Base and Manifold Casting of the Atlantic "Make-and-Break" Marine Engine

By Emily Scherer

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Mechanical Engineering at the Massachusetts Institute of Technology May 2023

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Abstract: The Atlantic Marine Engine, manufactured by the Lunenburg Foundry in Nova Scotia, was a revolutionary two stroke combustion engine that transformed the fishing industry on the east coast in the early 20th century. A replica project of this engine was initiated in 2016 in Pappalardo Lab at MIT by a group of students using modern machining and modeling techniques to understand how parts for this particular engine were cast more than 100 years ago. Students have been fabricating parts for the engine ever since, and as of Fall 2022, three components were left to complete. This thesis covers the casting and machining of two of these three parts: the upper base and the manifold. This thesis will explain how the patterns and cores were made, pour orientations, and machining techniques.

Thesis Supervisor: Dr. Daniel Braunstein
Title: Senior Lecturer, Director of MIT Pappalardo Design Laboratories

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1. Introduction

As technology progresses and manufacturing methods become more efficient, old methods of fabrication are often forgotten. Such is the case with the revolutionary Atlantic Marine Engine that transformed the fishing industry in Novia Scotia in the early 20th century, and was supposedly a favorite amongst “rum-runners” carrying alcohol in the prohibition era to outrun police boats. This project brings modern modelling and simulation software to this iconic engine design to gain an understanding of how the parts were made more than 100 years ago at the Lunenburg Foundry. This thesis describes work that was done towards a finished replica of the Atlantic “Make-and-Break” Marine Engine. I will describe the casting and machining of two key parts: the exhaust manifold and the upper base. I designed and machined the patterns and core boxes, fabricated custom flasks, made molds, cast iron, and machined the finished parts and assemblies. The completion of these parts relied on an accumulation of seven years of experience casting in Pappalardo Labs and the DMSE Foundry and the multiple previous attempts lessons learned.

Figure 1-1: Atlantic Marine engine installed in the back of a boat [1]

2. Background

2.1 The Lunenburg Foundry and the "Make-and-Break" Atlantic Marine Engine

> "Lunenburg Foundry is part of the heart and soul of Nova Scotia, and its influence and objects may be found in every corner of the province."
>
> ~ Cope and Finlay-deMonchy, *Casting a Legend: The Story of the Lunenburg Foundry [2]*

Established in 1891 in Novia Scotia, Canada, The Lunenburg Foundry has engineered, fabricated, and manufactured a wide range of marine and industrial equipment for over 125 years. Their most successful product was the Atlantic Engine, also known as a "Make-and-Break" engine. It was designed and built at the Foundry beginning in 1909 and pioneered the development of marine internal combustion engines. The Foundry's red buildings became the production line for these popular engines, employing over 200 people at its height and making over 400 make-and-breaks a month. The Foundry is now known by the acronym LIFE (Lunenburg Industrial Foundry & Engineering) and still provides generational expertise in ship servicing, fabrication, casting, and machining. They have a legacy of incredible attention to detail and care for their customers, to which the success of the "Make-and-Break" is partially attributed.

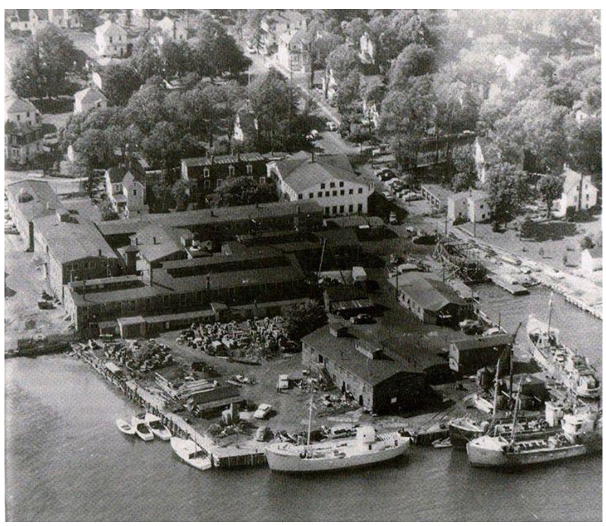


Figure 2-1: Lunenburg shipyard and foundry in Novia Scotia, Canada [3].

To understand the significance of the Atlantic Marine engine, the name must first be explained. One might think "Make-and-Break" refers to a simple engine that could be easily repaired when broken, but it actually refers to the way the ignition spark is created. The make-and-break ignition system is driven by a rod attached to the crank shaft, and as this rod goes through the full two-stroke combustion cycle, it allows an electrode to both "make and break" contact with the stationary electrode, and therefore fires at the correct time. This ignition system was popular in the early 1900s in marine engines because it does not require a high-tension coil like in a spark plug design and is therefore highly resistant to moisture. According to *Casting a Legend, The*

Lunenburg Foundry, the ignition would fire even after a bucket of water was poured on it. Because the majority of the 12,000 engines made at the Lunenburg Foundry before 1940 used this ignition system, this iconic two stroke engine became synonymous with this name [2].

You might hear someone refer to this engine as a one-lunger, which refers to the single piston attached to the crank shaft. This engine uses a two-stroke cycle, as compared to the four-stroke cycle that your car runs on, which will be elaborated on in the next section. All the parts are made of cast grey iron because grey iron was easily cast, cheap, strong, and easily machined.

This engine was frequently advertised as "The fisherman's favorite two-cycle engine" and was originally designed by Dan Young in 1909, who was widely regarded as a mechanical genius (although his formal education ended after 4th grade). When he and his son Charles designed this engine, gasoline engines were not yet very common on the Canadian seaboard, although they had been getting rapidly popular in the U.S. and Germany in the automobile industry (the first popularized American gas engine was in the Ford Motor Company's iconic Model T in 1903). Young designed this engine by studying popular engines, like the Model T, and taking detailed notes about compression ratios, port dimensions, and firing systems he wanted to mimic [2]. This marine engine was quite literally the "fisherman's time-saving and money making machine" because sailors were no longer at the mercy of the wind or calm which could save sailors days at sea.

The strengths of the Atlantic Marine Engines were the result of these careful observations and many generations of commitment to the town of Lunenburg and to the marine industry in Nova Scotia. His son Charlie said of the design: "I think our stuff was a lot heavier than anyone else's. If a casting was supposed to be an inch and a half thick, my father would say, 'Well, better to make it 1-5/8" just to be sure.'" The full 5 horsepower engine weighed in at a whopping 255 lbs. and the ten horsepower was 435 lbs. All parts were cast at the Lunenburg Foundry and Young originally drew all of them on wrapping paper, either full or half size, many of which still exist at the Foundry [2].

Figure 2-2: Advertising for the Atlantic Marine engine in 1925, boasting of its power and strength [2].

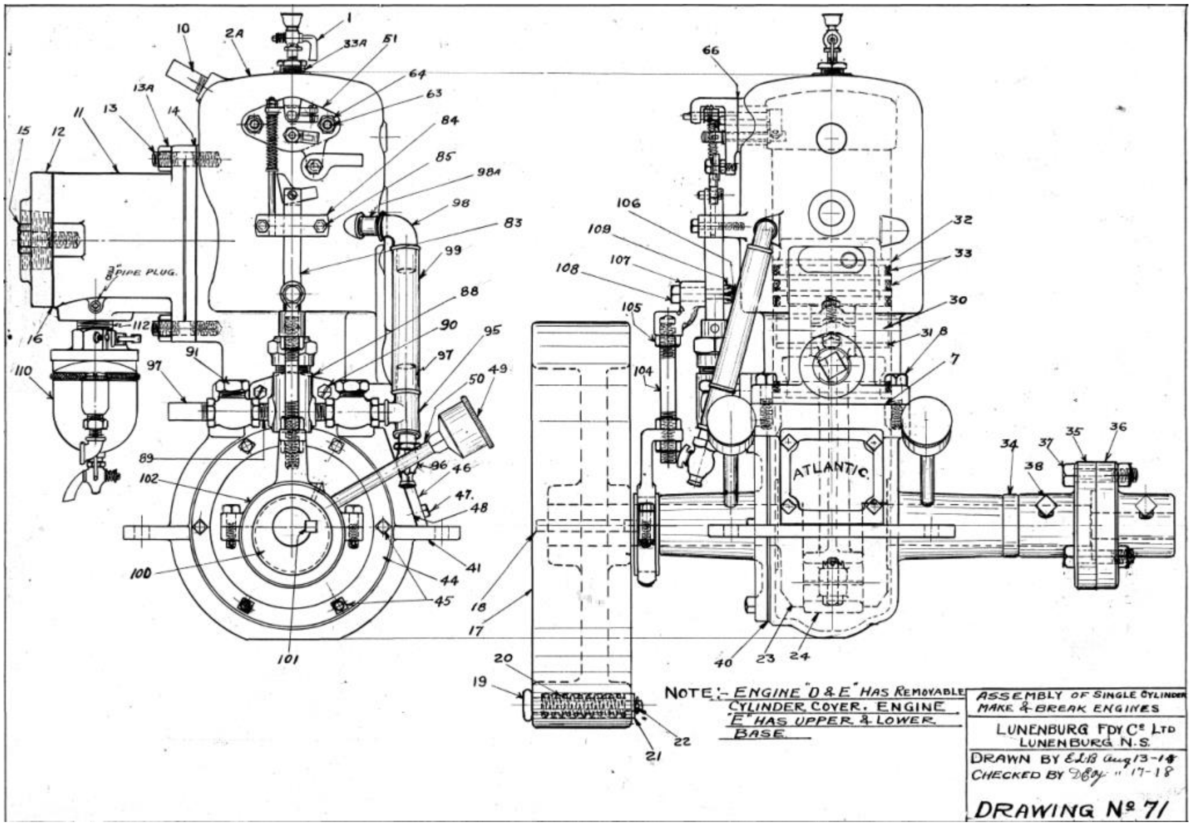


Figure 2-3: Original assembly drawing of the entire engine, drawn in 1918 [4].

The upper and lower base divide was invented by Dan’s son Charles in the 1930s, so that sailors could re-babbitt their engine’s crank shafts themselves and more easily service their machine. An MIT professor even visited the Foundry in the sixties and was flabbergasted that the engine even ran at all! He said due to the compression ratios and port locations that the engine should never have fired up. Charles replied: “Well that’s a strange thing, because we’ve sold 12,000 of them. And now we find they won’t work! [2]” Every old fisherman who owned one of these engines has their own funny and mostly endearing stories about their Atlantic Engine. My favorite story is of a sailor who got caught in a horrible winter storm on the Atlantic Ocean. He took down all his sails and in desperation, after removing the carburetor, tied a rope to the engine and threw it overboard to be used as an anchor. In the morning, after the seas had settled down, he lifted the engine up and dumped the water out, plugging the carburetor back in, and firing it up, and it worked just fine! This story is a testimony to the robustness of these engines, and how dear to many fisherman’s hearts they were.

The demand for this engine decreased as the more fuel-efficient four-stroke cycle was popularized. The last Atlantic Marine Engine was shipped out in 1995, the same year the Lunenburg Foundry closed. The neighborhood housing the Lunenburg Foundry is now a UNESCO world heritage site and LIFE still runs their shipyard, doing ship building and repair, machine-shop work, sheet metal work, and mechanical and electrical contracting. This thesis project is a continuation of an immense amount of work in a replica effort started in 2016 at the MIT Pappalardo Labs to recreate one of these iconic engines in the hopes to understand more fully the casting process used, and to use modern machining techniques on an old design.

2.2 Two-Stroke Combustion Cycle

The Atlantic Marine Engine being built in this project, as mentioned before, uses a two-stroke cycle to produce power. To understand the context of the parts that were built in this thesis, I must explain more about how the two-stroke cycle works. The first stroke (intake and compression) happens as the piston moves up the cylinder, compressing the air and fuel in the cylinder until the piston meets its highest point. While the piston travels up, the passive valve for fuel and air is open in the crankcase and fresh fuel and air rush in and the transfer port is closed. Once the piston reaches maximum height, the electrodes spark, and the piston is forced downwards due to the rapid expansion of the burnt air and fuel. This is the "second stroke" and is called the power stroke because it drives the piston downwards. As the piston moves down, the exhaust port is opened and the exhaust is pushed out by the fresh fuel mixture, leaving via the exhaust port. As the piston moves downwards, it pressurizes the fuel-air mixture in the crankcase which is then pushed into the cylinder via the transfer port and the cycle repeats itself. The process of simultaneously exhausting combustion gases while drawing in a fresh charge is often referred to as "scavenging".

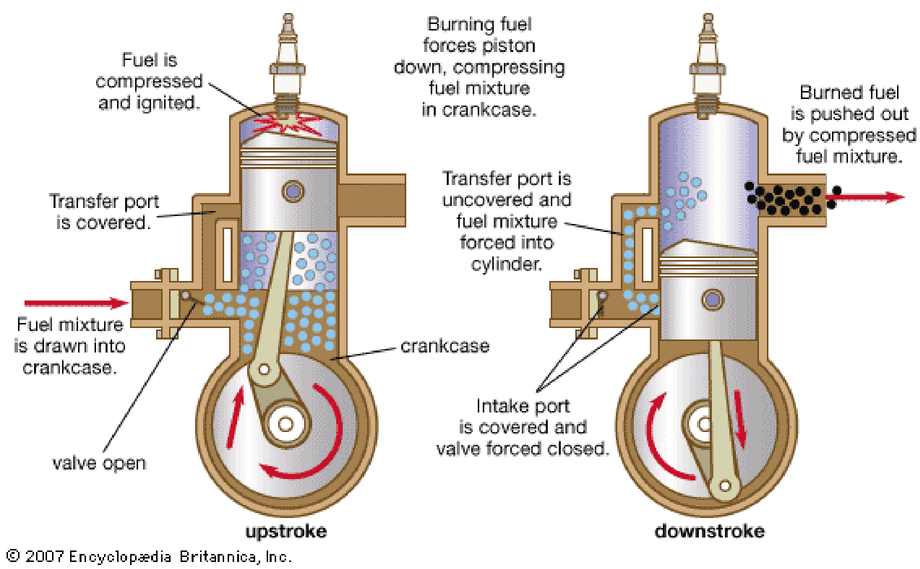


Figure 2-4: A diagram explaining the two-stroke combustion cycle [5].

In comparison to four-stroke engines, two stroke engines are simpler and require fewer parts, are easier to fix, are lighter and take up less space, and deliver twice as many power strokes per cycle, because the 4-stroke engine goes through two complete revolutions to complete one power stroke. Because of the passive nature of the ports in a two-stroke, unburnt fuel, however, can be exhausted from the combustion chamber, which results in lower efficiency, dirty emissions, and fuel waste. Additionally, a two-stroke engine has a narrow power band, or range of speeds where the engine is most efficient. Because of these drawbacks, the fishing industry gradually transitioned to using four stroke engines and the Atlantic Marine Engine was phased out of production in the late 1970s.

2.3 Pappalardo Atlantic Engine Recreation Project

The adoption of this project started with a surprise visit to the Lunenburg Foundry in 2015. Sally Miller (MIT '16) was in the first group of Pappalardo Apprentices, a program for juniors and seniors to learn various machining and casting techniques. She happened to be traveling near Lunenburg on break and Dr. Daniel Braunstein, director of Pappalardo labs and old engine enthusiast, was looking for a senior apprentice casting project. He suggested that she pay the Foundry a visit if she had time. She followed his directions and Peter Kinley, current CEO of LIFE, happened to be there.

Peter Kinley spent the entire day showing Sally the foundry, the original drawings, and old engines. She was blown away by the facility and when she came back and showed Dr. Braunstein photographs of the original engineering drawings, he immediately reached out to Mr. Kinley with a proposal. The support at the foundry and the historical significance of the engine made this the perfect senior project for the apprentices to learn about casting. He called Peter, who enthusiastically agreed to the proposed student project, sending scans of all the drawings and some original parts and notes. One of the retired foundrymen, David Allen, even came down to Boston to work with students in the DMSE foundry. David is a grandson of one of the original draftsmen/engineers/foundrymen at the Foundry and whose grandfather personally knew Dan Young. Peter and David have been instrumental in supporting this project and helping us uncover how to cast the parts. Once the replica is finished, it will be relocated to the Atlantic Fishery Museum, next to the Lunenburg Foundry.

Figure 2-5: Atlantic Fisheries Museum in Lunenburg, Novia Scotia [6].

Once the project was adopted, the first group of seniors to work on it were the 2016 apprentices. The engine was then modelled in CAD, which was no small task considering many dimensions were missing from the century-old drawings. Dr. Braunstein and the students were all new to casting and to the technical team at the DMSE foundry, so this semester was mostly experimental. Students experimented with 3D printed patterns, the lab acquired a 3-axis machine to CNC patterns, and the group attempted to cast many smaller parts. They successfully constructed a full ignition and water-cooling systems. The engine was then put aside, to support a time critical Herreshoff steam engine project, until 2019 when the senior apprentices picked it up again. The apprentices attempted many parts and completed the flywheel, crankshaft, connecting rod, and piston. By the end of the spring in 2019, only four parts remained: the lower and upper base, the manifold, and piston. The lower base was completed by Chiaki Kirby in fall of 2019 leaving only three parts to complete.

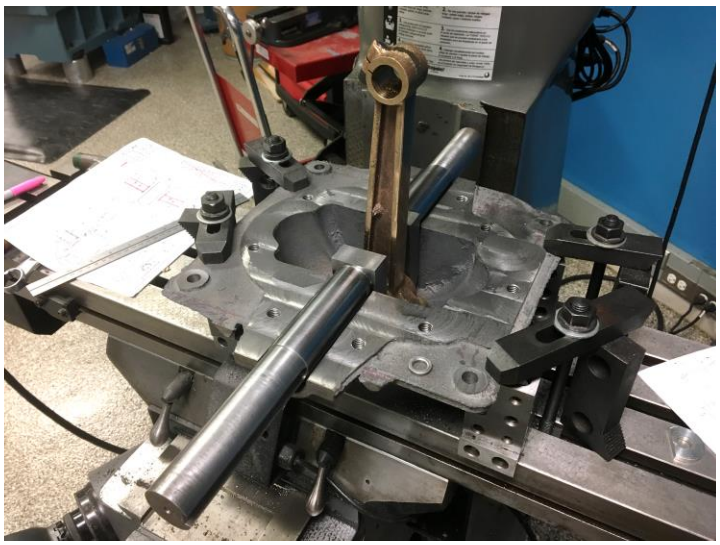


Figure 2-6: Completed lower base with crank shaft and connecting rod [7].

Figure 2-7: Core boxes and patterns of the water pump from 2016.

I was introduced to this project in the fall of 2022, with the original goal of completing all the remaining parts and assembling and firing up the full engine. While the full scope initially set was not completed, significant progress was made these last two semesters by completing both the upper base and manifold. By writing about the work done, hopefully I can contribute to the collective knowledge in Pappalardo Lab surrounding this engine that will inform the cylinder casting, assembly work, and eventual completion of the Atlantic Marine engine by future students.

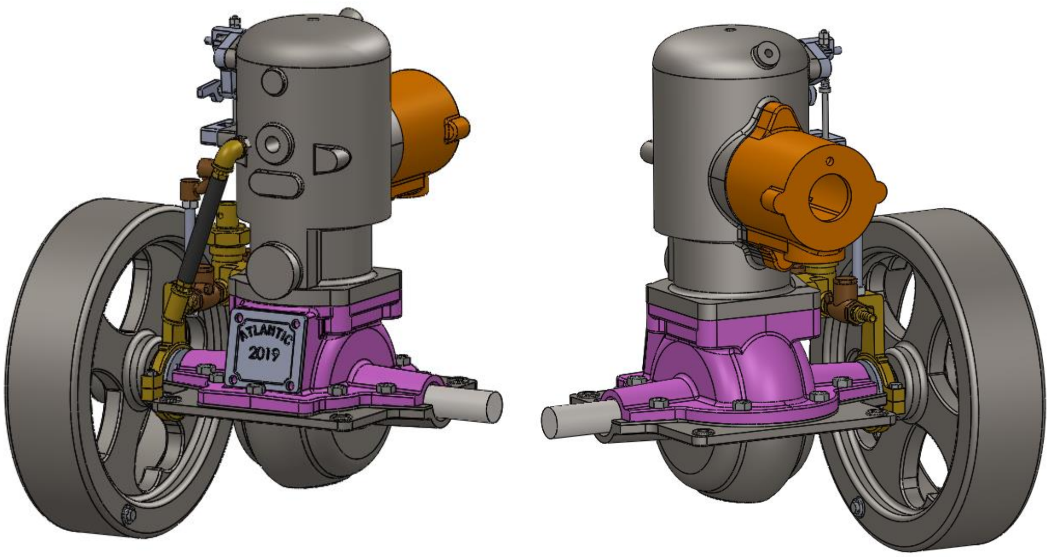


Figure 2-8: CAD of the full Atlantic Marine engine with my parts highlighted (the upper base is in pink and the manifold is in orange).

3. Upper Base

3.1 Upper Base Background

The first part I finished was the upper base. This part serves a few critical roles as it connects to the engine cylinder at the top and the lower base at the bottom, forming a sturdy foundation for the machine that is then bolted to the boat. The upper and lower base together hold the shaft bearing and house the crank shaft cavity, which allows the crank shaft and connecting rod to freely spin and houses the fuel mixture before it rushes into the cylinder for ignition.

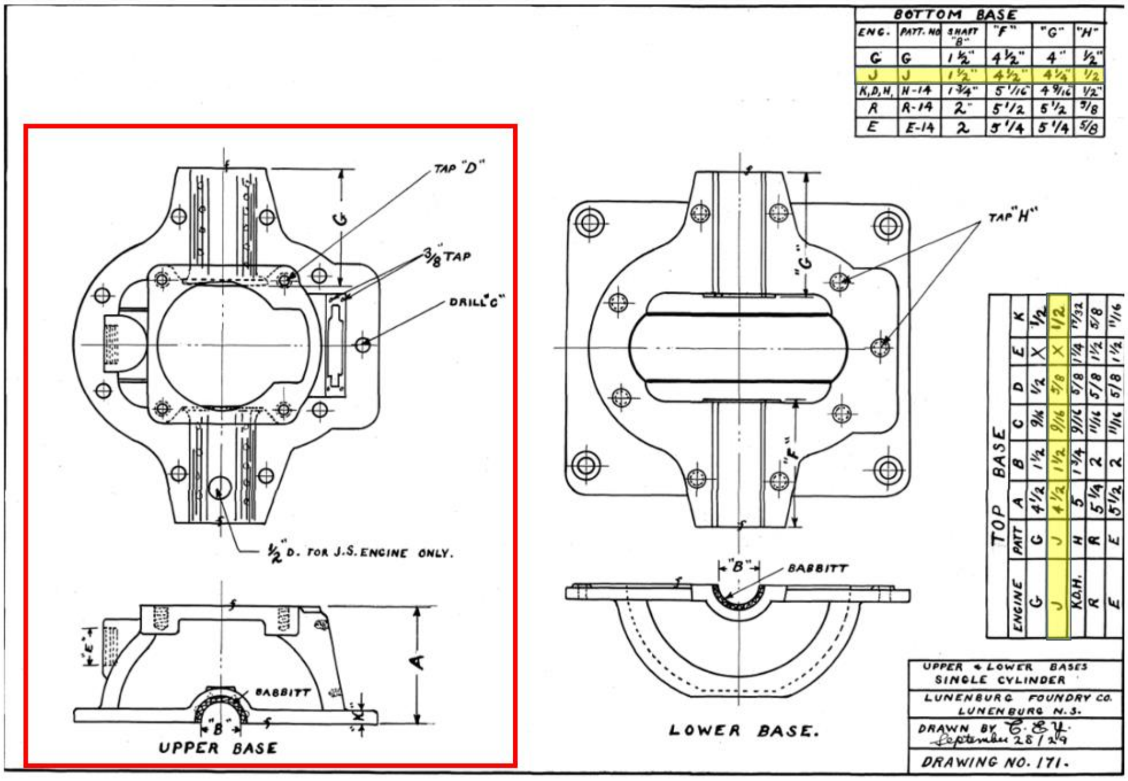


Figure 3-1: The original drawings for both the upper and lower base. We are using the J model dimensions [4].

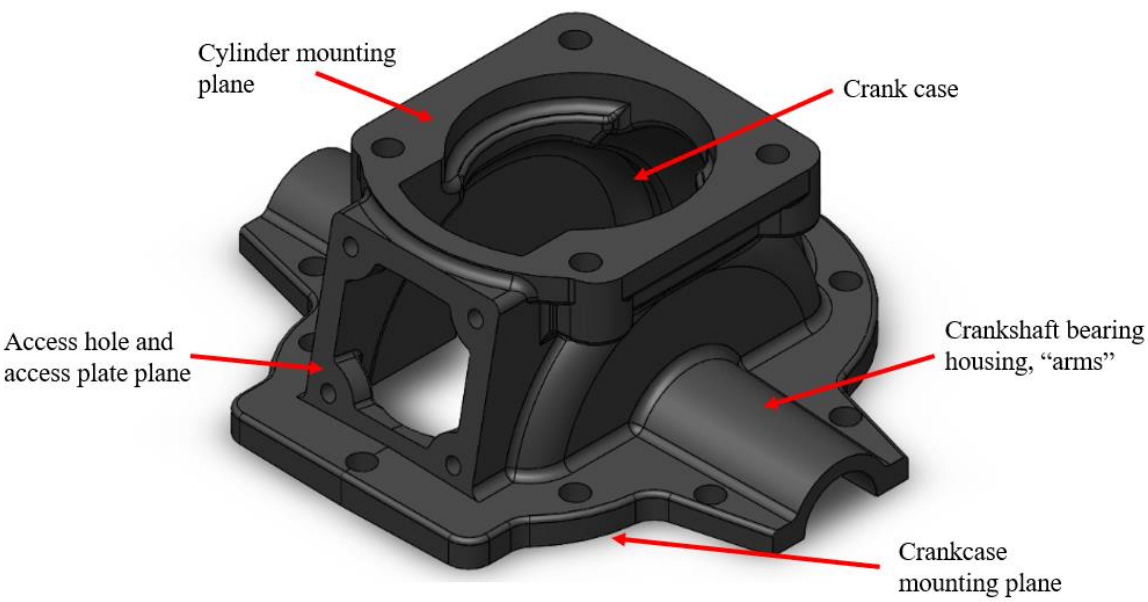


Figure 3-2: Labelled CAD model of the machined upper base.

ZhiYi Liang (MIT '19) designed and machined the first patterns and core boxes for the upper base in the spring of 2019 and completed the first attempt at pouring this part. This pour was done in a vertical orientation, meaning the long crankshaft bearings were aligned vertically in the mold. This was chosen because of the part's natural drafts in that direction due to the tapered arms and round casing.

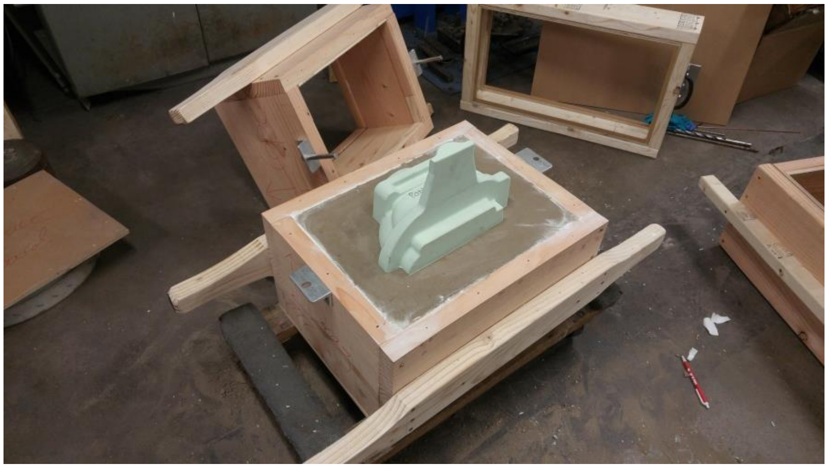


Figure 3-3: Partially packed flask by ZhiYi Liang in 2019 showing the vertical orientation that he used. Long, skinny arms stick up in the air.

Unfortunately, this method of casting used extremely long and skinny cores sticking out once placed in the pattern's core prints. These long cores for the "arms" probably bumped the sand walls as the flask was lowered onto it after packing, dumping lots of loose sand inside. This sand rose to the top of the iron which is why you see the slag on the top-most end of the part on the arm and the inside of the crankcase. These defects are called slag inclusions because of the conglomeration of sand that is embedded into the iron walls and the rough surface they leave behind. This defect, and the associated challenges of mold making and assembly, indicated that the part may best be cast in a different orientation.

Figures 3-4 and 3-5: Poured part by Liang in 2019, one end has defects due to sand that was trapped in the iron's way, requiring a part redo. You can see the gate along the center line in the picture to the left.

3.2 My approach

Building off the work completed by Mr. Liang, we decided to change the orientation of the pour from vertical to horizontal. This change required a complete redrafting of surfaces on the part in CAD so that the patterns can be easily removed once sand is packed around them. Once the orientation is switched however, there is an overhang that is created on the mounting plate which poses a significant challenge and is circled in Figure 3-6. With a traditional pattern, this would be impossible to remove because the undercuts would not permit removal from the sand. To solve the overhang issue, I made a seven-part pattern for the overhang, so that once the sand was packed around it, each corner could be removed without disturbing the sand.

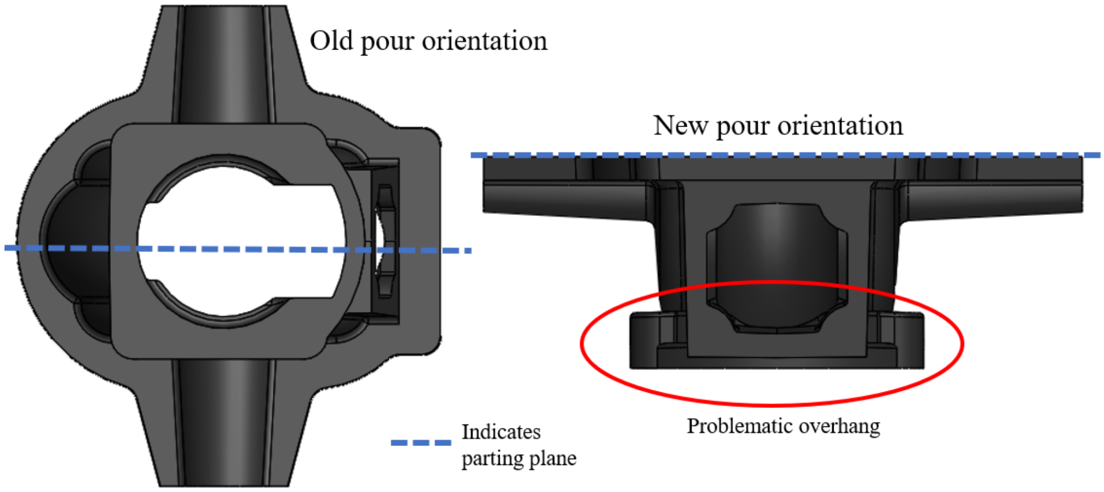


Figure 3-6: Old and new orientations and their parting planes. The problematic overhang is circled in the right image.

3.3 Packing prep

The redrafted surfaces required new patterns and cores. A pattern is a 3D shape that is used to hollow out the cavity in the sand where a casting is then poured. A core is a 3D shape placed inside this cavity, used to create negative spaces in a casting. Extra material was added to the top and bottom in CAD and I added core bosses to the pattern to accurately locate the core during the pour. The crankshaft bearing arms of the pattern were extended to leave plenty of room to cut them off and machine to length after casting. The pattern for the upper base consisted of two main parts: the body and the "top hat". The body pattern had to be made in two blocks because the height surpassed the tool length, so two separate parts were machined and then later glued together. To machine these foam parts, they were double-sided taped to a wood board, screwed in place from the bottom, and secured in the mill vice.

Figure 3-7: Machined upper base pattern, showing the two main sections and the core prints on the "arms" and crank case.

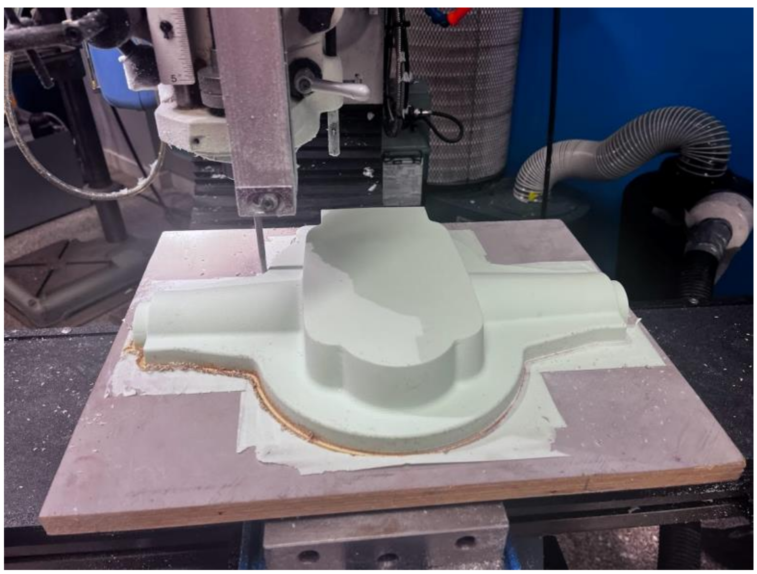
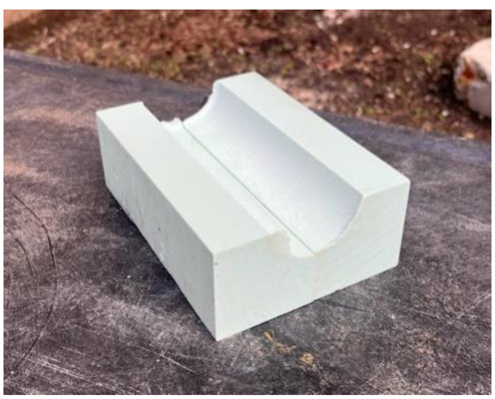


Figure 3-8: Machining one part of the body pattern.

To machine the top hat, the foam stock was cut into seven pieces using a table saw, then taped together using double sided tape and secured in the vice. Since there were features on both sides of the overhang, the part needed to be located on the board via pin holes and then flipped over to keep the origin and accurately finish the other side. The pin bosses are removed afterwards and barely show up in the finished part. The raised boss in the middle is called a core print and is there so that the core can sit in the perfect position during the pour.


Figures 3-9 and 3-10: Machining the top hat with a core print to locate the core and pin holes to locate the part after flipping it in the mill. On the right is the bottom side of the finished top hat pattern.

The core boxes were also re-made to match the pattern changes. As seen in the image below, the core consists of a big center part, creating the cavity for the crank case, and two arms which create the space where the crank shaft will be held by babbitt bearings.




Figures 3-11 and 3-12: Machined upper base core boxes.

The cores were packed using a new magnesium oxide formula developed by James Hunter of the MIT Materials Science Department. This formula combines sand, magnesium oxide powder, and phosphoric acid in a KitchenAid in a 100:1:3.5 ratio by mass. Mixed together, they create the mineral magnesium aluminum phosphate, essentially hardening the cores into a rock. The “rock” therefore releases very few volatile organic compounds (VOCs) during the pour. Unfortunately, this formula is too expensive to be used in mass production and therefore most production parts along with all the previous parts in this project were made with the more typical core binder: a furan curable resin. This core binder is particularly dangerous because of the fumes produced during mixing while the epoxy is still liquid. These fumes are sensitizers, meaning you can develop a sensitivity to them over time and they can cause serious health problems. The furan resin also releases lots of VOCs during pouring because of the carbon bonds that break at approximately 500ºC. The core mixtures were then packed into the core boxes and allowed to dry for a few hours before breaking them out. It's also important to vent the cores in the mold so that they are allowed to outgas through the flask during the pouring process.

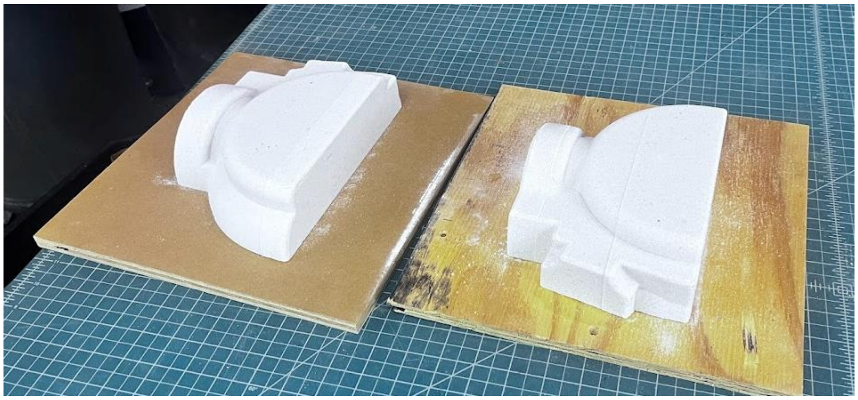


Figure 3-13: Magnesium crankcase cores. Both halves will be glued together using core cement

3.4 Packing and Pouring

The next step was to pack the flask, or the box into which you pour a cast part. To prepare the sand, we used a muller to mix the sand with water and southern and western bentonite and to get a packable texture that could hold the form of the part. After preparing the sand, the cope was placed with the parting line on the floor and the pattern was placed on the ground. I then sifted sand over the part to fill in the small details and corners, and then filled the flask with unsifted sand, tamping thoroughly to ensure the pattern cavity would hold its shape during the pour.

Figure 3-14: Packing the flask, parting line on the floor.

The cope was then flipped, and the drag was placed on top with the parting lines together. The second part of the pattern, in this case, solely consisted of the core print boss. The core boss was located on the rest of the pattern via steel dowel pins, and the packing process repeated. Once the sand was packed, the two halves were separated, and the patterns were removed. The tricky part about removing these patterns was the seven-part "top hat" and removing the corners was a stressful, but successful endeavor.

Figure 3-15 and 3-16: Flask with top hat fully in and one corner removed, showing the overhang this created.

Figure 3-17: All pattern sections removed, you can see the "MIT 2022" and my initials imprinted into the sand.

Once the flask was packed and the pattern removed, I dug out the sprue, runners, and gates, and put risers off the "arms" on the opposite side of the pour. I also poked ventilation holes throughout the part to get rid of gases that could build up during the pour. I calculated the weight of iron to be poured based on the weight of the previous attempt and the size of the sprue, gates, and runners, which ended up being 48lbs of iron.

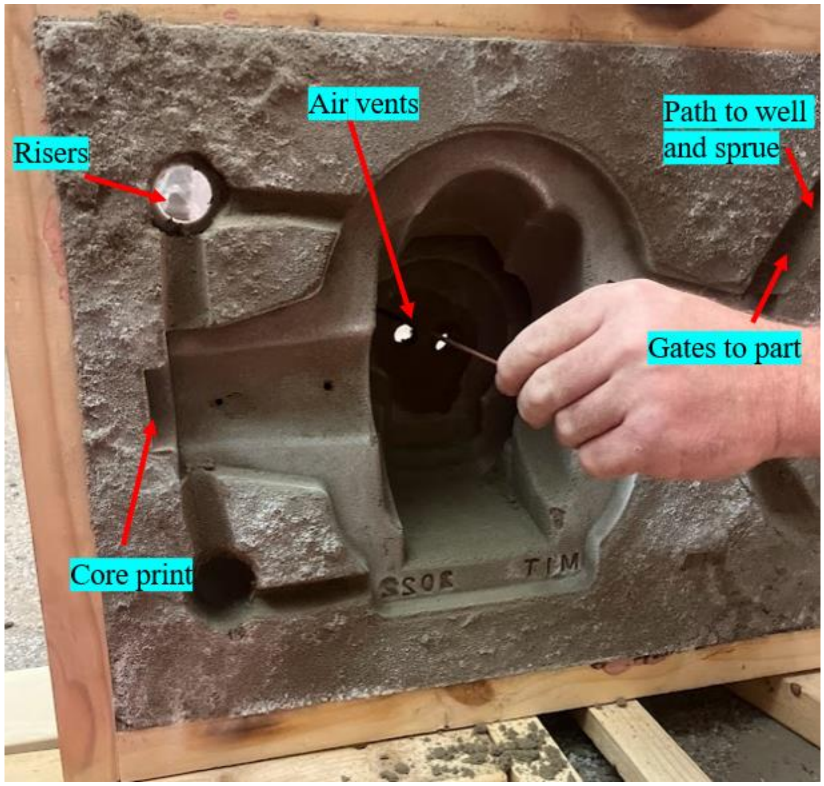


Figure 3-18: Labelled image of the packed flask.

Figures 3-19 and 3-20: Pouring molten iron into the flask, breaking the part out of the flask the day after the pour, looks good so far!

The pour went very smoothly, but we didn't see the risers fill on the opposite side of the pour, so we expected it to have been a short shot. When we came back the next day to break the part out, we were pleasantly surprised with a nearly perfect part! The pattern had filled completely and there were no wall defects!

Figure 3-21: Poured part with risers, gates, and well still attached. Minor flash around core prints.

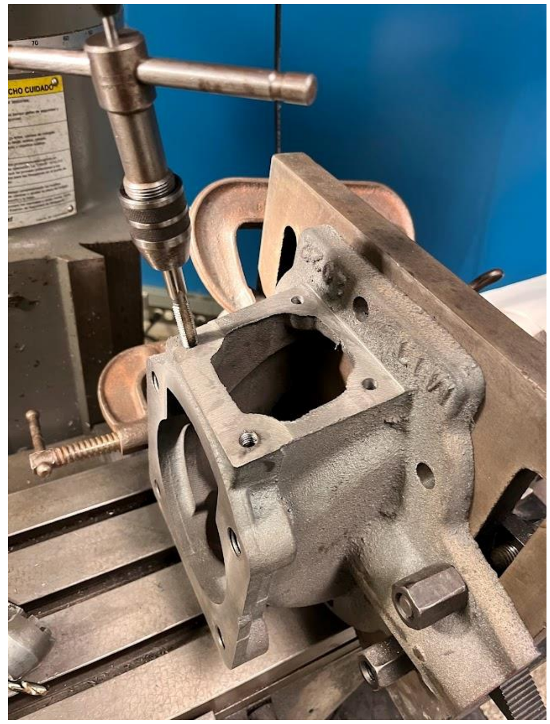
You can see the risers on the right were only barely full, which is why we thought the part hadn't filled. There was minor core print flash along both the top and bottom openings, but this would easily be machined off.

3.5 Machining

To machine this part, first all the gates and risers were cut off, along with the extra material on the arms. Next, a relatively flat surface had to be established on the bottom. To do this, I ground down the high spots on the crankshaft parting plane until the casting stopped rocking on a flat surface and used a square to make sure it was parallel to the table. The part was clamped to the mill bed with shims, and I used a shell mill to work the surface until it had a uniform height, being careful of the very shiny quickly solidified flash. I faced the crankshaft bearing arms next, bringing them to the dimensions specified in the drawings. The part also has nine clearance holes that the lower base bolts to, which I drilled using a program in the ProtoTRAK. Next, I flipped the part and repeated the process, bringing the part down to the height specified on the drawings. This side has four drilled and tapped holes for cylinder mounting.

Figures 3-22 and 3-23: Machining the crank shaft plane and the cylinder mounting plane until they were a uniform height.

To machine the angled access plate, I bolted the crankcase bolt plate to a large right-angle block and angled the mill head 10 degrees to match the angle of the casting. I then used a similar approach to the other faces, shell milling it until the surface was entirely flat. I then drilled and tapped the holes where the access plate bolts to. The final part is in the following pictures! Thank you, Simon Peng, for the small lettering that I used to write MIT 2022 and my initials!



Figures 3-24 and 3-25: Machining the access plate plane with a tilted mill head, drilling and tapping mounting holes.

Figure 3-26: Finished upper base bolted to the lower base.

4. Manifold

4.1 Manifold Background

The manifold bolts onto the cylinder, delivers the gas to the engine, and exhausts the spent fuel via an exhaust port. At first glance, it seems like a much smaller and less complex part than the upper base. While easier to machine, the manifold is one of the most difficult parts to cast due to its many thin walls, explaining the five unsuccessful attempts in previous years. Having three separate passages for the exhaust, fuel intake, and cooling water jacket, the cores for this part are particularly complex and difficult to assemble into the mold. Every attempt taught us new things about pour orientation, gating locations, and core layout.

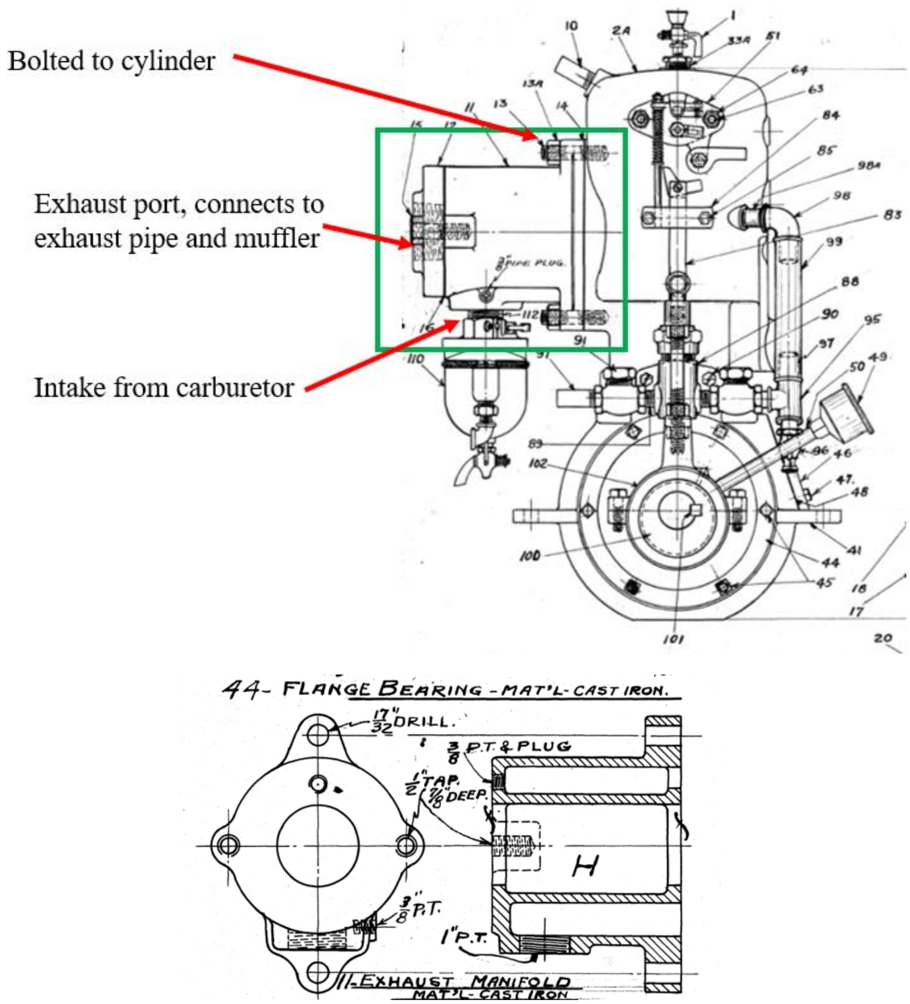


Figure 4-1 and 4-2: Original drawings of the manifold.

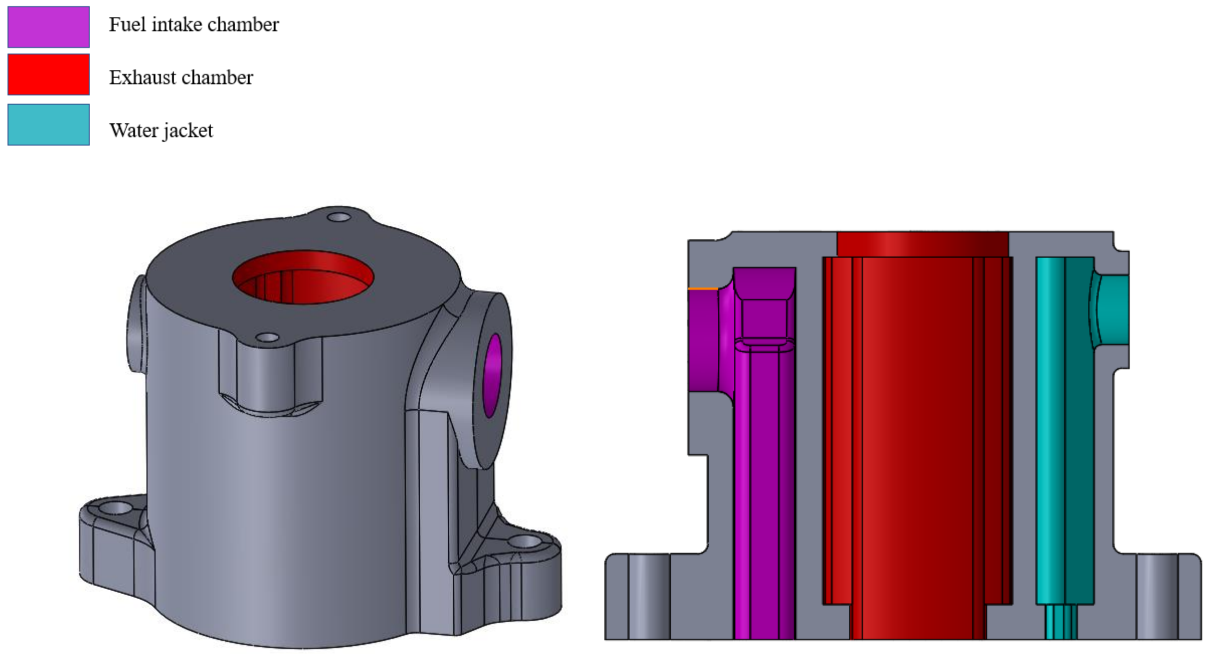
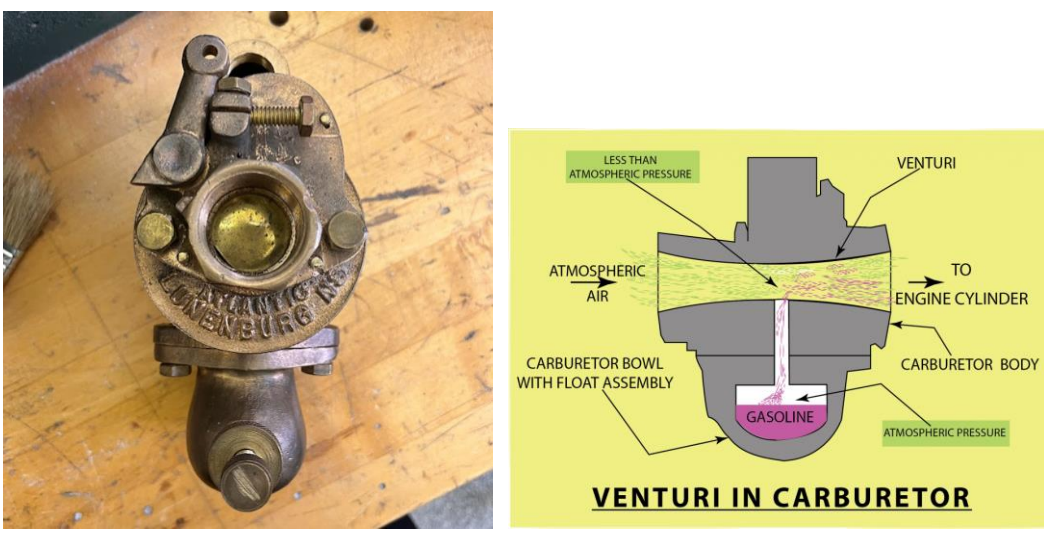


Figure 4-3: CAD model of machined manifold and color-coded chambers.

The carburetor that will be attached to the intake in our replica, shown in the original drawings, is the last known original carburetor manufactured at Lunenburg Foundry. All the Atlantic carburetors were made at the foundry originally, until they eventually outsourced the production. The carburetor is responsible for mixing gas and air and uses high speed air to reduce the pressure, prompting gas and oil to atomize and flow into the air stream, a process based on the Venturi principle. The amount of gas let in is controlled via a needle in a hole, which the user can adjust.



Figures 4-4 and 4-5: Original carburetor made in Lunenburg and a diagram explaining the Venturi principle that mixes the air and gasoline.

Gordan Andrews (MIT 2016) was the first student to work on this part and developed the part's CAD model as well as the patterns and core boxes. All components were CNC milled out of polyurethane foam the same way as in the upper base. The cores posed his biggest challenge, because of the long, skinny nature of them making them susceptible to breaking once packed with sand. He decided to pack the cores in two complete halves, then glue them together to make one core.

When he tried removing the cores from the core boxes, the shear stresses from the foam on the sand were too large and the bottom puck broke off. This was the first testament to developing "sand empathy," meaning designing core boxes to make it extremely easy for the sand to come out and avoiding high shear stresses from the foam that results in broken cores. To modify this design, he shimmed the core box as shown below, making three separate cores that all would rest in the same core print.

Figure 4-6: Andrews' core boxes with shims.

Andrews attempted three pours that semester, all in the horizontal orientation. The first was a short shot, resulting from an air vent filling with iron from the significant gap between the core print and core due to the shimmed cores and therefore not leaving enough iron for the part. The second attempt had fewer defects, but two of the internal walls had holes, likely due to trapped gas due to the high volume of VOCs generated during pouring from the epoxy used in the cores.

Yet another attempt by Andrews resulted in hollow outer walls of the manifold due to trapped air and center line shrinkage, making the part very fragile. To dissect why these attempts might have failed, one can look at the location of the defect in the part in relation to the flask. In this case, the void was on the topmost wall in the part which leads us to believe that it was caused by a bubble formed from the outgassing cores. From these attempts, we learned that a horizontal pour would likely not work due to the gasses affecting the thin top wall and that the orientation would likely need to be adjusted for the next pour. These attempts laid a strong foundation from which to proceed.

Figure 4-7 and 4-8: Various defects from the second and third pour attempts, suggesting a vertical orientation would likely work better.

Matt Quejada worked on the manifold in the spring of 2019 and developed a new pattern and cores that had much larger core prints. This was to circumvent the severe flash issue that Andrews encountered in his attempts. Quejada split the core boxes into different sections by cutting the foam on a table saw and then clamping them all in a vice to machine them. This allowed each section of sand to be removed individually, lowering the chances of breakage. The splitting down the middle of each cavity increased sand empathy by not forcing the sand to break out of the long skinny sections. This technique was used in my core box.

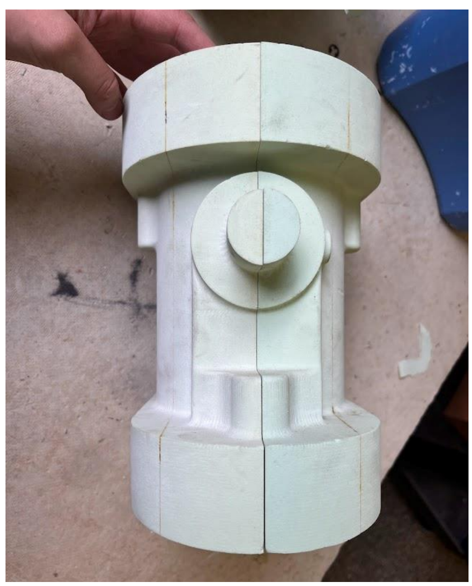


Figure 4-9: Old pattern by Quejada with large core prints to prevent core flash.

Quejada's attempt ultimately failed for a variety of reasons. To pour the part, one must scale the CAD dimensions up by 1% for iron (for aluminum, 10%), which was forgotten in this attempt. Additionally, due to severe flash around the cores and the parting plane, only about half of the part filled. Another reason for the short shot could be due to the large core prints, which created a very long runner which could cause the iron to prematurely solidify in the small runner.

Figure 4-10: Fourth attempt at casting the manifold, resulting in a short shot due to significant core flash.

These attempts all demonstrate how difficult this part is to properly fill, and that significant changes must be made to have a successful casting. The fifth attempt of this part was done by Chiaki Kirby (MIT 2020) in the spring of 2020. She chose to use Andrews's patterns from the spring of 2016 to decrease the amount of toxic epoxy-bonded sand necessary for the cores. Besides the different orientation, another major adjustment she made was creating a more complicated core box, consisting of seven parts cut on the table saw and milled in a vice.

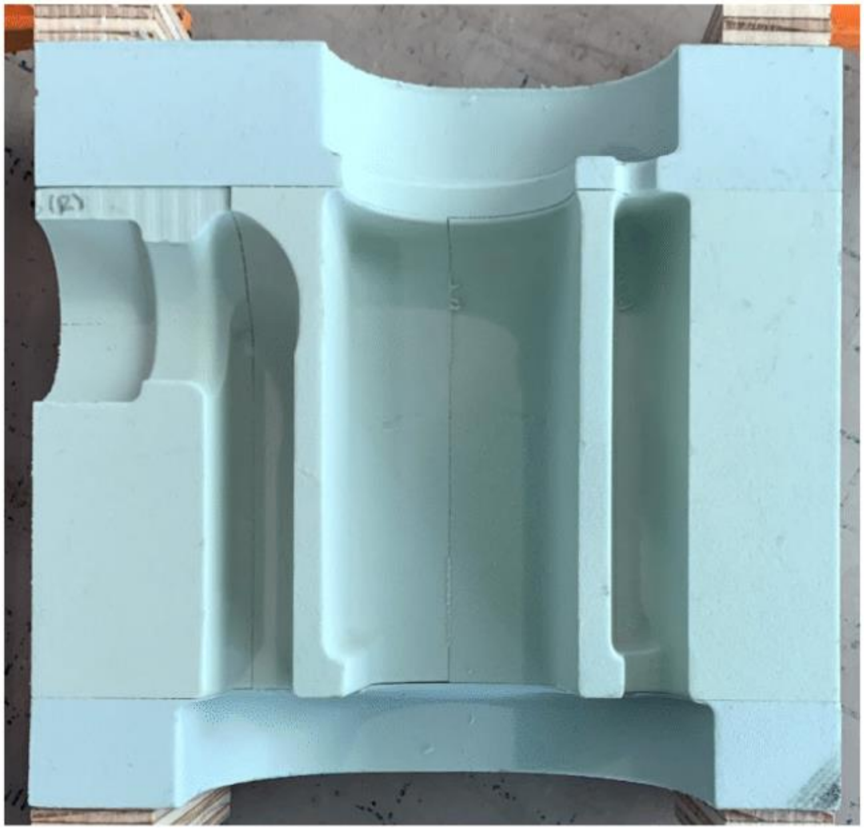
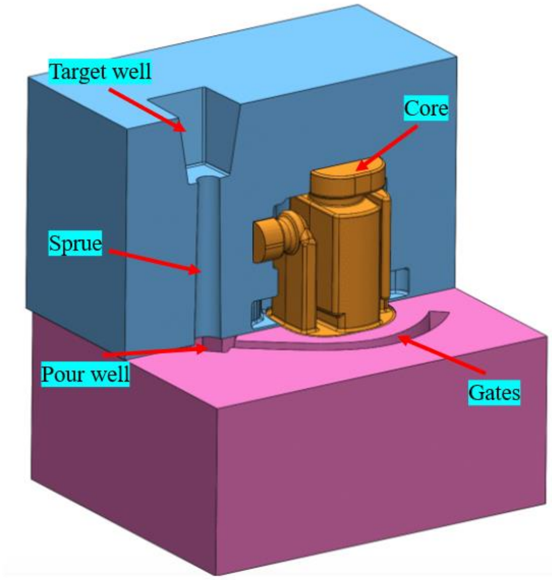


Figure 4-11: Core boxes by Chiaki Kirby. Each chamber has a split line down the middle to ensure the cores can easily fall away once they are packed and set.

This new core box was packed in 4 separate chambers and glued together after they set. This resulted in 8 separate sand parts that needed to be glued together but led to very easy core removal and accurate dimensions. Using Andrew's pattern, she packed the flask and poured the manifold for the fifth time. She used a three-part flask to be able to pack in the same, horizontal orientation but then flip the flask to do a vertical pour. This set up also allowed her to gate the part radially from six different locations to all the thin walls around the part.



Figures 4-12 and 4-13: Vertical pour orientation and 3-part flask set up, Chiaki Kirby, Spring 2020.

The resulting part was nearly perfect, except for a bulge in one of the walls. This was because the sand in the flask wasn't packed down enough and the iron was heavy enough to push the loose sand outwards, resulting in "mold swell". Based on the success of this attempt, I chose the vertical orientation to move forward with.

Figures 4-14 and 4-15: Results from the fifth attempt at the manifold pour. There were two small holes on the top, resulting from not enough material left over after the significant bulge in the right picture.

4.2 First Attempt

Sticking with the same orientation, pattern, and cores as Chiaki Kirby, I decided to use a simpler two-part flask due to the added complexity that the three-part flask created. This setup forced me to gate solely along the parting plane in four separate places. I thought this would be sufficient because it would still leave one gate for each wall of the part. Since the core puck was in the way of the two inner-most walls, I drilled holes through the bottom puck to allow iron to flow through. To allow the cores to vent, I drilled holes in the sand cores and carved channels in the sand to allow VOCs to escape during the pour.

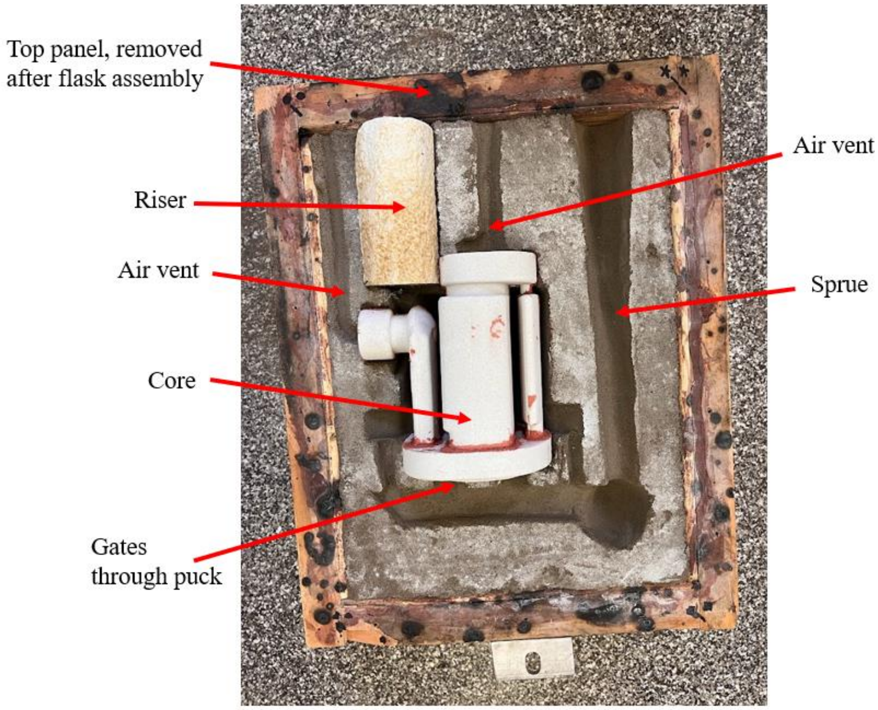


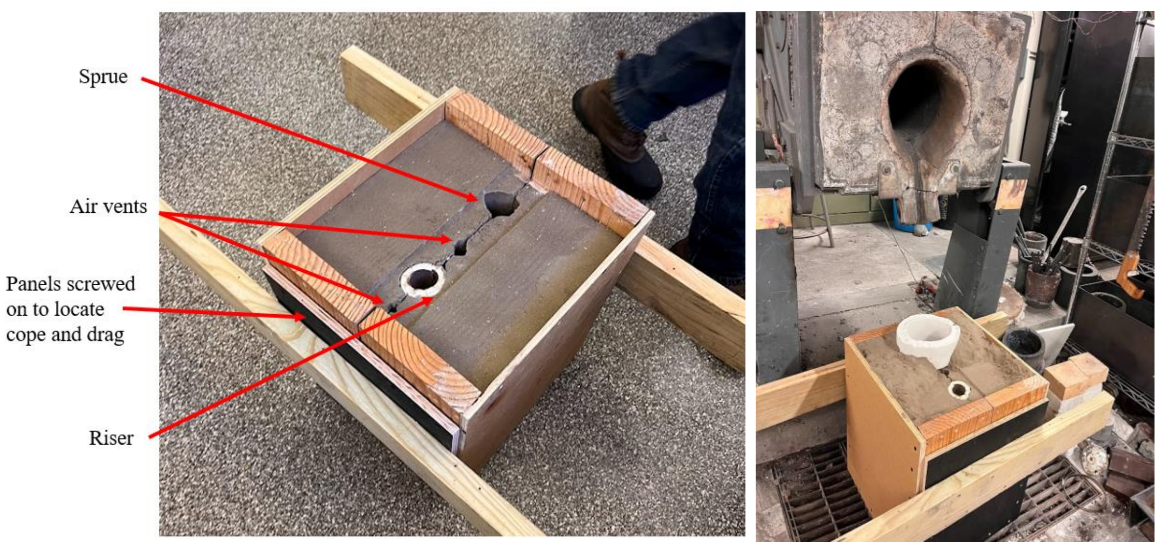
Figure 4-16: Flask set up in my first attempt.

When attempting to insert the cores into the flask, I ran into a multitude of problems. First, the cores didn't fit correctly into the core prints that were left behind from the pattern. The whole core assembly appeared to be too tall, and the intake core boss didn't align with the core print in the sand. To compensate for this, I dug out the sand where there was interference so that the whole core assembly would fit into the flask. This would inevitably leave a large amount of flash at the core prints.

The second issue I encountered was that the base puck, to which I glued everything to, was very mushy, causing all the glued cores to fall off. This was likely because I mixed the core sand in the incorrect proportions or didn't mix it long enough. I remade the puck core and glued everything back together and went to assemble the flask.

Figure 4-17: Mushy core puck and broken core.

The last mistake I made was forgetting to build locating pins on the flask. Usually, flasks are built with locating pins that ensure the cope and drag are in the same position with respect to each other during packing and when you reassemble for the pour. Without those pins, it was very difficult to know if things lined up internally when we lowered the drag. Because we poured the part in the vertical orientation, down the parting plane, the top side of the flask had to be removed. To do that, I screwed panels onto five of the six sides and then flipped the box to the correct pour orientation. Then I took out the top to expose the sprue hole, vents, and riser.



Figures 4-18 and 4-19: Pouring set up in the first attempt. A big target well was made from core sand for easy pouring.

I calculated the amount of iron to pour based off the weight of a previous attempt and the dimensions of the sprues, wells, gates, and runners and decided to pour 38 pounds of iron. I made the mistake of adding a bit extra to “fill the risers” along with the pour well and this ended up being far too much, contributing to the defects seen in this first attempt.

4.3 First Pour and Results

The pour went well at first, until the riser overflowed due to my overcalculation of poured iron. Once the iron hit the damp sand on the top, sparks started to fly and the iron pooled on the top of the flask, trapping air underneath. These sparks were caused by VOCs erupting out of the riser, spraying very dense molten iron into the air. The iron inside of the flask leaked and contacted the wood along the parting plane in multiple locations, causing it to ignite.

Figure 4-20: Cast part, dug out along the parting line to see the path the iron took as it filled the part. The iron contacted the wood on the left side of the flask, causing the wood around the parting plane to catch on fire.

In this picture, the core flash on the top and left side is extremely evident, and one reason for the eruption witnessed was that the air vents that were supposed to extend from the cores were filled with iron from the core flash. The vents also could have been filled from pool of iron on the top of the flask leaking back down.

Figures 4-21 and 4-22: Severe flash around both the intake and exhaust core prints. This caused the air vents to fill up, preventing VOCs from escaping.

There were a few defects that we noticed immediately upon opening the flask. One of these was the gunky outer surface. This was caused by metal penetrating the sand because of loose sand packing, allowing iron to sneak between sand granules. Another defect was the cavity on the bottom corner, likely from sand falling from another part of the flask and getting stuck there. The most concerning defect, and the reason for the second attempt, was the small holes in the internal walls which would result in exhaust and intake mixing and resulting in a highly inefficient engine. These holes were near the extreme flash shown in the pictures, and therefore might be the effect of the rapidly cooling flash shrinking away from the part, called a draw. Because of all these defects, it would be quicker to redo the pour rather than attempting to repair the existing part, along with having better structural integrity.


Figure 4-23 and 4-24: Metal penetrations created a bad surface finish caused by loose sand packing. A defect on the bottom of the part, likely from sand being caught in that corner from corner shrinkage.

4.4 Second Attempt

Going into my second attempt of pouring the manifold, I knew I wanted to redo the cores and patterns for multiple reasons. (1) I wanted to add extra material to the top and bottom of the manifold that could be sawed off post-pour to defend against potential cavities due to sand inclusions. (2) I also wanted to remove the tiny hole for the manifold water jacket because in a single cylinder engine like this one, it is plugged and doesn't connect to anything. This would result in three separate cores which would be easier to place in the packed flask. To make a self-supporting core for the water jacket, I decided to make a 1-inch hole on the side of the manifold to allow for an L-shaped core supported on both ends. After pouring, this would be tapped so that a plug could be screwed in or welded on. I decided to keep the same gating and pour orientation because the defects in the first attempt did not suggest a need to switch the orientation.

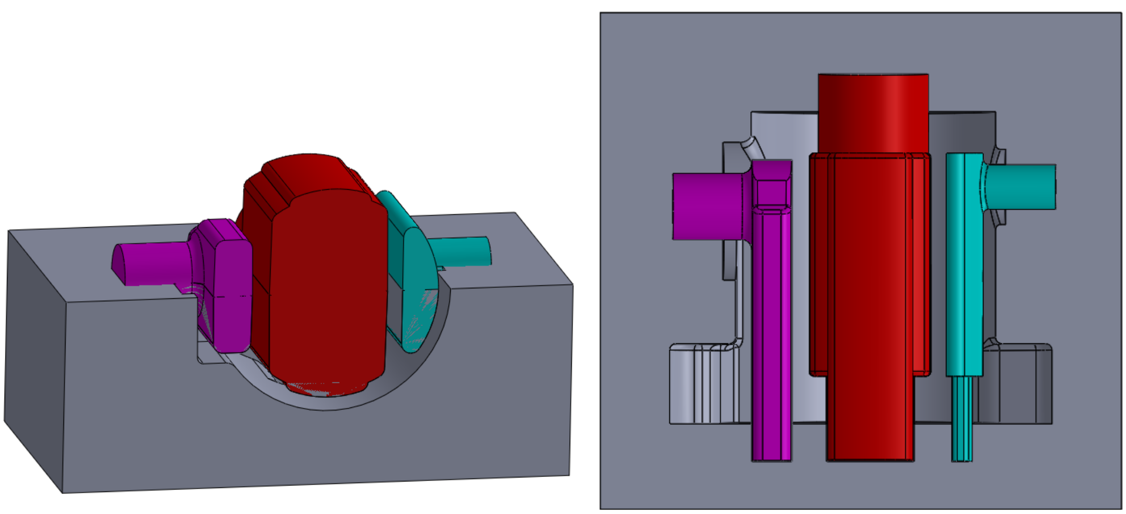


Figure 4-25: CAD of how the new core layout will sit in the flask once packed.

All these adjustments required another iteration of patterns and core boxes, again machined out of high-density polyurethane foam. The pattern had three core prints to match the three separate cores and a side boss for the new water jacket plug. The three cores each had their own core boxes since they were all completely independent from each other, which made them much easier to machine. Each core again had two halves that would be packed separately and then glued together once dried. The foam was cut beforehand and then clamped in the mill and machined together to create a seamless finish.

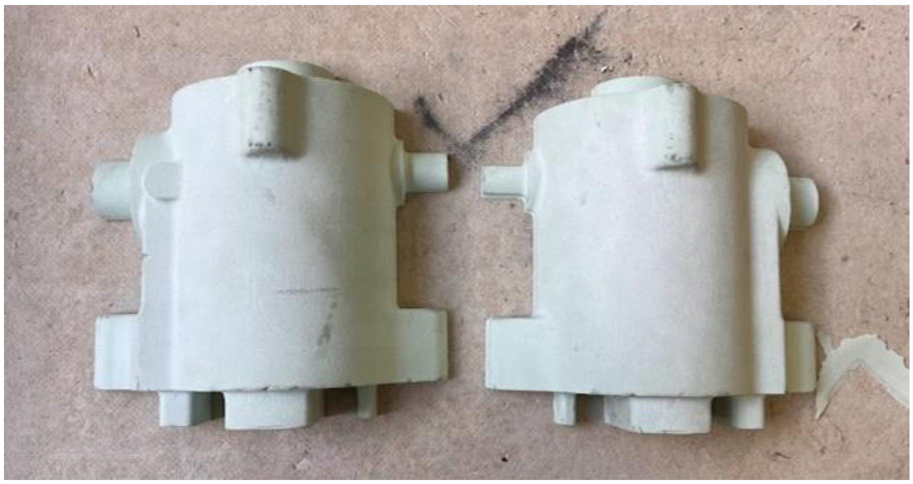


Figure 4-26: New patterns with three core bosses and a water jacket core print.

Figure 4-27: New core boxes, two for each core because each is made in two halves and then glued together.

4.5 Packing and Pouring

Packing the flask in the second attempt was almost the same as my first attempt. To make the cope and drag sit nicely together, the parting planes were power planed until they sat flush with each other. I also added locating pins and kept the air vents further away from the wall. I also used core cement to seal the flask perimeter and to glue the cores into the core prints to prevent flash around the cores like in the first attempt.

Figure 4-28: Second attempt flask layout.

The one issue I ran into while packing was that it was extremely difficult to get the patterns out of the sand once sand was packed around them. This is because the sand was trapped in the long channels between the three core bosses on the bottom of the pattern, cracking the sand in the flask. Eventually they came out, but in a future attempt I would have made those draft angles larger. I decided to pour much less this time – only 31 lbs. During the pour, the riser again had a trapped air bubble which rose to the top and popped. Because of this eruption, the closest wall blew out, creating a cavity defect in the resulting part. Even with this defect, we determined the part would still be usable! To repair the water jacket's outer wall, Scott Spence of MIT Pappalardo Lab and welder extraordinaire ground and tig welded the entire area, sealing the hole and removing the defect. Thanks Scott!

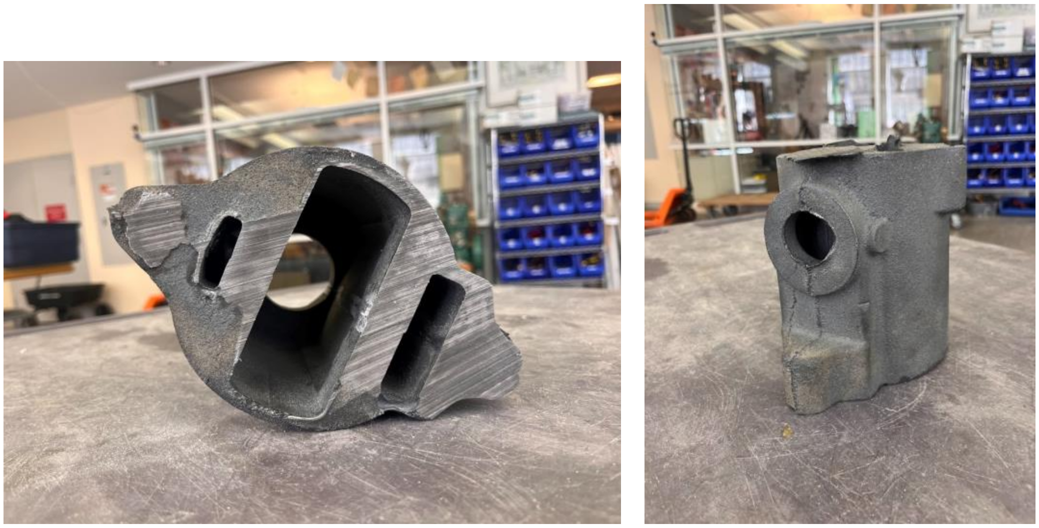
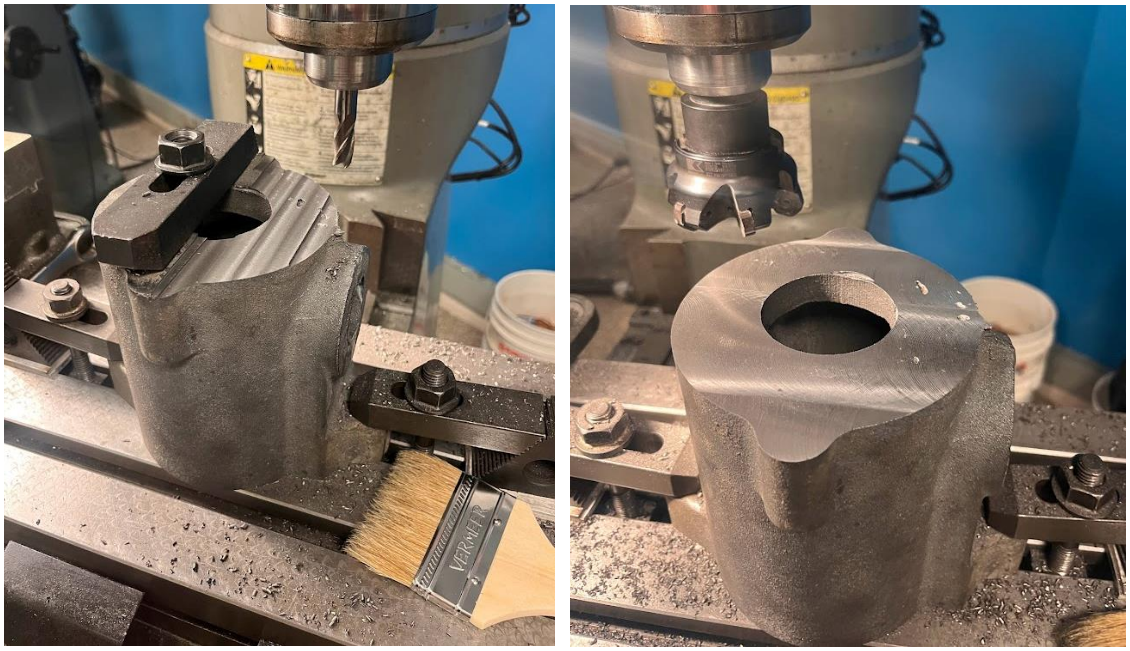


Figure 4-29 and 4-30: Second attempt results, showing solid walls and uniform wall roughness.

Figure 4-31 and 4-32: Welding magic, thanks to Scott Spence.

4.6 Machining

To machine the part, I followed the same procedure used on the upper base. I ground the bottom of the part until it roughly laid flat on a table then shimmed the part on the mill table using aluminum stock. After clamping the part, I used a ½” end mill to rough the surface down to a uniform height. Then I finished it with the shell mill, giving it a nicer surface finish. The next step was to drill and tap mounting holes so that this face can be bolted to the exhaust port. The part was then flipped over, and the process repeated on the other side, with through holes so that it can attach to the cylinder.



Figures 4-33 and 4-34: Machining the manifold, using a ½” end mill first and then a shell mill for the finished touches. You can see a few sub-surface pinholes in the second picture, which could be caused by excess oxygen or hydrogen in the flask [9].

The side surface was machined next with a long end mill until just flat. The defect on the tapped area was filled in using weld bond and then tapped with a 1-¼” NPT tap to attach to the carburetor. Finishing the manifold was an exciting accomplishment and would not have been possible without the information passed down through the previous six attempts before this successful one!


Figure 4-35 and 4-36: Tapping the carburetor hole and the completed part!

Conclusion

The original goal of Danny Braunstein and the senior apprentices in 2016 was to finish casting all the parts, assembling them, and firing up the engine in just one semester. They quickly found out that if a student can get through one part a semester, it's a huge win. Such was the case for me. I started the year hoping to complete three parts and full engine assembly but only got through two parts. But after seeing how much trial and error goes into every part, I'm excited and content with the work laid out in this thesis and can't wait to return some day and see the engine fire up! All that's left is to cast now is the cylinder, the biggest and most complex part in the entire engine. One attempt of this part was done in 2019 by Shannon McCoy, and much can be learned from this attempt to inform the next iteration. The final goal of this project is to bring the engine to the Atlantic Fishery Museum next to the Lunenburg Foundry, coming full circle to where the engine was first created over 110 years ago.

Acknowledgments

I want to extend my biggest gratitude to Danny Braunstein for inviting me to work on this exciting project and for his many hours spent mentoring me throughout the last three years. This work would not have been possible without the support of the rest of the Pappalardo staff: Steve Haberek for his steady company, Bill Cormier for his casting and machining expertise, Scott for his welding skills and his dad jokes, and Simon for sharing his love of machining me and always telling me "You're fineeee" when I would get stressed. Thank you to Mike Tarkanian and James Hunter from the MIT foundry for pouring the parts in their lab. Lastly, thank you to Peter Kinley and David Allen and all the people at the Lunenburg Foundry who have supported this project throughout the years!

References

[1] Braye, Crystal, "Calvie Meadus' Motorboat," Boats and Builders Blog. https://boatsandbuilders.com/boats/calvie-meadus-motor-boat.

[2] Cope, Karin and Finlay-deMonchy, Marike. 2002, "Casting a Legend- The Story of the Lunenburg Foundry." Nimbus Publishing LTD, Halifax, NS, Canada.

[3] Homfield, Max, 2015, "Lunenburg Foundry & Engineering Limited (Atlantic Engines)," Everything About Boats Blog. https://everythingaboutboats.org/lunenburg-foundry-ltd/.

[4] Young, Charles and Young, Daniel, 1929, Atlantic One-Lunger Engineering Drawings. Lunenburg Foundry & Engineering Limited, Lunenburg, Nova Scotia.

[5] Encyclopedia Britannica, "Two-stroke cycle," *Technology and Engineering*, 2023. https://www.britannica.com/technology/gasoline-engine/Two-stroke-cycle.

[6] "Discover Lunenburg," Your Trip to Novia Scotia, 2012. https://www.your-nova-scotia-holiday.com/lunenburg.html.

[7] Kirby, Chiaki, 2020, "Manifold and Base Casting of Lunenburg Foundry Atlantic Marine Engine," MIT Senior Thesis.

[8] "Two-Stroke Engine Troubleshooting," Happy Wrench Motorcycle Repair. https://happywrench.com/two-stroke-carburetor-troubleshooting/.

[9] Rowley, Mervin. 1993, "International Atlas of Casting Defects." *American Foundrymen's Society, Inc.* Des Plaines, Illinois.