Fabrication of an 1897 Herreshoff Marine Steam Engine

by

Priscilla Agosto

Submitted to the
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in Partial Fulfillment of the Requirements for the Degree of

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Abstract

A 19th century Herreshoff marine steam engine was developed using a combination of traditional and modern fabrication methods. Background on Nathaniel Herreshoff, his connection to MIT and the Herreshoff Manufacturing Company was provided. The process for selection of appropriate steam engine with the input from the Francis Russell Hart Nautical Museum at MIT was explored. CAD models were developed from the original drawings from MIT's Haffenreffer-Herreshoff Collection. Pattern making options, casting, sand types and machining practices were explored and analyzed. Furthermore, a blueprint for a single-semester course in advanced fabrication methods for MIT 2.007 Senior Undergraduate Apprentices was proposed.

Thesis Supervisor: Daniel Braunstein
Title: Senior Lecturer

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1 Introduction

Steam engines can be dated back to the 1st century AD with descriptions from Heron of Alexandria. Centuries later, in the 1600's and 1700's, they reappear when Taqi al-Din and Giovanni Branca explained primitive forms of turbines driven by the power of steam. In the 1700's steam engines helped solve one of the most significant industrial challenges of the time, removing water from coal mines. In 1698 Thomas Savery patented a pump with hand-operated valves to raise water from mines by suction produced by condensing steam. Around 15 years later, Thomas Newcomen developed a more efficient steam engine which was greatly improved by James Watt in 1765. Watt added a separate condenser to avoid heating and cooling the cylinder with each stroke and then developed an engine that rotated a shaft instead of just performing the up-and-down motion. William Symington developed the first practical steamboat in Scotland in 1802, the tug Charlotte Dundas. And in 1807, Robert Fulton applied the steam engine to a passenger boat in the United States. [11] [12]

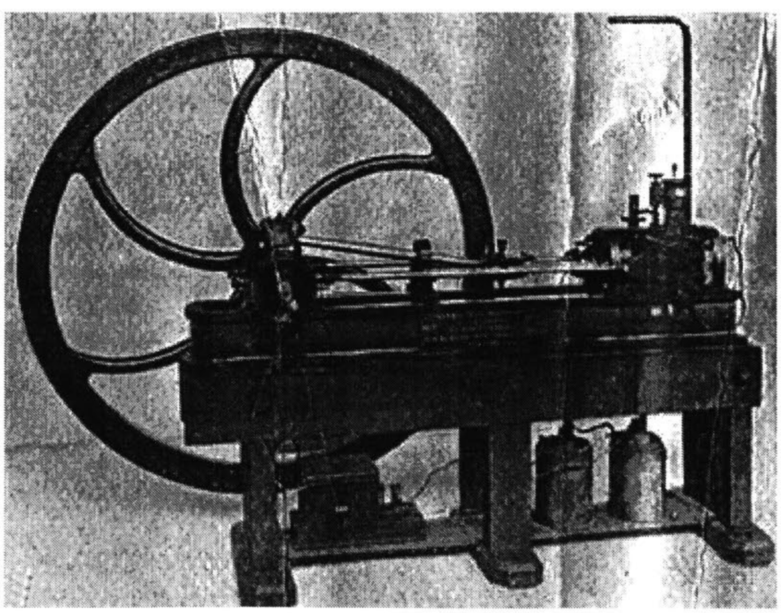


Figure 1: Jean-Joseph-Etienne Lenoir's steam engine [2]

By 1838 the use of the stationary steam engine was largely stabilized in the United States. The best types of steam engines for steamboats and locomotives were known and used [11]. In 1878 the Herreshoff brothers created a firm which built steam-powered vessels. For this thesis, one of the engines used in their steam-powered vessels will be converted to CAD and fabricated as a part of a curriculum for the MIT Pappalardo Senior Apprenticeship Program.

The MIT Pappalardo Apprenticeship Program is a two-year program that provides machining experience for juniors and seniors studying mechanical engineering at MIT. For juniors, the program consists of mentoring students taking 2.007 Design and Manufacturing I. In addition to mentoring, juniors are responsible for machining and assembling a working sterling engine from a parts kit provided at the beginning of the term. The program educates them on speeds and feeds for different machines and materials, safety measures to take in machine shops, precise machining using mills and lathes, and using indicators to check the quality of the parts they have machined. Senior apprentices that return to the program for a second year as seniors are given the task to fabricate an engine from scratch. The first year the seniors fabricated an engine it was a 2-stroke Atlantic marine engine, for the second year a Herreshoff marine steam engine was made. This program teaches its apprentices to become mechanical engineers and mentors who can pass on their acquired knowledge to others.

2 Herreshoff History

Captain Nathanael Greene Herreshoff, also known as "the Wizard of Bristol", was a naval architect and steam engineer born in Bristol, Rhode Island on March 18, 1848. In 1870, he graduated from Massachusetts Institute of Technology after completing a three year special course in Mechanical Engineering. After graduating from MIT, he worked with the Corliss Steam Engine Company in Providence, Rhode Island as a designer/draftsman. In 1878, he partnered with his brother John to create the Herreshoff Manufacturing Company. Nathanael was attributed as being an innovative boat designer, an accomplished sailor, talented naval architect and steam engineer. He died on June 2nd, 1938 at the age of 90. However, two of his sons, Sidney Dewolf Herreshoff and Lewis Francis Herreshoff, continued to work as yacht designers. [3] [4] [5]

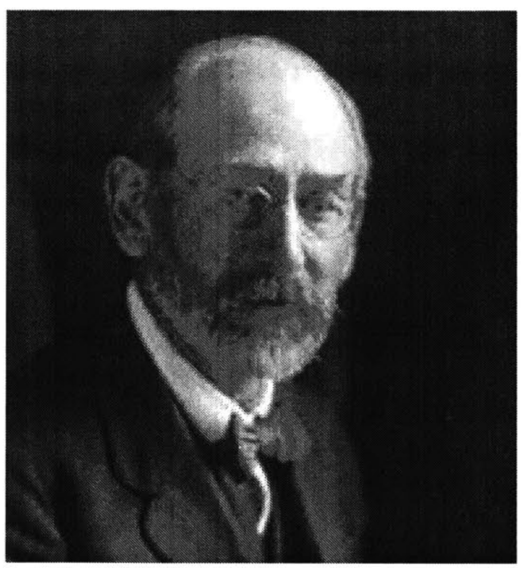


Figure 2: Nathanael Herreshoff [3]

2.1 The Herreshoff Manufacturing Company

John Brown Herreshoff, Nathanael's older brother, alongside other family members, had been building boats in their home property in Bristol Rhode Island for several years. In 1878, however, Nathanael Herreshoff went into partnership with his brother John to create a firm dedicated to building boats and engines called the Herreshoff Manufacturing Company. John, worked on the business side of the firm, while Nathanael dealt with the engineering aspects of the company. Together, they grew the business from about 20 employees to over 400. [3]

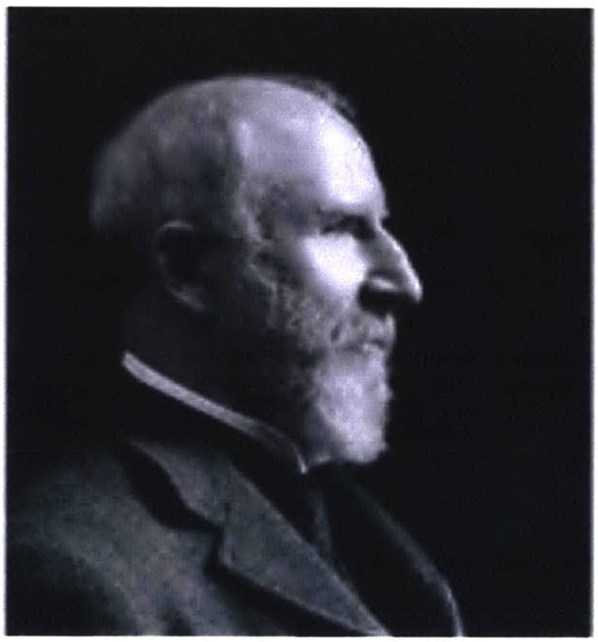


Figure 3: John Herreshoff [3]

For the first several years after the firm was founded, the company focused on building steam powered vessels for private and military customers. They eventually moved on to building torpedo boats for the US Navy. In 1893 they began building sloops to defend the America's Cup. This lead to the creation of seven of the biggest, most powerful and complex sloops in history. Five were selected as defenders for the America's Cup and all five were victorious. [3] [5]

The Herreshoff brothers maintained 100% ownership of the Herreshoff Manufacturing Company from 1878-1915. Within a year of John passing away in 1915, the trustees of his estate sold their interest in the company. Soon after Nathanael also sold his interest to wealthy yacht owners from Boston and New York. In 1924, the Herreshoff Manufacturing Company was put up for auction and was bought by Rudolph F. Haffenreffer who, like Nathanael, was a MIT alumni. The company kept building vessels throughout WWII but finally closed down in 1945. [3] [5]

Figure 4: Herreshoff MFG.CO. Bristol R.I. [3]

3 1987 Herreshoff Torpedo Boat Circulating Steam Engine

The engine selected for this thesis was a recirculating steam engine used in an 1897 Navy torpedo boat, the USS Talbot. The USS Talbot was laid down on the 8th of April 1897 by the Herreshoff Manufacturing Co. in Bristol, R.I. It was launched on November 14th, 1897 and commissioned on April 4th, 1898. The torpedo boat traveled many places including, Maryland, Virginia, North Carolina, Cuba and New York. On May 1st, 1912 it was inactivated but retained "in service" as a ferry operated between the Washington Navy Yard and the naval facilities at Indian Head. It was later renamed to Berceau on 11 April 1918. Finally, on June 18th, 1940 it was placed "out of service". The USS Talbot or now Berceau was stricken and sold for scrap four years later. [6]

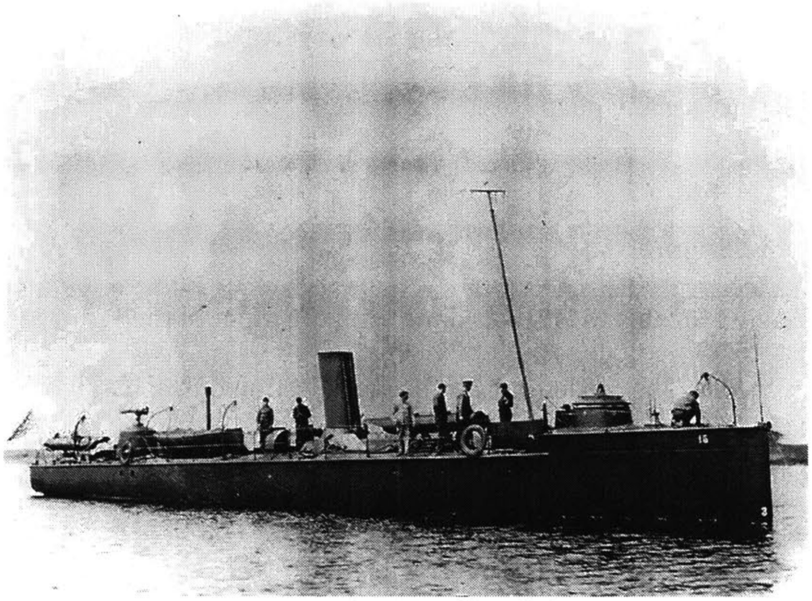


Figure 5: USS Talbot [6]

The engine was used to forcibly and continuously circulate the water in the tube boiler to prevent local steam pockets from forming within the propeller engine used to propel the USS Talbot. If the pockets were left to form it would have resulted in local metal overheating and the tube being damaged meaning that this engine greatly increased the lifespan of the USS Talbot.

3.1 How Steam Engines Work

In general, steam engines function by hot steam expanding under pressure converting heat energy into work. The engine selected for this thesis works by having steam enter through the intake valve and push the valve upwards, this opens channels that allow the steam to move into the piston side of the cylinders. The steam moves the piston to one side allowing steam from the previous cycle to escape through the exhaust. Steam is let in again and now it travels through the channels on the other side as that is the side that is now open. This again pushes the piston in the opposite direction as before and so on. The piston and valve are connected to a crank shaft which turns this steam vertical energy into rotational energy that can be used to serve many purposes.

3.2 Selecting the Engine

Selection of the Engine for this thesis was done with the input of the Francis Russell Hart Nautical Museum at MIT. The Museum has a broad selection of steam engine plans divided into folders. The first step was to look at the folder names within the Series V Drawings of the "Guide to the Haffenreffer-Herreshoff Collection". Based on the sizes of the steam engines within the folders, folder 12 (Steam Engines – Primarily 4" and 5" Stroke) and folder 13 (Steam Engines – Primarily, 3", 3 ½" and 4" stroke) were chosen. The Francis Russell Hart Nautical Museum sent an excel file containing all the plan names contained within the two folders. Based on this the search was narrowed down to engines within folder 13, an archiving system used by the Herreshoff Manufacturing Company. PDF versions of the plans within folder 13 were evaluated and two engines were picked for closer inspection of the physical plans, alongside Kurt Hasselbalch; the 3 ½" by 3 ½" circulating engine and the 3" by 3" Electric Light Engine.

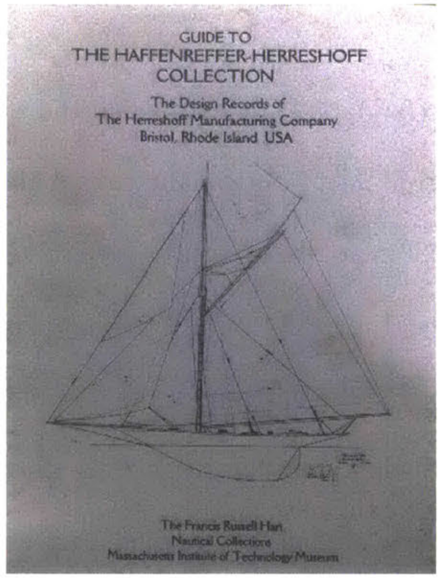


Figure 6: Guide to the Haffenreffer-Herreshoff Collection [5]

The 3 ½" by 3 ½" circulating steam engine was selected for its size, part count, plan completeness and clearness, the estimated amount of work to be divided between the seven Pappalardo Senior Apprentices and finally, the history behind the torpedo boats. The engine had to be small enough so that all the parts to be cast could be completed in the Merton C. Flemings Materials Processing Laboratory at MIT with the help of Mike Tarkanian.

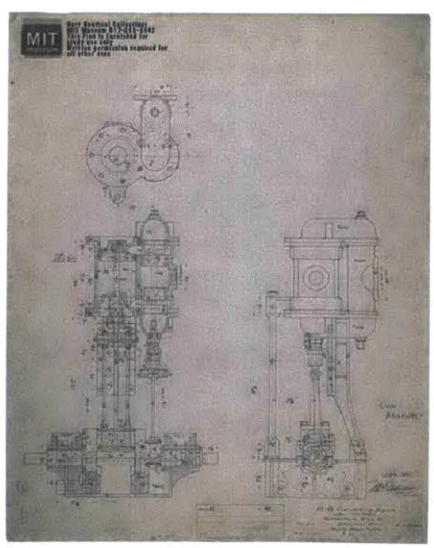


Figure 7: Assembly Plan for the 3 ½ by 3 ½ circulating steam engine

3.3 From Plans to CAD

From September-December 2016 CAD was developed for the entire engine from the plans borrowed from the Francis Russell Hart Nautical Museum at MIT. This proved to be a challenge for multiple reasons. Some of these drawings were very complicated and all the views were not available for all of the parts. Some drawings also had pattern numbers which corresponded to a drawing of the pattern for the part illustrated. Those pattern drawings were not available, which meant that some of the details were not dimensioned. However, a ruler and the scale indicated in the drawing were used to get a close estimate of various dimensions.

Figure 8: Assembly CAD for the 3 ½ by 3 ½ circulating steam engine

The next step taken after creating all the CAD for the engine was to assemble the group of senior apprentices to work on the engine and divide the most challenging parts equally to commence fabrication.

4 Casting Process

For centuries the art of casting has been used to make anything from primitive tools to steam engine components in the 19th century, to intermediate compressor casings for turbine engines in the present day. With simple resources like sand, clay, ore, and charcoal, useful parts can be formed. In general terms, casting is the process of pouring molten metal into a mold cavity with a desired shape in order to duplicate that cavity shape in metal. The mold is made by packing sand around a pattern which is the size and shape of your desired casting. Sand casting is a way of making complex parts with hollow insides that cannot be machined. There are many metals that can be machined and various temperatures at which to cast them. The table below shows pouring temperatures for some casting alloys.

Table 1: Pouring Temperatures for Casting Alloys [8]

Casting Alloy	**Pouring Temperature(°F)**
Aluminum	1148-1328
Magnesium	1148-1328
Copper	2102-2354
Copper-Chromium	2192-2300
Copper-beryllium	1850-2300
Copper-tin	1922-2300
Copper-lead-tin	1850-2102
Copper-aluminum	2048-2300
Copper-zinc	1760-2120
Copper-nickel	2462-2642
Nickel-copper	2498-2732

Grey iron	2444-2696
Cast steel	2732-3092
Titanium	3092-3272
Zinc	788-1076

A diagram of the components of a casting mold as well as definitions needed to understand the casting process can be found below. [1] [7]

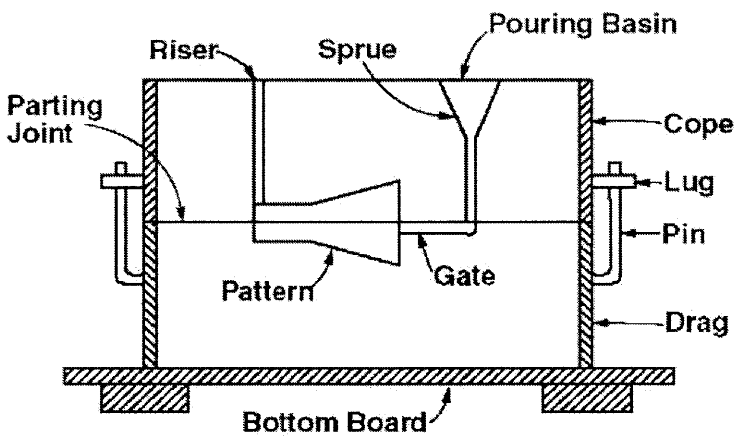


Figure 9: Diagram illustrating a casting mold and its components [9]

Flask Box that contains the sand that makes up the mold. It hold the sand in place with a lip around its top and bottom edges.

Cope and Drag The upper and lower halves of the flask, respectively.

Pattern Used to make the mold into which metal is poured, it should be the size and shape of the desired casting. Typically made of wood, plastic, metal, foam, or anything that can indent the desired shape into sand and be released easily from the mold.

Core	To create hollow cavities within the casting. If large enough, they should be hollow to allow the core to vent or allow heat to escape. Typically made out of sand, metal or anything with a higher melting point than the pouring temperature of your chosen metal.
Core Mold	Mold used to make the core when it is of sand or a material that can be molded. Can be made out of plastic, metal, foam, wood, etc.
Parting line	Also known as joint, is where the cope and drag meet. A well placed parting line has a significant effect on the quality of your part.
Sprue	The main channel where the metal gets poured. Usually has a funnel shape cut out at the top for ease of pouring. The sprue leads to runners.
Runner	Series of channels that connect to the sprue and end in the gate. These channels transports the molten metal to the empty mold cavity, filling it with metal.
Riser	Also known as feeder is a chamber that fills with molten metal providing creating a reservoir to compensate for losses due to shrinkage as the metal solidifies.
Vents	Passages that allow gases to escape the cavity when the mold is poured.
Rammer	Tool used to pack sand into the molds.
Sieve	Tool used to separate coarser materials from the sand. This also makes the sand finer so that it can provide more details and a nice finish on the cast part.

Facing Sand	Sand that is packed around the pattern an produces the surface in contact with the molten metal.
Gate	The portion of the runner where the metal enters the cavity of the mold.
Draft	Taper added to vertical walls of patterns in order to allow it to be removed from the mold without tearing the sand.
Shrinkage	The amount a part contracts during solidification.
Green Sand	Sand commonly used in casting to make molds. It is moist and bonded using clay.
Resin Sand	Chemically bonded sand used for casting.
Melting Point	The temperature at which a solid changes state from solid to liquid.
Pouring Temp.	The temperature the molten metal needs to be raised to before being poured.
Machinability	How easy it is for a material to be machined permitting the removal of the material with a satisfactory finish at a low cost
Castability	How easy it is for a material to be used for forming a quality casting permitting easy development, minimal tooling costs, minimal energy, and few rejections.

A typical casting process is shown below.

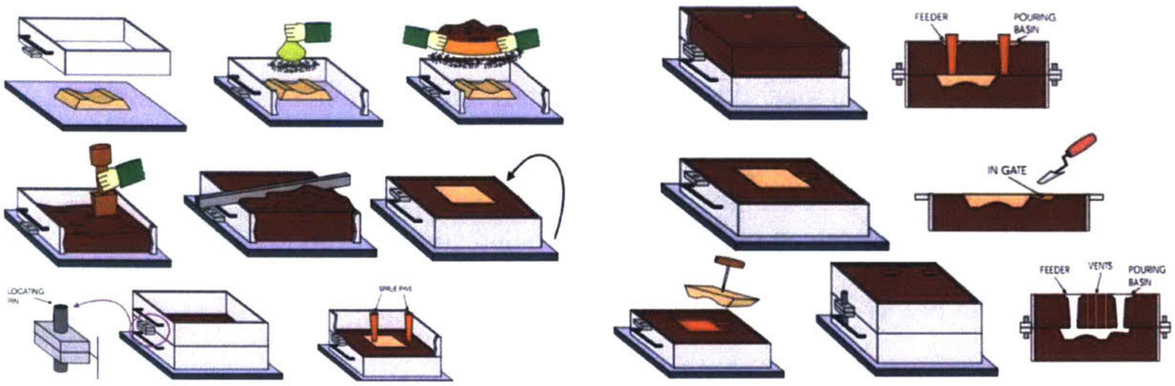


Figure 10: Diagram showing the casting process [10]

1 Pattern half is placed on the molding board and the drag flask is placed on top of it.

2 Sand is packed around the pattern and the rammer is used to compress the sand as much as possible

3 Excess sand is taken off using a straight board to create a flat surface on the top of the mold

4 Drag is rolled over and the cope flask is secured on top.

5 If applicable, the other half of the pattern is placed and sand is again packed around the pattern but this time a sprue and riser are placed.

6 Molds are separated, the patterns are taken out and a gate is made.

7 If necessary, vents are added to the mold.

8 Finally, the metal is poured through the sprue.

4.1 CAD for Casting

CAD needs to be modified for casting. Before modifying the part, however, there should be a final version of the machined part saved separately in order to use it later for post machining purposes and to keep a record of the final engine. Some of the modifications usually made include adding drafts and scaling parts depending on their material shrinkage when cast. For some patterns other changes are made like splitting the pattern into multiple segments in order to machine them separately and put them on a pattern board. Small machinable features are removed to minimize the number of cores used. After these changes are made, the pattern can be machined. Detailed steps for modifying CAD for casting can be found below using the example for the Bottom Cap.

1. Make sure that the method preferred for fabricating the part is in fact casting. Sometimes it is easier and more efficient to machine parts instead of casting them. This applies to parts that need to be made out of materials with low castability and that might be thin and structural.

2. Determine where parting line will be, how many cores will be needed, and how many patterns will need to be fabricated. Also determine if the use of a pattern board would be beneficial. For the bottom cap a pattern board was used.

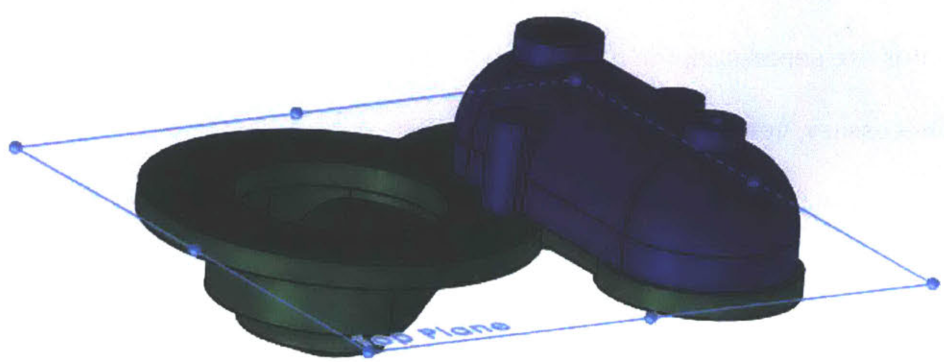


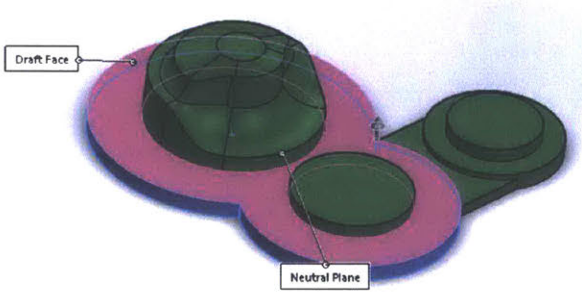
Figure 11: Bottom cap CAD showing the plane used as a parting line and to split pattern (Refer to Figure 8)

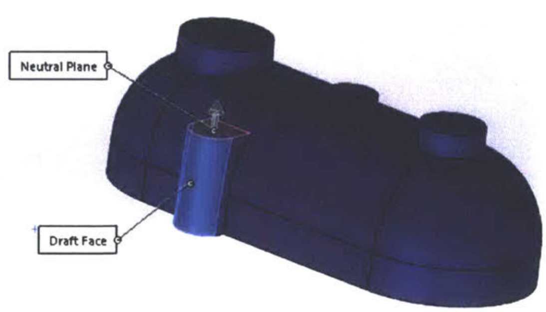
3. Once you have multiple solid bodies, save them as individual parts. These individual parts will serve as your pattern CAD.

4. Remove small holes and features that can be easily post machined and fill in the hollow areas. These hollow areas will later be made into cores but are unnecessary for the purpose of fabricating the pattern. Save these modified parts as copies for patterns.

Figures 12 & 13: Holes and hollow areas are filled in

5. Add draft on the outside of part, making sure that it is in the correct direction to make it easy to remove the pattern from the sand mold.





Figures 14 & 15: Draft is added to parts

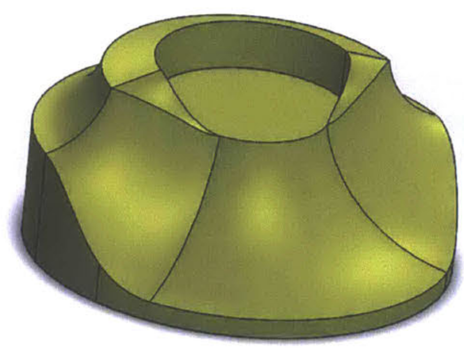
6. Add fillets on outside corners to make it easy to remove the pattern from the sand mold.

Figures 16 & 17: Fillets are added to parts

7. Apply a scaling factor that corrects for the shrinkage of the material when cast.

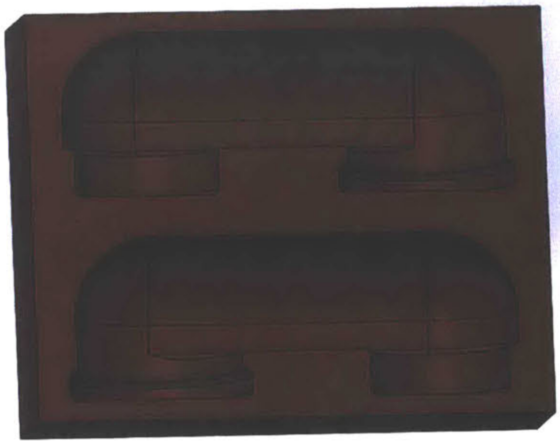
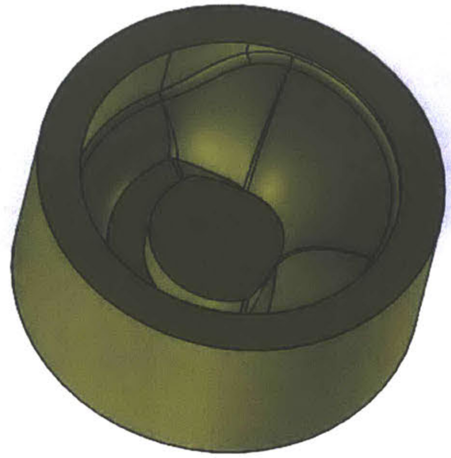
8. For hollow cavities within parts, cores need to be made. The bottom cap had two cores, one for the channel that lets smoke escape from the cylinders to the exhaust, and another for the inside of the cap dome. Open the two individual parts from before. Using the cavity tool in SolidWorks it is possible to get the hollow shape and make it solid and get rid of the rest of the body. Save parts as copies for cores.

Figures 18 & 19: Core replicas are made using cavity tool

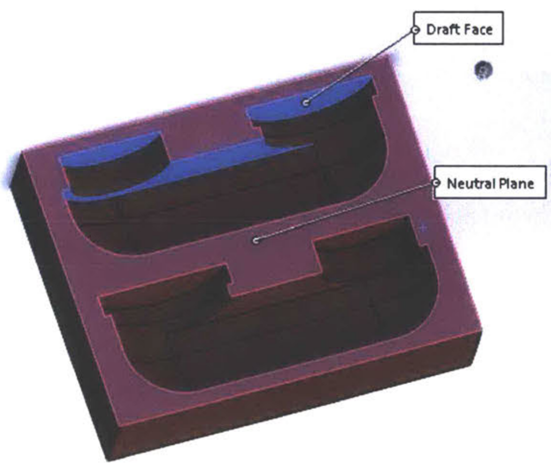
9. Apply scaling factor that corrects for the shrinkage of the material when cast.

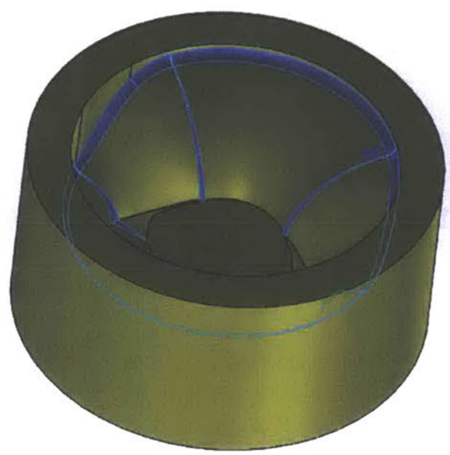
10. Cores for casting are made out of resin sand and thus a mold is made to shape the sand. Using the cavity feature again you can get the shape for the molds that will be used to make the cores.

Figures 20 & 21: Core molds are made using cavity tool

11. Add draft and fillet to the inside of the molds in order to make it easier to remove the resin sand cores from the molds.





Figures 22 & 23: Drag and fillets are added to core molds

5 Pattern Making

Patterns are made to look like the desired part. Anything that can be rammed into sand and removed to leave a clean cavity can, in theory, be used to make a pattern. Common materials used for patterns include wood, plastic, wax and parts that want to be copied. For this thesis, patterns were made using rigid polyurethane foam.

5.1 Rigid Polyurethane Foam

For this engine, most patterns and core molds were machined using rigid polyurethane foam. This foam proved to be easily machinable, more so than plastic and wood. To machine this foam a programmable 3-axis mill in the Pappalardo lab was used. HSM works was used to program tool paths. The tool paths were chosen based on the tool library and the available shop tools. After the gcode was generated from HSM works, it was uploaded into the mill and the mill set up to run the program. Measures needed to be taken before machining in order to ensure that the foam sticks properly to the wooden board holder which was placed on the mill. The process for prepping the foam and board can be found below:

1 Cut foam to the size of the stock box programmed in HSM works.

2 Remove any foam dust left over from cutting using compressed air.

3 Wipe down the bottom of the foam block with alcohol, and leave to dry.

4 Spray a layer of clear paint on the bottom of the foam block.

5 The wooden board is also wiped down with alcohol and left to dry.

6 Attach foam to the wooden board using double sided tape with canals left in between the tape strips. These channels are left to remove the part after machining.

When removing the foam pattern from the board after machining is finished, denaturalized alcohol is poured in between the foam and wooden board. The alcohol seeps through the canals and makes removing the foam less of a hassle.

Finally, after the foam is machined, it is sanded down to get a smooth surface that is easy to pull out of the sand after it has been packed around the pattern.

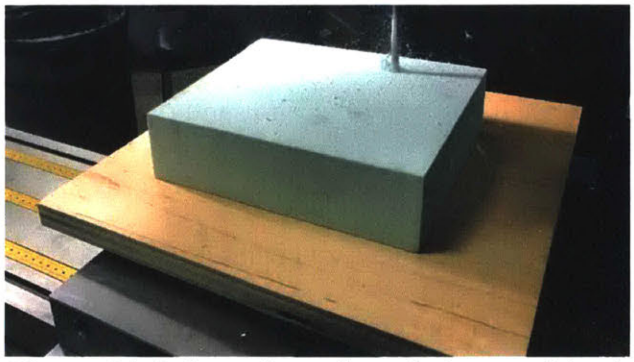


Figure 24: Polyurethane foam being machined

Some of the benefits of using rigid polyurethane foam for pattern making include the ease of machining, and how fast patterns can be made. The drawbacks to using this method include; if not properly prepped, the foam can stick to the sand used for making molds and the mold can be damaged when the pattern is removed, polyurethane foam dulls the tools, and HSM works or Mastercam must be used to program a 3-axis mill which doubles the amount of time spent getting the pattern ready to be made.

5.2 3D printing

Last year, Samantha Castellanos who was a senior apprentice in 2016, wrote a thesis in which she described the use of 3D printing for pattern making. [13] Some of the benefits of this method are that once you start the 3D print you do not have to look over the part or change tools, and that no extra programing is needed, only saving the part as a stl file. However, some of the drawbacks include the cleaning process for 3D printed parts and how long it takes to print parts. Printing one of these parts can take up to 24 hours and, to get rid of support material, the parts need to stay in an caustic solution bath for at least an additional 6 hours. After the part is cleaned there are still surface imperfections. In order to get rid of these you can fill in the line gaps using wood filler and then sand the part. Another thing you can do is leave the part in a bucket full of acetone vapor and have it slowly melt the surface smooth. If you add filler and sand the part down this could take several more hours as filler takes around 30 minutes to dry fully and sanding by hand is a slow process. After the part surface is where you want it to be you are ready to use it to pack sand. The 3D printed part with the correct draft, was easy to take out of the mold, sand did not stick to it much and it left the correct cavity for the part needed to be cast. [13]

6 Types of Sand for Casting

There are different types of sand that can be used for casting depending on your needs and budget. The two main types used in the MIT foundry are resin sand and green sand. Green sand is the most commonly used and is very inexpensive, however you are just using the moistness of the sand and pressure in order to have it maintain its shape, this can work but if not properly pressured the mold can easily break apart. On the other hand, the resin sand uses a type of adhesive so that it does not come apart as easily but you have to deal with chemicals that are toxic and expensive. The two types of sand are described in more details in the following sections.

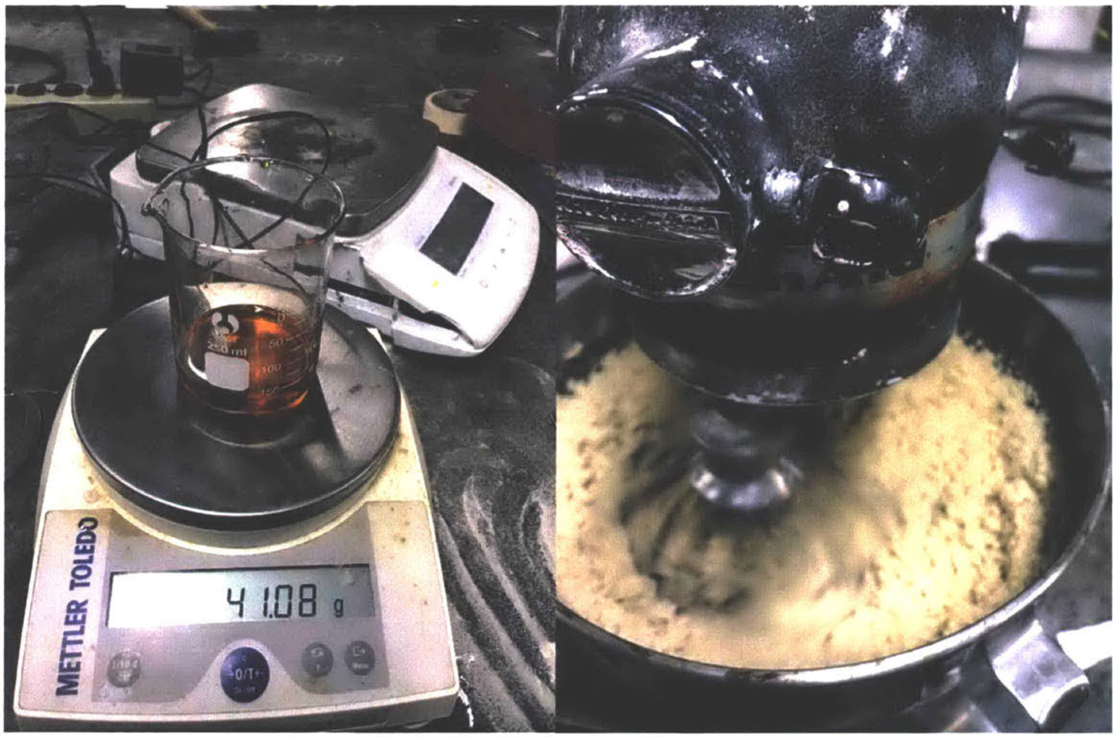
6.1 Resin Sand

The resin sand used for the engine is made up of Kenset R binder and a sulfuric acid catalyst. This binder is 6.5% Nitrogen, 10-12.5% water and maximum 5% free formaldehyde. Resin sand is made by adding 3% of the total of the weight of the sand you are going to use of the resin and mixing them together. From that total 3%, 2% comes from the binder and the other 1% comes from the catalyst. This sand is good for making cores because it is bonded together using adhesive and it is unlikely to come apart. It also provides more accurate dimensions for your part and a smoother surface. However, the resin is expensive and the chemicals used to make this sand are toxic. Another downside to using resin sand is that if packed too tightly, it can be challenging to remove pattern from the mold after the sand has set. The process for making resin sand can be found below:

1. Make sure to wear gloves when working with resin sand.
2. Determine how many grams of sand you will need. Weight it and place it in a mixer. Make sure that you zero the scale before anything is weighed.

Figure 25: Sand is weighted and placed in mixer

3. Measure 2% of binder using the same scale. Account for the weight of the beaker that is being used. Slowly add it to the sand. Mix at a slow speed. Increase speed and mix until sand is evenly colored and mixed.



Figures 26 & 27: Binder is added and mixed

4. Measure 1% of catalyst using the same scale making sure to account for the weight of the beaker. Add it slowly and evenly to the sand and binder mixture. Mix at a slow speed and increase speed until sand is evenly colored. At this point the sand should look light green. If there are still parts that aren't green, it might be best to turn mixer off and mix sand by hand.

Figures 28 & 29: Catalyst is added and mixed

6.2 Green Sand

Contrary to what the name might suggest, the sand is a brown or tan color. It gets its name because it is not baked or cured before the molten metal is poured into the mold, rather because it is wet. Green sand is silica sand which contains clay as a binder. This sand is very inexpensive and easy to deal with, it has no strong smell or harmful chemicals. However, if not packed properly, it can fall apart easily as it does not actually have any adhesive holding it together. Another downside to using this type of sand is that more of the details on the cavity get lost and parts are not as smooth or dimensionally accurate as they would be with resin sand.

7 Core Making

Many times complex parts with internal channels or features need to be cast. These features are attained by creating one or more cores. Cores are made out of resin sand and are placed and fixed on your cavity so that when you pour the metal, it fills everything around your core but not the core itself. This means you will have a metal part with a sand part inside it which you will latter break off and be left with a channel. Cores are commonly packed in halves and glued together using an acetone based adhesive.

Figure 30: Core halves are glued together using an acetone based adhesive

8 Bottom Cap Casting

The CAD for the bottom cap was altered by adding draft in any vertical wall so that it would be easy to pull out the pattern and part from the sand mold. Also, a 1.01 scaling factor was used on all the patterns and core mold because the material being used is iron which tends to shrink by approximately 1% when cast. For the bottom cap, it was decided to make a pattern board because its geometry was complicated. This way, there was one fewer core to insert to the cavity. The pattern board then had three distinct patterns attached to it. All three patterns and the core mold were done with the rigid polyurethane foam. The step by step process for casting the bottom cap can be found below:

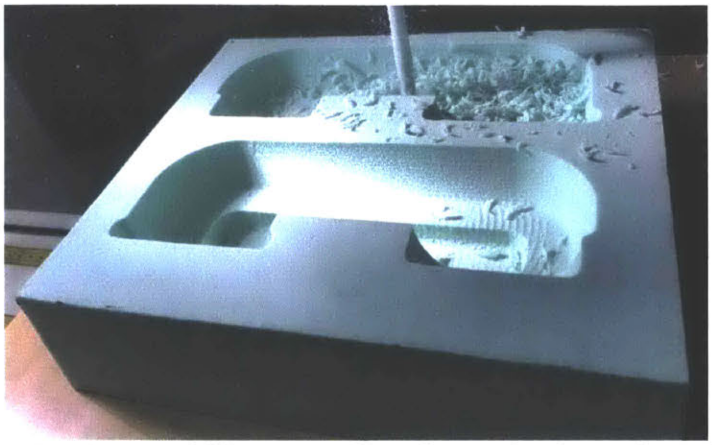


Figure 31: Core mold being machined out of polyurethane foam

1. Tool paths were typically generated using a succession of tools, from large tools intended for rough machining and fast material removal to smaller ball end mills for higher resolution surface finishes.

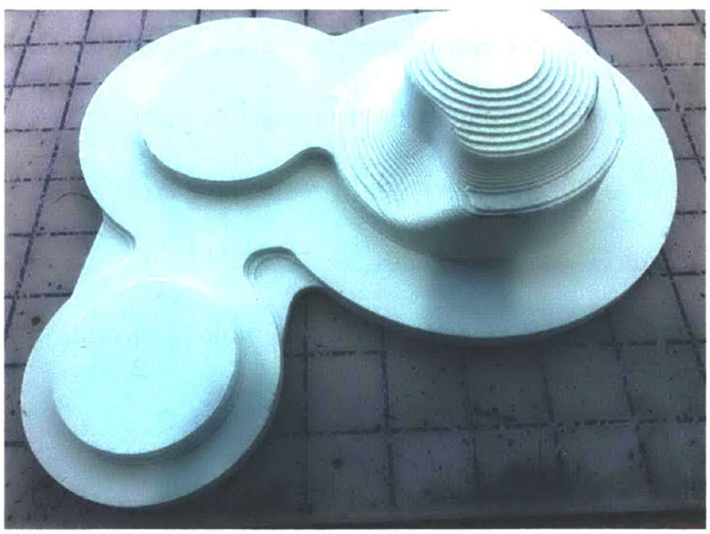
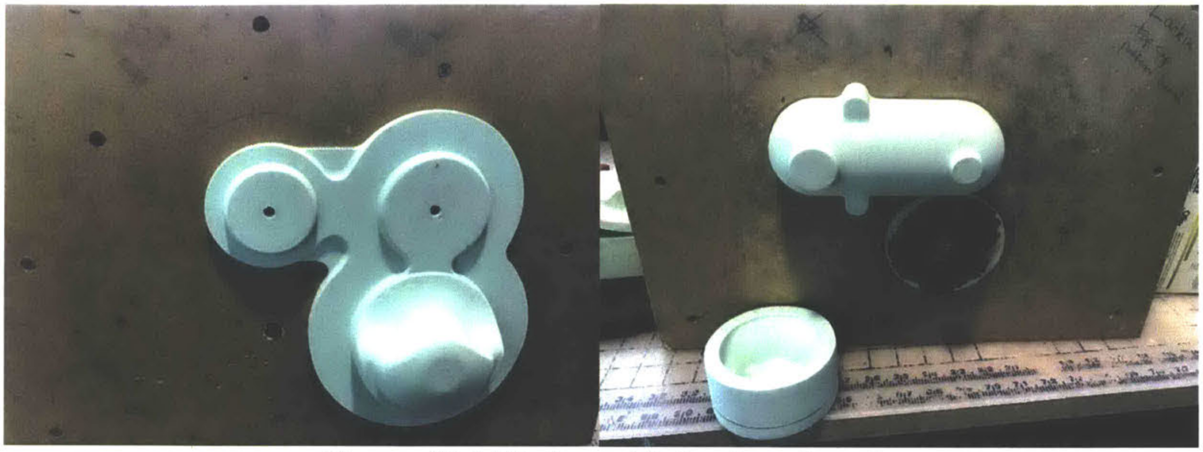


Figure 32: Pattern after machining

2. Holes were drilled into the patterns in order to fit ¼" alignment dowel pins. These pins were used to keep the patterns in place on the pattern board.



Figures 33 & 34: Assembled pattern board

3. In addition to the three patterns for this particular part, a core mold was also made using the rigid polyurethane foam. This core mold was for an internal pathway inside the cap that allows the steam to escape to the exhaust cylinder.

4. The rigid polyurethane mold was prepped by adding baby powder all around it to make it easier for the core to eject from the mold.

5. The mold was then filled with a layer of resin sand. A cavity was left in the middle of the core as a vent for escaping gases.

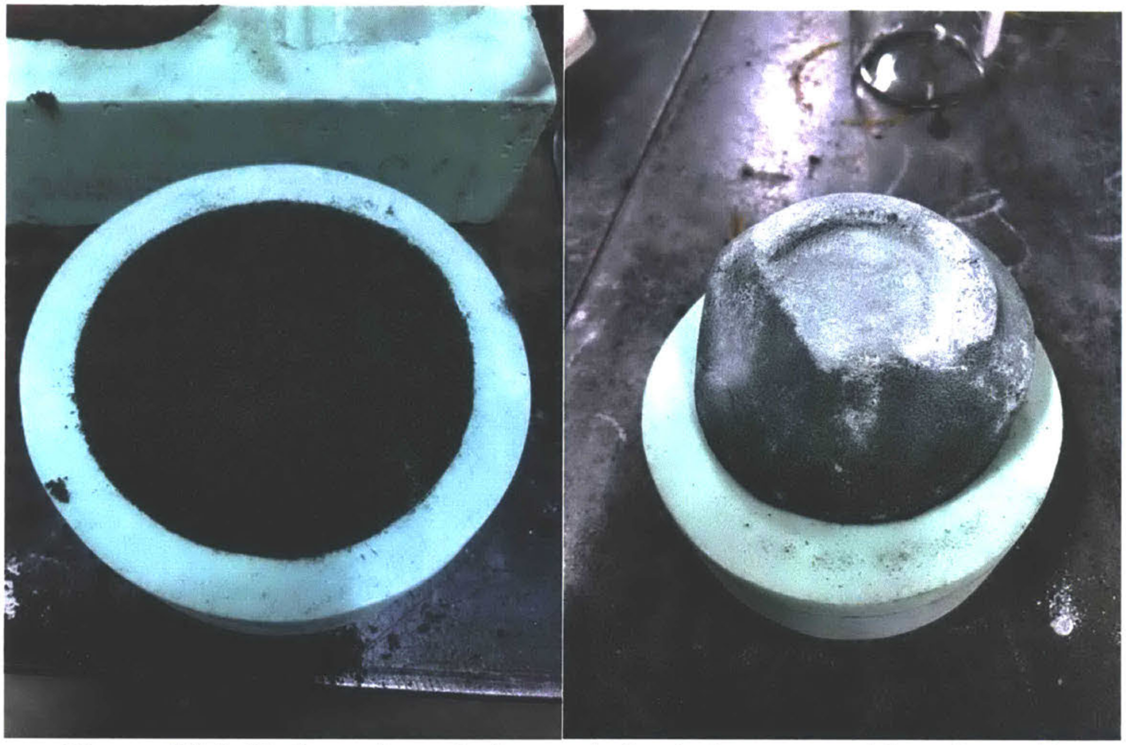
6. The two core halves were removed from the mold by prodding the part using a flat screwdriver.

Figure 35: Core halves after being removed from core mold

7. The acetone based adhesive was used to glue the two core halves together.

Figure 36: Two core halves glued together using an acetone based adhesive

8. A second core was molded to obtain an internal feature of the cap using the same steps 4-6 that were used for the first core.



Figures 37 & 38: Second core before and after being removed from its mold

9. Pattern board was secured onto the flask and baby powder was placed all over the pattern to allow for easy removal of the mold afterwards.

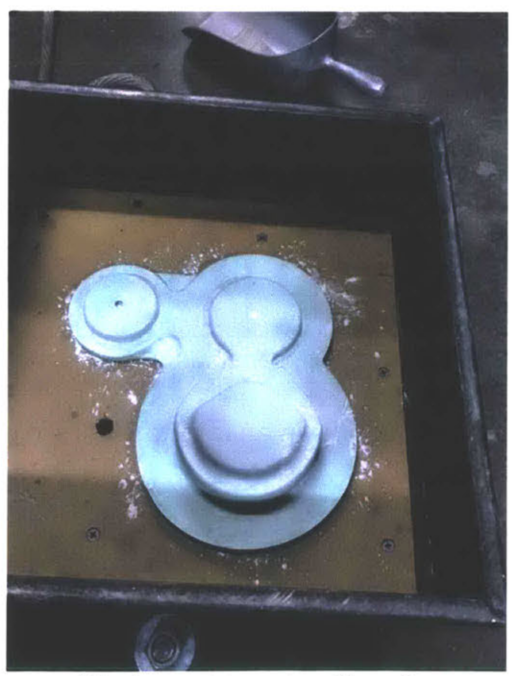


Figure 39: Baby powder was added to pattern to allow for easy removal from sand mold

10. The mold was packed using green sand. Sand was passed through a sieve in to get finer sand that would show greater details on parts and would provide greater surface finish.

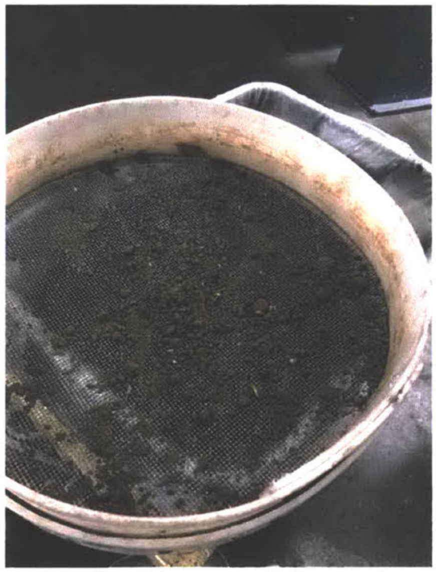


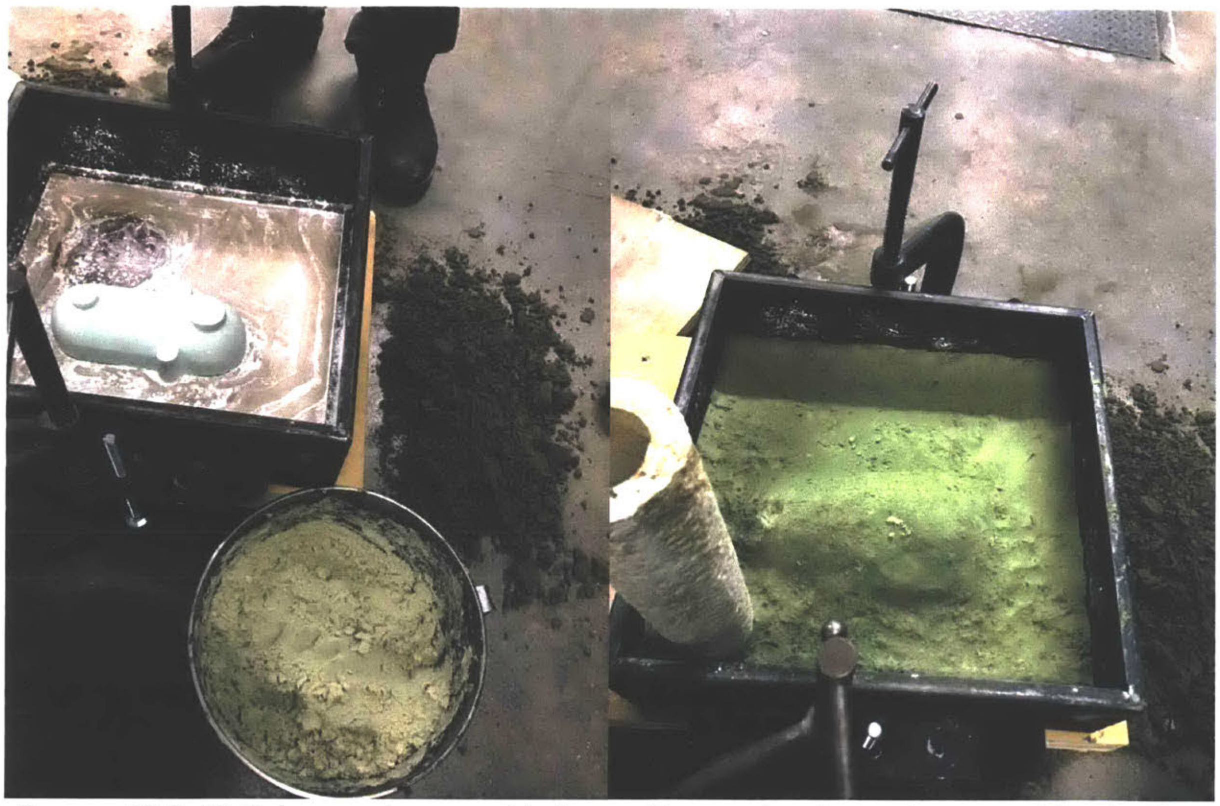
Figure 40: Sand is passed through a sieve

11. Several layers of sand were placed and after each layer, the sand was compressed by hand as well as a rammer to make sure the mold would not break apart.

Figure 41: Rammer is used to pack sand tightly

12. The mold was over packed with sand and a flat board was used to flatten out the top of the mold.

13. After all the sand was well packed and solid, the box was turned over and another box was placed on top of the other side of the pattern board. Baby powder was again added to the pattern. On the other side it was decided to place a layer of the resin sand over the pattern to achieve a better surface finish and precision.



Figures 42 & 43: Baby powder was added on pattern and resin sand was used for the first layer of the mold

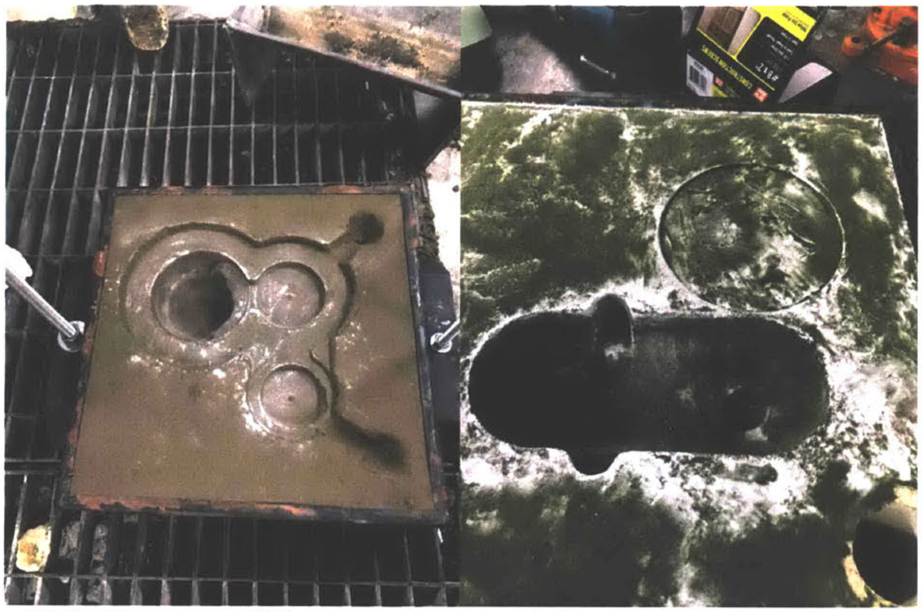
14. The rest of the mold was then packed using the same process as before. On this side, however, the sprue, where the material would be poured into, was inserted before the sand was packed.

Figure 44: The sprue was added and green sand was used to pack the rest of the mold

15. The mold was over packed with sand and the excess sand was removed using a flat board in to have a smooth mold.

Figure 45: Flat board was used to remove excess sand and achieve a flat surface on mold

16. After both sides were packed properly the two halves were taken apart and the pattern board was removed.



Figures 46 & 47: Two mold haves were separated and pattern board was removed

17. For the case of the cope, the pattern remained attached to the mold instead of the pattern board and thus two holes were drilled into it and screws were used to pull the pattern out of the mold.

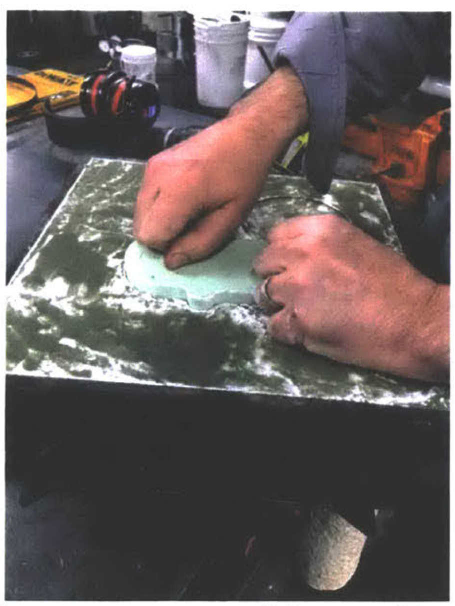
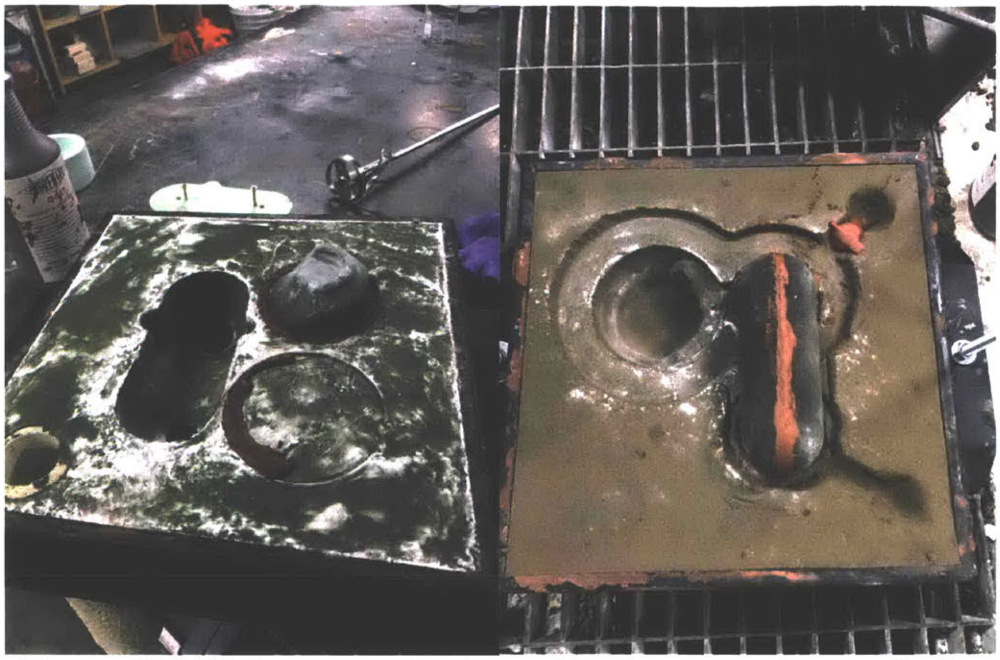


Figure 48: Pattern was removed from mold using screws

18. The core was inserted and bonded to the mold with an acetone based glue. More resin sand was also added around the cavity to minimize flash.



Figures 49 & 50: Cores were glued to mold using acetone based adhesive

19. The two halves of the mold were put back together and clamped shut.

Figure 51: Mold clamped shut and ready for pouring

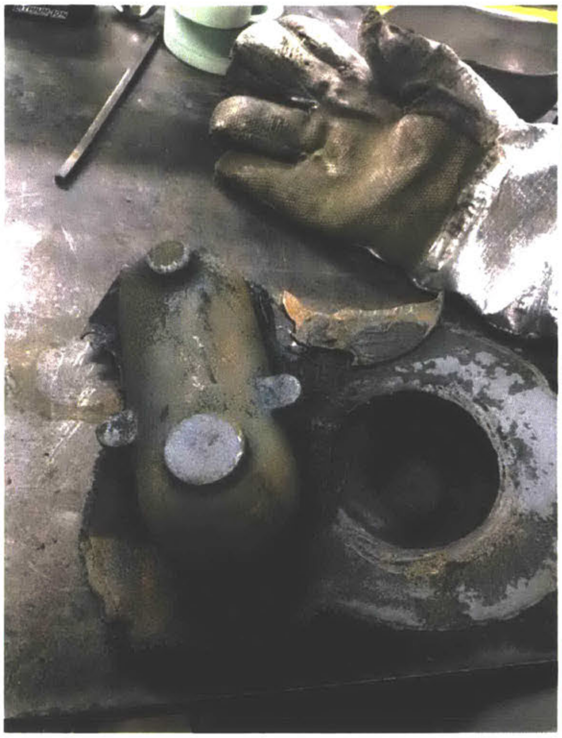
20. The grey iron was melted, poured through the sprue.

Figures 52 & 53: Metal being melted and mold after metal being poured through the sprue

21 In this case, some of the cast iron was accidentally poured on the outside of the sprue. Endeavor to pour through the sprue; to avoid molten iron spills.

Figure 54: Aftermath of sprue exploding

22 After waiting several hours, 5 hours in this case, the mold was opened and the part was removed.



Figures 55 & 56: Bottom cap removed from mold after 5 hours of cooling

8.1 Top Cap Hardening and Annealing

During the casting process for the top cap made by another of the apprentices, Larkin Sayre, the part was removed too quickly after it was poured. This caused the part to harden because of the rapid cooling. The part had flash around the edges that needed to be removed but because the part was hardened it wasn't possible to do with the available machinery.

To fix this, the part was annealed. Annealing consisted on placing the part inside an oven at 1400 degrees Fahrenheit for one hour and decreasing the temperature by 200 degrees every hour until reaching a final temperature of 100 degrees.

9 Post-Machining

After the part is cast, there is extra material that should be machined off and there are also features that need to be made like holes that need to be added after the casting as post-machining. For the bottom cap, several holes need to be drilled and the interface to the cylinder needs facing to obtain a completely flat sealing face.

10 Curriculum Refinements

The curriculum for this program is different than from last year as all the CAD was done before the start of the program. Only checking of the CAD was needed at the beginning. Each student was responsible, however, to make the necessary CAD changes for casting purposes. After this, each student had to take a major component of the engine and go through the casting process for their part. When casting was completed, machining of some other smaller parts was divided among all the students. Of the 14 weeks of the semester, the first 2 weeks would be used to check CAD. During this time, as well, students are expected to gain an understanding of steam engines, how they work and how this specific engine was used. The next 2 weeks would be used to modify the CAD by adding drafts, scaling, etc. The next two weeks would be devoted to CAM, creating the tool paths and HSM works gcode to program the mill to machine the patterns and core molds. The next 4 weeks would be used to machine all the patterns, make changes if necessary to casting CAD and HSM works code. The next 2 weeks would be used to cast the parts. The next 2 weeks would be used to machine the rest of the necessary parts and assembly of the steam engine. The table below shows the suggested schedule. Not accounting for the inevitable revisions.

Table 2: Suggested Curriculum for MIT Pappalardo Senior Apprenticeship Program

Week	Lecture	Work
1	Steam Engines and how they work	Check CAD
2		
3	Pattern Making	Modify CAD for pattern making
4	HSM works Tutorial	
5	HSM works review	HSM works for pattern milling
6		
7	Casting Basics: Sand types, packing	Machine all necessary Patterns
8	methods	
9	Pouring temperatures, trial and	
10	error	
11	Casting Parts	
12		
13	Part Machining and Engine Assembly	
14		

11 Conclusion

Steam engines as well as casting have been used for many centuries. The Herreshoff Manufacturing Company revolutionized the use of steam engines in marine vessels. Casting is a long and difficult process that requires plenty of patience and practice. Rigid Polyurethane foam is a material that is easy to machine, yet dense enough for pattern making using CNC machine tools. This thesis is intended to aid in the fabrication of future engines for the MIT Pappalardo Apprenticeship Program and to provide a curriculum that can be used in the future.

Acknowledgments

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