the flame holder is not slowing enough air then there will be energy wasted out the
exhaust. In a perfect world all engines would act the same and if it were seen that additional backpressure was needed the flame holder would be redesigned to perfectly match every J85. In the real world it is seen that each J85 is a bit different and having the ability to increase the amount of surface area on the afterburner slightly in real time is a critical feature to allow for engine tuning. Another feature of the flame holder is how difficult it is to install and remove the flame holder. One-way Larsen has found to keep this a simple task is by making the design hexagonal allowing it to be put in the exhaust at an angle. When a flame holder has a round design it must also come in half to fit in the back of the exhaust. If this is not possible then the entire exhaust cone must come off every time the flame holder is changed or modified.

6. Due to the loss in fuel efficiency aircrafts must be able to turn on and off the afterburner. For an engine to function with the afterburner off the exhaust will converge to a smaller diameter than the turbine section. This will increase the mass flow rate, increasing thrust. This convergence is done up till the choked state. That choked state would exist when the exhaust gasses break Mach 1. When the afterburner is turned on the exit nozzle of the exhaust must be of a larger diameter compared to normal operation to allow for the mass flow rate to stay constant through the engine. Keeping that mass flow rate constant allows everything forward of the afterburner to continue to function as if there were no afterburner. To accomplish this, variable geometry exhaust nozzles are used so that the mass flow rate can be controlled. Again, it is seen that on the drag strip where the afterburner is always in use that there is no need for the addition of a heavy complex variable geometry exhaust nozzle.

7. The lack of a variable geometry exhaust on the afterburner means that all flow tuning must be done manually. When a variable geometry exhaust is used the engine can meter the mass flow rate in real time by adjusting the opening on the exhaust. This is not the case for Larsen Motorsports though as they have fixed
exhausts to save on weight. To account for the fixed exhaust Larsen spends a significant amount of time tuning the engine for optimal performance. After years of testing they have found a specific combination of length, diameter, and taper for the exhaust that works well across all their J85 powered cars. Small adjustments can be made by decreasing the opening in the exhaust. This is done by bolting small metal obstructive pieces into the exhaust to increase the mass flow rate and increase engine back pressure. Obviously, this is a very delicate balance and each variable adjusted affects the entire system.

8. The General Electric J85 engine is a turbojet engine manufactured between 1954 and 1988. Over this time General Electric delivered over 12,000 J85 engines to power over 18 different production aircrafts (3). The J85 is the engine of choice for Larsen Motorsports due to the availability and serviceability. Since this engine has been used in so many aircrafts over the years there are several of them for sale with a wealth of spare parts available. The J85 is 18” in diameter and 45” long weighing ~395lb (3). At ~2,900lb thrust the J85 has a thrust to weight ratio of 7:1 making it one of the most efficient jet engines in this class.

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Figure 2: J85 Cutaway View
PURPOSE

9. The purpose of this tool is to provide a repeatable operation to quickly fabricate flame holders at Larsen Motorsports for use on the J-85 engine. The design of the tooling was analyzed for longevity, consistency, and user friendliness.

10. The flame holder tool will satisfy the following criteria:

   a) Keep flame holder fabrication time below 4 hours.
   b) Stay within budget of $2,000.
   c) Able to withstand typical welding temperatures heat cycling.
   d) Tooling shall accommodate a reasonable range of material stock to incorporate manufacturing tolerances.

11. I will also provide testing criteria for possible future design and a suggestion for an updated design option.

Figure 3: Tooling Iso View
TOOLING REQUIREMENTS

STANDARD TOOLING REQUIREMENTS

12. All machine shops face similar tooling requirements considerations. Tooling can be anything from a standard vice, to custom fabricated clamps for a specific material and part. The later are most commonly found on high volume runs with a 3-axis CNC. This is because machine shops have more machining capability with 3-axis than 5-axis due to the cost of the machines, but many parts require more than just the 3 major axis. To compensate for this machine shops come up with these custom pieces of tooling, or sometimes referred to as shop aids. In Figure 4:

![Figure 4: Standard Shop Aid](image)

Standard Shop Aid an ID clamp is used to hold the part from the bottom. This allows the part to be clamped quickly and efficiently for machining on the other faces. In Figure 5: Tormach Holding Fixture a Tormach CNC specific shop aid which is more generic is shown. This tooling allows the user to clamp a wide variety of pieces, given that they are flat, on the machining surface. This is a great example of tooling which can perform more than just the one task, and thus is a good investment for a shop to make early on, but looking at the ID clamp above it is seen that not all tooling is so easily justifiable. These pieces of tooling become the backbone of what defines the tolerances a shop can hold to a specific type of part. Some shops will outsource this tooling to companies which specialize in creating tooling, while some others will make this tooling in-house. This is the
major reason why a small run of complex CNC’d parts is so expensive. There is typically a need to produce tooling specific to that job, greatly increasing schedule and cost. In Figure 6: Knife Tooling Fixture (4) a fixture which holds a knife blank

Figure 5: Tormach Holding Fixture

through each of the machining stages is shown. This allows the machinist to take one blank from a block of metal to a proper knife ready for final sharpen and sale. The largest advantage here is only one set of tooling was required to take the blank all the way to a knife. If instead a custom piece of tooling was made for each step

Figure 6: Knife Tooling Fixture
in the manufacturing process, then five separate tools would have been required. In
addition, the tooling would have needed to be changed between stages and stored
somewhere out of harm’s way. This all contributes to an increase in productivity as
there is less machine down time and as a bonus less up-front cost.

13. As mentioned, the tolerance required of the design plays a role in the tooling.
The most accurate way to machine a part is to not re-fixture. This is because every
time human hands get involved error is introduced. A standard CNC will not have
any issue holding a +/- .005” tolerance, but a human would require a good bit of
patience and skill to match that. Tooling really comes into play here when two
machining operations can be simplified to one, increasing accuracy between the
two operations by reducing variables. Here is where the flame holder tooling
fixture becomes a clearly good investment. This is an example of a part which
requires tight tolerances and necessarily has large human input due to the welding
process. For this reason, creating a jig which holds all the sections of L stock down
consistently is crucial.

14. A big part of the design of a shops tooling will come from the amount of time
saved from its use. When placing a part into a fixture it is best to have the ability to
have some adjustability in the tooling to account for any other tolerance issues.
When holding the part down, one way to think about how the part is constrained is
to think of each Degree of Freedom that is used. It is useful in many cases to start
with a flat plate. If your part has at least 3 points to naturally sit on this eliminates 3
DOF. Then adding in two locating pins will take out translation, leaving only
rotation along the vertical axis. This is finally taken out with the clamping action
typically. There are different ways which this final DOF can be constrained, and it
will really depend on the shape of the part being fabricated.
ENVIRONMENTAL REQUIREMENTS

15. The environment in which any part will be stored and used is a factor in its design. In this case the storage and use environment will be a machine shop with climate control. This is important because if the tool were to be stored outside, or in a non-climate-controlled environment there would be an increased need for corrosion resistance. Tooling shall be able to survive a sustained relative humidity of 90%. The storage temperature will range from 60°F to 115°F. In use temperatures could raise to 2,500°F from the welding operation. Tooling will be rested on a table and will contact the flame holder during assembly. This introduces dissimilar metals into the process. To limit the contact on the bottom feet were added with rubber pads. The number of cycles that the tool sees could influence the design. In this case there are not enough heat cycles to warrant a complete heat cycling analysis.

HUMAN FACTORS REQUIREMENTS

16. Any tooling should always consider how easy it is to use. In this case some of the key considerations were mobility and simplicity. Mobility is the driving requirement keeping the design weight in check. Simplicity refers to both the design and the implementation. In design to keep the cost of the project down and to ensure a successful project. Simplicity in implementation to ensure that there is not a large amount of skill required to use the tool. There is no need to consider different anthropomorphic sizes for this application. This is because the flame holder is already set in size, and the tool must match the part, which will already be suitable for most people. Leaving the tool uncluttered enough so that it is accessible from a variety of angles while welding was also a consideration.

FLAME HOLDER SPECIFIC TOOLING REQUIREMENTS

- The tolerance needed for this application is primarily in the symmetry. The flame holder tooling shall be able to handle L extrusions from local hardware stores. This requires the tooling to incorporate a variety of sizes due to the lack of quality control at many hardware stores. The welds which come out of this tool must be
strong enough to handle the extreme temperatures of an afterburner. For this reason, giving ample room for the welder to have access to the work piece is crucial to the usefulness of the tool. The tool must be able to hold the flame holder in such a way that it is easy to weld each of the pieces together on both sides.

Table 1: Requirements List

<table>
<thead>
<tr>
<th>Requirement ID</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FH-001</td>
<td>Tooling <strong>shall</strong> be capable of existing in machine shop setting without seeing significant corrosion. Testing to be completed per ASTM G50</td>
</tr>
<tr>
<td>FH-002</td>
<td>Surfaces within 1” of welds <strong>shall</strong> not deform or corrode under temperatures of 2,500°F</td>
</tr>
<tr>
<td>FH-003</td>
<td>Tooling <strong>shall</strong> not weigh more than 80 pounds</td>
</tr>
<tr>
<td>FH-004</td>
<td>Tooling <strong>shall</strong> have no more than 4 setup stages</td>
</tr>
<tr>
<td>FH-005</td>
<td>Tooling <strong>shall</strong> accept L extrusions with legs of 1.00” +/- 0.050”</td>
</tr>
<tr>
<td>FH-006</td>
<td>Welding operation <strong>shall</strong> be easy enough for a level 1 welder</td>
</tr>
<tr>
<td>FH-007</td>
<td>Tooling <strong>shall</strong> not corrode the surface it sits on.</td>
</tr>
<tr>
<td>FH-008</td>
<td>Tooling <strong>shall</strong> come with instructions for use</td>
</tr>
<tr>
<td>FH-009</td>
<td>Models and drawings <strong>shall</strong> be included in delivery package</td>
</tr>
<tr>
<td>FH-010</td>
<td>Design <strong>shall</strong> not have more than 10 unique parts</td>
</tr>
<tr>
<td>FH-011</td>
<td>Tooling <strong>shall</strong> be able to be disassembled and reparable</td>
</tr>
<tr>
<td>FH-012</td>
<td>Tooling <strong>shall</strong> not slide on work surface</td>
</tr>
<tr>
<td>FH-013</td>
<td>Project cost <strong>shall</strong> not exceed $2,000</td>
</tr>
</tbody>
</table>
TOOLING DEVELOPMENT

TOOL DESIGN

17. From looking at all the requirements levied on this project I started with a flat plate. As mentioned above this takes out 3 of the 6 DOF. This will also keep all the 9 initial pieces flat relative to each other. I then started looking at how to constrain the individual pieces, trying to reduce the amount of hand tools needed to use the tooling. Based on this positioning pins were chosen to hold the angle stock in place.

![Figure 7: Tooling First Setup](image)

Initially I wanted to use all round pins. After the first pins were placed, I found that this design did not account for enough slop. To take up the manufacturing tolerances present in the L stock diamond shaped pins were selected for the interior pins, and round for the exterior. This design allows for pieces to be placed into the tooling and the user can adjust the diamond pins for an exact fit. Once the L extrusions are cut and placed into the fixture a quick clamp is used to hold the

![Figure 8: Tooling Pin Closeup](image)
pieces down. These are the optimal choice due to not needing a hand tool to enact and the adjustability in the clamp. This style of clamp can be adjusted easily and should not need adjustment once initially set. To use this first setup quantity 6 L stock is cut at 30°+/− 0.5° ends at 6.99” +/- 0.005” long. The quantity 3 L stock pieces cut with 45° ends at 3.82” long are placed in as well. These are placed into the fixture with the point facing up. This gives great access to the entire bottom side to weld. Drawings for these details are shown in Appendix C: Drawings.
18. Now that the underside of the base is welded undo the clamps and flip the flame holder and place the rest of the L stock into the vertical holders. These vertical holders could have been designed lighter, but I ran out of time to implement this design improvement. The vertical holders take out 5 DOF from the angled pieces. The last DOF is taken up by the flame holder contact giving a natural stop to the linear movement. These vertical pieces were machined in a CNC to ensure they were accurate. These vertical holders have a simple “V” shaped cut in them to match the underside of the L extrusions. The benefit here is that these are agnostic to any tolerance issues in the stock. These pieces are then held in place by the same type of quick clamps used on the base plate. This configuration gives access to the majority of the welds which are left.

19. The final welding configuration is done on the underside of where the three angled pieces meet. To perform this welding operation an optional small block can be added to the corner of the jig to allow the tool to simply rest in place. At this point the tool is heavy enough and welded enough to not need any additional
clamping. If additional access is needed the tool can be rotated easily to see the other sides using the same block for support.

20. For a corrosion coating, all components were coated with CRC Marine Corrosion Inhibitor. This product comes in aerosol form and is used in a wide variety of applications to prevent steel from corroding by giving a light layer of inhibitor. This type of corrosion inhibitor is often used on the underside of cars, boats surfaces, electrical connections, throttle bodies, etc. CRC’s Corrosion Inhibitor does not wash off easily and is not harmful if touched. It is highly flammable in aerosol form, but once sprayed on and dried all flammable chemicals evaporate leaving a stable coating. To ensure that there is no possibility of a fire a test was conducted on a sample piece of steel using a torch.

**MATERIAL CONSIDERATIONS**

21. To handle the high temperatures present while welding, steel was chosen as the base material. A36 steel in 0.500” plate was provided by Larsen Motorsports from their scrap bin. This was able to keep the cost of the project very low and the
machining was done for free at Northrop Grumman using their facilities afforded to the employees. A36 has a high melt point, but since it is close to the upper limit of the requirement listed, holes around the welding areas were added to reduce the amount of heat seen in the tooling and prevent accidental welding to the tool. Another advantage to using a steel base is the ability to tap the plate at any point.

Aluminum could also be used, and would be lighter too, but would require Heli-coils to thread into. The increase in cost also helped steer the decision towards the materials already on hand. Once this decision was made, picking the rest of the materials was easy as I did not want to play with different thermal expansion rates and dissimilar metal issues. For these reasons steel was used for all the rest of the components as well.

Table 2: Steel Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.282 lb/in³</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>58000 - 79800 psi</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>36300 psi</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>20%</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>29000 ksi</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>23200 ksi</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.26</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>11500 ksi</td>
</tr>
<tr>
<td>Melting Point</td>
<td>2,800° F</td>
</tr>
</tbody>
</table>

**TOLERANCES**

22. Tolerances are a key aspect in design. All too often you hear someone throw out that a design requires zero tolerance or that a particular machine is zero tolerance. In the real world there is no such thing as a perfectly drilled hole though. In this application there is no need to hold incredibly tight tolerances as the design is all placed on one base plate. Using a single base plate means there is no stacking tolerances. To account for the variation in the L brackets a diamond shaped machining pin is used. To drill precise holes that are tight tolerance I used a
waterjet to drill the pilot holes. Pilot holes were drilled because the waterjet available does not have a tilting head which means all the cuts made with this machine have a 3° slope. These pilot holes were then taken to final size using a mag-drill. A mag-drill keeps the drill bit much more normal to the surface than would be possible by hand. A drill press could have been used, but the added fixturing to clamp in place made it not feasible. These holes were finished using a reamer to get a tight tolerance fit. Using diamond shaped positioning pins allows for a large variance in L brackets. These diamond shaped pins can be twisted in place to take up variance in manufacturing and positioning, giving a solid hold over a wide variety of extrusions placed into the jig. These diamond shaped pins also allow for the tool to release after the weld in the case of extreme warping which preloads the pins. If this happens the diamond pins can simply be rotated to release the part.

23. The height of the FH101 blocks can be shimmed easily giving height adjustability. This feature gives relief to the manufacturing process for the blocks themselves. The bocks are held down with screws from the underside which were drilled to match after the blocks were placed. This simply meant that there was no extraneous layout required for the FH101 blocks when drilling their bottoms.

**WELDING SETUP**

24. The world of welding covers a large amount of skills and applications. Because of this sometimes a design will rely on having extremely skilled welders. While sometimes this is required it is always best to try to design such that the skill of the welder does not impact the quality of the final product. For this reason, the requirements state that the tasks must be able to be completed by a Level 1 welder. A level 1 welder refers to someone who can weld when the work piece is in a flat positions level 2 welder can weld in the horizontal position. 6 different levels of welding exist but keeping the tooling to a simple implementation is key to ensuring
success in the build. The welder which is suggested to use is a TIG welder so give the best final product.

**HARDWARE SELECTION**

25. Since the goal was to keep the total number of individual parts to a minimum, fasteners were a part of that consideration. For this reason, the pins chosen were press fit to the tool. The 3 blocks are held down with only 2 screws each. These screws are steel to prevent any dissimilar metal contact with the steel plate or steel blocks. These offer more than enough strength between the two. The feet have integrated screws as well. The feet were chosen such that they would keep the steel from contacting the tabletop and allow the user to comfortably get their hands under the plate to move it. The rubber on the feet in conjunction with the weight of the tool itself keeps it all planted on the tabletop. Steel spacers on the side of the keeper blocks could be used to space the toggle clamps. This would allow adjustability in the clamp in this direction. This keeps the need for a tight tolerance on this thickness down. This plate was drilled to match the holes in the push clamp using a drill press. The drill press kept the normality of the hole consistent. These were simply clearance holes so did not require much consideration towards tolerance. Since these have height adjustability if Larsen wants to experiment in the future with different depths of flame holders then all they will need to do is adjust the height of the FH101 block. If that is not enough adjustability a new block can be made relatively easily and replace the current one seeing as it is just screwed on. The screws which hold the push clamp on are also steel.
METHOD OF FUTURE TESTING

26. To test the fixture as fabricated I cut some stock and welded it in the fixture to ensure that the pins were able to function as designed to take up the tolerances in the stock purchased from the local Lowe’s. What was found is that some of the pins are $1/32$ of an inch closer to each other than some others. This is seen by taking a single piece of extrusion between each of the six positions and seeing how much the diamond pin needs to be rotated to hold the extrusion in. Once the welding in position one was complete the flame holder was rotated to ensure that the tool was completely symmetric in each of the six positions. This tool will ensure that the L brackets angles are held at a constant angle to each other. The flame holder was then flipped, and the last 3 pieces of L bracket were added, clamped, and welded. This position allows the user to weld the top side of all 6 connections on the hexagon and the 4 welds for the flame holder legs.

FLAME HOLDER FUTURE DESIGN AND TESTING

27. To perform follow-up testing on flame holders the following procedure could be used.
• Model the new flame holder using CAD and perform a FEA
• What the desired results are reached fabricate flame holder either using existing tooling if the new design permits or create new tooling to aid fabrication.
• Inspect new flame holder after fabrication to ensure the CAD model and produced unit are within design tolerance.
• If available place the flame holder in a wind tunnel to compare results to FEA. This prevents wasting money on more expensive testing and allows for design updates if the FEA turns out to have been inaccurate.
• Once the FEA has been shown to be accurate the flame holder can be installed in a drag car.
• With the new flame holder installed the engine can be turned on to ensure proper flow through the engine.
  o If the flame holder is too large or small the engine will not flow the correct amount of air leading to an increase in internal pressure. To prevent damage to the engine slowly ramping up to full throttle should be done to ensure minimal risk to the engine.
  o This step it critical to ensuring the new flame holder interacts correctly with the engine.
• Afterburner pops should be done to ensure proper airflow.
  o These pops are performed by turning the engine up to full throttle and turning the afterburner on for 1-3 seconds at a time. This will ensure that the flame holder still produces the correct flame and allows quick small updates to the design before going to the track.
  o During these afterburner pops the expected result will be a consistent flame.
• Once the flame holder has been tuned using the results from the afterburner pops the car should be taken to a track and put down the ¼ mile.
  o Comparing results from the first 200ft allows for good comparisons between flame holder designs. If the entire run is counted there will be too much deviation due to all the factors that go into a drag race. Due to this the first 200ft allow for keeping down on the external effects on the track time.

28. Throughout testing there should be a test conductor who ensures there is a test plan and that it is followed. The test conductor should have created ahead of time the test cards for the expected data to get. In this case the FEA can give how much drag is seen in the flame holder, which can then be recorded on a card so that on the day of wind tunnel testing the results are immediately obvious. The test conductor is responsible for ensuring that come test day everything runs smoothly.
29. A safety officer should also be established during the afterburner pops and when at the track. The safety officer’s job is to ensure that all standards for that county are followed and that there is no one put in danger during testing. This should be done by determining the tests planned for the day ahead of time so there is time for review and re-plan should it be required.

30. During the wind tunnel testing standard practices must be adhered to which will ensure a safe and accurate test. I suggest following LPR 1710.15 as a testing standard. For afterburner pops testing standard operating procedures used by Larsen Motorsports should be followed to ensure a safe test.

31. During wind tunnel testing the standard equipment already installed at the testing facility should be sufficient. The primary data point in question is the amount of drag the flame holder creates. This can then be directly compared with the FEA model to ensure an accurate model. Instrumentation on the afterburner pops is minimal. A heat measuring device could be used to get quantifiable numbers on the afterburner flame. Something like a Flir temperature gun would be great for giving a detailed quantifiable picture of the flame creation. Temperature probes should also be installed on the exhaust at set intervals to help show more detail. For the drag strip the Flir could be used again with the car in motion. All tracks will be equipped with extremely accurate timers which will give great feedback on performance.

Figure 14: Flir Smart Phone Attachment
CHAPTER 2
RESULTS, EVALUATION, AND ANALYSIS

TOOLING BUILD-UP AND USE

INSTRUCTIONS FOR FABRICATION

32. To use the tool the following set of instructions should be used.

- Place the Flame Holder Fabrication Tool on a metal work surface.
- Cut 1.00” x 1.00” legs to length using drawing provided.
- Place Flame Holder Base detail parts in the tool with the point facing up as shown in Figure 15: Flame Holder Tooling First Setup

![Figure 15: Flame Holder Tooling First Setup](image1)

- Cut Flame Holder Mount detail parts to length and place in tool jig in the same orientation as the other pieces.
- Once all 9 pieces are placed attach the grounding stud and, using a TIG welder, weld these parts together.
  - There should be a weld performed on each of the 6 joints on the hexagon and on each of the 3 connections between the base and mounts.
- With this first weld completed flip and rotate 60° in tooling so that the legs are lined up with the Keeper1 blocks.
Place the three Flame Holder Legs into the tool so that the bottoms are flat against the already welded assembly.

Clamp these in place using the toggle clamp, adjusting the toggle clamps as necessary.

Place the Flame Holder Keeper tubes in place on the mounts.

Figure 16: Base Layout

Figure 17: Flame Holder Tooling Second Setup
• Weld the last 6 connections points on the base, the 3 connections from the base to the legs, the top where the legs come together, and the 3 keeper tubes.
• With these complete remove the flame holder from the tool and flip to weld the underside of where the 3 legs meet to complete the flame holder.
• Now weld the underside of the top.
• The tool should be wiped down after each use to prevent corrosion.

Figure 18: Final Setup
POST USE ANALYSIS OF FUNCTIONALITY

KEY ADVANTAGES

33. The diamond pins were very efficient at keeping the pieces held in place. These require little effort to turn and hold the pieces which are to be welded in place very well. The tool makes positioning and clamping all the parts a trivial task, which will lead to more consistent flame holders over time.

34. The feet allow the tool to be very easily moved and is tall enough to easily see if a tool or something has rolled under it. The feet have also not marred or scuffed the work benches used thus far while still giving great grip so that the tool does not slide.

DEFICIENCIES

35. One primary deficiency that I did not see would be cutting the L brackets to length accurately. A DeWalt chop saw was used with an abrasive wheel. If I had access to a cold cut chop saw with a metal blade or a horizontal bandsaw the fabrication of the stock would have gone much quicker.

36. The holes for the pins were drilled such that I could experiment with a couple different sizes of positioning pins, but this meant that 100% Silicone had to be used to keep them in long term. If a second tool were to be made the positioning pin holes should be drilled at 0.3745”-0.375” instead of the 0.3755” they are drilled at. This would allow the pins to be pressed in keeping them there permanently without the need for a holding agent.

37. Clamps are needed to hold the base down while welding to prevent warping in the weld joint. These were considered and ultimately decided not to include these thinking the L brackets would not warp. Unfortunately, I did not consider the weld itself simply lifting the parts slightly introducing error.
EXPECTED TESTING RESULTS

38. From researching flame holders, it is quickly found that this topic is incredibly complex and not very well understood. It is well known what a flame holder does, but it is not well understood the exact math behind what makes a certain flame holder make more power than another. This is due to the competing theories on how many vortices should be seen in the flow. Some argue that the more vertices that exist in the flow the better mix of fuel and oxygen will be seen. While others argue that having a nice laminar flow is better for flame propagation. “Flame-holder shape did not greatly affect combustion limits” (5). Here Nakanishi, Velie, and Bryant investigate flame holder shapes and their effects, finding that using rounded gutters was 7% worse than V-shaped gutters and vortex generators helped by an additional 3.5%. Considering all this the way Larsen Motorsports has tested their flame holders in the past is by running the designs down the track and checking that off the line time. This just limits the number of variables acting on the testing compared to looking at the entire quarter mile time. To this end they have found that using a V-shaped gutter does give the best performance. They have also tested other shapes for the outline other than hexagons. Hexagons were found in their testing though to be the easiest to handle when installing/removing from the car and had the best performance.

39. One design which has not yet been tested is a circular V-shaped flame holder. This design would theoretically be more symmetric leading to better flame development. This design would be much more difficult to fabricate as the gutter would have to be either hydroformed or CNC’d. This would dramatically increase the cost and manufacturing lead time. The other disadvantage would be the additional hassle that would be seen from having a flame holder which does not fit in the exhaust nozzle.
CHAPTER 3
CONCLUSION

The purpose for this thesis is to provide Larsen Motorsports with a tooling to aid in the fabrication of flame holders in a reliable way. This was a success as the tooling as described in this paper satisfies all requirements listed. The primary advantages of this new manufacturing method lie in the consistency which results from using a tool like this. By using this tool, it is guaranteed to have a very similar flame holder each time regardless of welder skill. The main shortcomings are that this tool does not make it any easier to cut the L stock to length in the first place. This can easily be overcome by having a cold cut chop saw or a horizontal bandsaw instead of an abrasive disk chop saw.

The tooling drawings provided allows for design modification or replication in the future. The provided flame holder drawings list the detail parts needed and the manufacturing notes needed for fabrication. For future testing the procedures listed for flame holder testing can be followed. These can be used in a follow-up project to test new designs for the flame holder layout.
REFERENCES


APPENDIX A: DETAILED FABRICATION LIST

MACHINES USED

WATER JET

1. The first tool used was a WardJet E-1530 water jet. This particular water jet does not have an articulating head to compensate for the 3° of taper that is standard in water jets. This taper only really effects thicker pieces or precision holes. To compensate for this, I undersized the holes and drilled them to the correct size manually after the water jet. This water jet has a capacity of 5’ x 10’, uses a 0.020” nozzle with garnet, and will cut through most any material.
MAG-DRILL

2. A Milwaukee Mag-Drill (PN:4272-21) was then used to drill the pilot holes up to size. This is a 2.3 HP electromagnetic drill press with a 1-5/8” chuck. This tool has only two speeds making drilling steel a bit more difficult as the feed rate had to be sped up to match the spindle speed. Boelube was used as a drilling lubricant. This paste is easily applied to the drill bit or work surface using a brush or tongue depressor and turns liquid when heated from the drilling process.

![Mag Drill](image)

Figure 20: Mag Drill

CORE DRILL BITS

3. Boelube is great because number one it is a quality lubricant, but it also is very easy to apply to only where it is needed. Using a drilling lubricant will reduce friction and thus heat buildup in the work piece. These holes were up sized using carbide core drill bits to ensure the mag drill was centered on the hole, and give the highest amount of accuracy possible using hand tools. As you can see in Figure 21: Carbide Core Drill Bit, a core drill has a pilot section which should match the current size of the hole in the work piece. This portion of the bit simply keeps the bit aligned to the hole while drilling. This was also used to help ensure the mag
drill was setup as close to the center of the hole as possible before turning the electromagnetic on. After the holes were sized to 0.3750 a reamer was used to take the holes to 0.3755. This gave a tight fit while still allowing the pins some room to be removed if needed. The pins were then secured in place used 100% silicone to keep them in place, while still be removable. This allows for growth in the design of the flame holder in the future.

3-AXIS CNC

4. A 3-axis Tormach CNC was used to fabricate the Keeper1 blocks. The 3-axis CNC is such a diverse machine which made this process much easier.

Figure 23: Tormach 3-Axis CNC
FLUX CORE WIRE WELDER

5. A Chicago Electric flux core wire welder was used for the test piece. This was a good test as the heat generated from this welder will accurately simulate how much heat will be given off by the welders at Larsen Motorsports.
CHOP SAW

6. A D28715 DeWalt chop saw was used to cut the L brackets to size and at the correct angle. This saw features a 14” abrasive disk for cutting and runs at ~3500 RPM. The advantage here is the blade will cut through case hardened steel. If I had more money to spend on the chop saw, I would have gotten something with a metal blade like the EVOSAW380. This saw has half the RPM and a metal blade. The metal blade would not have walked as much and would have allowed for thinner cuts to be made.

Figure 24: DeWalt Chop Saw
APPENDIX B: RECOMMENDATIONS

GENERAL

7. Use stop blocks in either a cold cut chop saw, or a band saw to keep the lengths of the L brackets consistent. This will make cutting the stock a trivial task instead of a daylong event.

8. If another tool were to be made the holes for the pins should be such that the pins are pressed in.

9. A Millermatic TIG welder should be used to give a cleaner weld than could be achieved on the Chicago Electric Flux welder used.

10. Base plate should have been made slightly larger to allow for instructions to be etched into the base plate.

11. Initial holes should have been larger in steel plate to reduce number of step up drill sizes to 1.
APPENDIX C: DRAWINGS

Figure 25: Detail Drawing Page 1
Figure 27: Assembly Drawing