Fabricating Sand Cast Parts for a Herreshoff Steam Engine

by

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Abstract

Through a Pappalardo Apprenticeship program, MIT undergraduates in mechanical engineering collaborated to construct an 1897 Herreshoff steam engine for intent for demonstration at an MIT Museum exhibit scheduled to open in fall 2018. With a brief overview of the functionality and inner workings of the engine provided, this thesis focuses on the fabrication process followed in making a sand cast part for this project. Two specific parts exemplify the variations followed in this fabrication process: the iron column and the bronze bearing crosshead. In both cases, the same CAD and CAM practices, pattern fabrication processes, and post-machining techniques were used.

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# Table of Contents

Abstract 3  
Table of Contents 4  
List of Figures 5  
List of Tables 7  
1. Lighter, Stronger, Faster: MIT Museum Exhibit 8  
2. Nathanael Greene Herreshoff 8  
3. Pappalardo Apprenticeship 9  
4. USS Talbot 11  
5. Architecture of the Recirculating Steam Engine 11  
6. Process of Replicating Herreshoff Steam Engine Parts 14  
6.1 Process for Fabricating a Steam Engine Part 14  
6.2 Sand Casting Terms 16  
6.3 Process for Fabricating a Sand Cast Steam Engine Part 22  
7. Fall 2017: Column and Gibs 29  
7.1 Drawing Interpretation and CAD Model 30  
7.2 Pattern Manufacturing 33  
7.3 Properties of Iron 36  
7.4 Packing and Pouring 36  
7.5 Post-Machining 38  
8. Spring 2018: Bearing Crosshead 41  
8.1 Part and Pattern Design 42  
8.2 Pattern and Core Design and Manufacturing 42  
8.3 Alloy Selection, Packing, and Pouring (and Repeating) 44  
8.4 Post-Machining 47  
9. The Completed Recirculating Engine 53  
Acknowledgments 54  
References 55
List of Figures

Figure 1: Announcement for the Lighter, Stronger, Faster MIT Museum exhibit 8
Figure 2: The Pappalardo Apprenticeship application promotion poster [10] 9
Figure 3: The Pappalardo staff and Apprentices from spring 2017 10
Figure 4: The USS Talbot in 1898 [5] 11
Figure 5: Part of the assembly drawing of the recirculating engine [8] 12
Figure 6: An “exploded view” of the engine parts in April 2018 13
Figure 7: A drawing of a view of the bearing crosshead [8] 15
Figure 8: A muller for green sand casting 16
Figure 9: Diagram of components of a sand casting mold [12] 18
Figure 10: Example of shrinkage [13] 19
Figure 11: Example of porosity [13] 20
Figure 12: Example of slag [13] 20
Figure 13: Example of excessive flash [13] 21
Figure 14: Green sand chunks of green sand in a sieve on top of a flask 21
Figure 15: A rammer in use 22
Figure 16: Applying paint on the bottom of foam for pattern making 24
Figure 17: A foam block fixtured for machining a pattern 24
Figure 18: Following the milling tool with a vacuum 24
Figures 19-22: A corebox and resulting core 25
Figure 23: A packed flask half using green sand before pattern removal 26
Figure 24: A flask half after pattern removal 27
Figure 25: A flask half with cores placed and runners cut 28
Figure 26: Melting iron in a crucible 28
Figure 27: The original column drawing [8] 30
Figure 28: The assembly drawing showing the column with a T cross-section [8] 31
Figure 29: The three pattern iterations fabricated for the column 32
Figure 30: The column drawing for a Herreshoff electric light steam engine [8] 32
Figures 31-32: Models of the finished column compared to the cast column 33
Figure 33: The column CAM job in HSMWorks 33
Figures 34-37: Operation toolpaths for column pattern machining 34
Figures 38-41: The machining operations to achieve the column patterns 35
Figure 42: Typical volume change pattern for iron 36
Figures 43-45: Packing the column flasks 37
Figure 46: The flask halves for casting the column 37
Figures 47-49: Pouring, unpacking, and the resulting column 38
Figures 50-51: Establishing initial datums on the column 39
Figures 52-53: Custom vise jaws for fixturing the column 39
Figures 54-55: Machining the bearing surface and gib holes 39
Figures 56-57: Machining the bed plate mounting surface and holes 40
Figure 58: Machining the cylinder mounting surface and holes 40
Figure 59: The original power connecting rod and bearing crosshead drawing [13] 41
Figure 60: The bearing crosshead CAD model 42
Figure 61: The bearing crosshead pattern CAD model 43
Figure 62: The bearing crosshead CAM job in HSMWorks 43
Figures 63-65: Operation toolpaths for bearing crosshead machining 44
Figure 66: Cores for the bearing crosshead 44
Figures 67-68: The second attempt at casting the bearing crosshead 45
Figures 69-70: Shrinkage shown in cross-sections of failed bearing crosshead casts 45
Figure 71: The successful bearing crosshead cast in red leaded brass 47
Figure 72: Drawing used to assist in machining the bearing crosshead 47
Figures 73-74: Establishing initial datums on the bearing crosshead 48
Figures 75-76: Zeroing the mill using a center finder 48
Figure 77: Machining the bearing crosshead arms to length 48
Figure 78: A drawing to assist in locating the bearing crosshead center 49
Figures 79-80: Machining the cylindrical profile and fillet on the bearing crosshead 49
Figure 81: The results of machining one cylindrical feature on the bearing crosshead 50
Figure 82: The clamping fixture for machining the second side of the cylindrical arms 50
Figure 83: Machining the bearing surface of the bearing crosshead to size 51
Figure 84: The bearing crosshead after machining the tapped hole 51
Figures 85-86: Machining the step-down on the bearing crosshead to fit the gib gap 52
Figures 87-88: Machining the dovetail feature on the bearing crosshead 52
Figure 89: The subassembly of the column, two gibs, and bearing crosshead 53
Figure 90: The engine assembly in mid-May 2018 53
List of Tables

Table 1: Commonly Used Copper Alloys for Marine Castings [10] 15-16
Table 2: Foundry Properties of the Principal Copper Alloys for Sand Casting [10] 46
1. Lighter, Stronger, Faster: MIT Museum Exhibit

Scheduled to open in the fall of 2018, the Lighter, Stronger, Faster exhibit aims to recognize, demonstrate the technical contributions of, and describe the long life of one of MIT’s oldest and most accomplished alumni: Nathanael Greene Herreshoff [1]. The exhibit will feature and outline Herreshoff’s contributions to the sailing and maritime industry, through a collection of technical drawings, photos, and physical replicas held by the Francis Russell Hart Nautical Museum at MIT.

This thesis aims to provide the context of and the actions taken for a project replicating a steam engine designed by Herreshoff in 1897. Upon completion, this engine will be on display for interactive demonstration at the Lighter, Stronger, Faster exhibit in the fall of 2018.

2. Nathanael Greene Herreshoff

Herreshoff was a lifetime sailing and boating enthusiast, expert, steam engineer, as well as a graduate of MIT’s mechanical engineering program in 1870 [2]. In his technical abilities, his son L. Francis Herreshoff described his father as the holder of “all of the tricks and techniques of pattern making, casting, forging, machining, sheet metal work, and general wood construction” [2]. His contributions to ship and engine design changed the entire industry. Herreshoff’s legacy is illustrated by his design of five America’s Cup winning yachts, building the first torpedo boats for the navy, filing the first US patent for sailing catamarans, and inventing many pieces of present-day boat hardware [3].
3. Pappalardo Apprenticeship

The Pappalardo Apprenticeship began in the spring of 2015 as an opportunity for undergraduate mechanical engineering students at MIT to combine mentorship with technical advancement in fabrication skills and methods. Every year, the Apprenticeship is publicized across campus using posters with themes that match the spirit of making or the subject of the making. For 2018, the nautical theme was a tribute to Herreshoff, as shown in the promotional poster in Figure 2 [4].

Figure 2: The Pappalardo Apprenticeship application promotion poster [4]

Linked to the mechanical engineering robotics course 2.007 Design and Manufacturing, Pappalardo Apprentices spend half of their Apprenticeship commitment mentoring students in 2.007 and the other half further developing their own design and manufacturing experience. The latter part of this commitment has taken the form of individual students'
manufacturing of stirling engines or combined efforts towards a larger project. The emphasis of these projects is on best practices in fabrication methods, namely machining and sand casting. The remainder of this thesis will refer only to the combined Apprenticeship project for senior Apprentices, excluding the junior Apprenticeship stirling engine project.

As a way to contribute to the Lighter, Stronger, Faster MIT Museum exhibit on Herreshoff, the Pappalardo Apprenticeship program took on the task of fabricating a Herreshoff engine design for demonstration and interaction at the museum exhibit. This endeavor would take the form of a process beginning with original Herreshoff technical engine drawings and resulting in a finished engine, true to Herreshoff's specified manufacturing methods. While making progress on the engine construction, the Pappalardo Apprentices would learn about sand casting techniques, best practices in fabrication methods, the functionality of the engine, interpreting often incomplete sets of technical drawings, converting these technical drawings into modern CAD models, and Herreshoff himself.

Beginning in the spring semester of 2017, senior Pappalardo Apprentices began working on a recirculating steam engine designed by Herreshoff for the USS Talbot. This particular engine was selected for the Pappalardo Apprenticeship due to size, complexity, and completeness of the available Herreshoff technical drawings. This thesis will cover the history of this recirculating steam engine, the process that the Pappalardo Apprenticeship program follows in order to replicate Herreshoff parts, and two examples of how that process was followed in practice.
4. USS Talbot

The USS Talbot was a US navy torpedo boat, entirely designed by Herreshoff and built entirely by the Herreshoff Manufacturing Company in Bristol, RI [5]. This boat, shown in Figure 4, was launched on November 14, 1897. In 1912, the boat was removed from military use and instead used as a ferry. In 1940, the boat was officially deemed out of service, and it was sold for scrap in 1944 [5].

![USS Talbot](image)

Figure 4: The USS Talbot in 1898 [5]

On the USS Talbot, there was the original recirculating steam engine that the Pappalardo Apprenticeship program is working to replicate. This engine was not used to propel the boat; this steam engine is much too small to output such power for the large torpedo boat. Its purpose was to continuously circulate the water in the tube boiler of the propeller engine. This ensured that local steam pockets would not form within the boiler, increasing risk of an engine explosion [6].

5. Architecture of the Recirculating Steam Engine

The recirculating steam engine is a double-acting steam engine. A double-acting steam engine is one whose valve allows the high-pressure steam to act on both the up and down strokes of the piston [7]. The entire system converts heat energy into mechanical work, beginning with heat in the form of steam and providing rotational energy of the crankshaft. In Figure 5, the valve cylinder is on the right, and the power cylinder is on the left. The crankshaft is shown in profile at the bottom in the bed plate.
To convert heat into mechanical work, steam engines take advantage over the pressure gradient between steam of different temperatures. The steam intake draws hot, high-pressure steam into the valve cylinder. The valve position in the cylinder determines where the steam is next directed. At the beginning of a cycle, the valve directs the steam into one side of the power cylinder, in which the high pressure pushes the piston to the other side of the power cylinder. Any gases in that other side of the power cylinder are pushed out...
into one of the exhaust chambers, then expelled through the gas outlet. Through constraints in the crankshaft construction, the power piston’s motion leads to the repositioning of the valve. When repositioned, the valve now directs the steam into the other side of the power cylinder and blocks that side’s exhaust hole. The same actions happen on this side as what finished happening on the other side: the power piston now moves back to the first side of the cylinder, those gases are pushed and exhausted out of the engine, then the valve switches again.

There are many other ways to achieve this conversion of energy. Thus, steam engines can vary drastically in design, output power, and efficiency. In the Pappalardo Apprenticeship project, we frequently referred to other Herreshoff steam engines and designs to see other designs or manufacturing methods that could serve the same purpose. These comparisons provided insight into Herreshoff’s possible intentions in the cases that our collection of his drawings for the recirculating steam engine were incomplete.

Figure 6: An “exploded view” of the engine parts in April 2018
6. Process of Replicating Herreshoff Steam Engine Parts

The Pappalardo Apprenticeship curriculum has had to reconcile the goals of teaching fabrication best practices in a semester to its Apprentices with delivering a project on an external timeline. No Apprentice ends the semester with the same experience, as the steam engine parts vary in material composition, manufacturing method, and complexity. There are a couple of considerations taken in order to determine for which engine parts each Apprentice is responsible:

- The unique opportunity for the Apprentice to learn about sand casting.
- The order in which parts have to be assembled in the final assembly.
- The Apprentice’s prior relevant experience.

With these considerations in mind, parts were split amongst the 9 senior Apprentices this spring 2018 semester. Nearly every Apprentice was able to individually work on at least one sand cast part. Some Apprentices worked on one or more machined-only parts. Due to drastic differences in size and complexity, some Apprentices worked on only one part, while others were able to complete upwards of ten. Some Apprentices worked with bronze alloys, others with iron, others with steel. The difference in tasks across the Apprentices aligned with the differences in parts available in the project, though the variations did not come at the expense of experience or knowledge gain.

6.1 Process for Fabricating a Steam Engine Part

The process for fabricating a part for any collective Pappalardo Apprenticeship project is as follows:

1. **CAD model from original Herreshoff technical drawing:** Since the recirculating steam engine project was initiated earlier, spring 2018 senior Apprentices verified an already developed CAD model of each of their parts against the Herreshoff drawings. Frequently corrections needed to be made.

2. **Manufacturing plan:** On the Herreshoff drawings, there are pattern drawing numbers next to any parts that were intended to be sand cast parts. Figure 7 shows an example of a part with a labeled pattern number “#6822.” For parts that were not specified as sand cast, we determined what other manufacturing method would be the most practical. This selection process often required referring to other engines to determine what manufacturing methods are common for specific parts. In certain cases, the authentic manufacturing method that Herreshoff’s company would have used was not feasible for our Pappalardo Apprenticeship. Namely, the connecting rods, which are typically forged parts, were cut using a water jet from two directions then post-machined, due to a lack of access to a large enough hydraulic hammer necessary to forge such large parts.
3. Material selection: All of the parts on the recirculating engine drawings are labeled as one of the following 3 material options: steel, iron, or bronze. However, each of these three materials have a large variety of alloys, as exemplified in Table 1. Notes from Herreshoff’s chemist brother, John Brown Francis Herreshoff, indicate more specific chemical makeup of “Herreshoff Bronze,” which most closely resembles the makeup of present-day C902 Tin Bronze [9]. However, it is unknown whether this alloy was used for all parts labeled “bronze” (such as that shown in Figure 7) on Herreshoff drawings or whether this alloy was made precisely for every batch. Based on the manufacturing method and purpose of the part in the context of the full engine, it was necessary to select an alloy to be used. In practice, during the time period in which most of these engines were made, the exact composition of the metals used were determined by the craftspeople most familiar with the method of manufacturing. This “tribal knowledge” came to be through decades of experimentation, and was a challenge to partially reconstruct as a new generation of Herreshoff builders.

Table 1: Commonly Used Copper Alloys for Marine Castings [10]

<table>
<thead>
<tr>
<th>Family</th>
<th>CDA #</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Brass</td>
<td>836</td>
<td>general and through hull</td>
</tr>
<tr>
<td>Semi Red Brass</td>
<td>844</td>
<td>plumbing fittings</td>
</tr>
<tr>
<td>Yellow Brass</td>
<td>854</td>
<td>hinges, latches for interior fittings</td>
</tr>
<tr>
<td>Manganese Bronze, High Tensile</td>
<td>862, 863</td>
<td>gears, brackets, cams, not for use underwater</td>
</tr>
<tr>
<td>Manganese Bronze, Low Tensile</td>
<td>865</td>
<td>propellers, anchors, rudder fittings</td>
</tr>
<tr>
<td>Silicon Bronze</td>
<td>873, 875, 876</td>
<td>underwater hardware</td>
</tr>
<tr>
<td>Tin Bronze</td>
<td>903, 905</td>
<td>steam fittings, bearings, gears</td>
</tr>
<tr>
<td>Material</td>
<td>Grade(s)</td>
<td>Application</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Leaded Tin Bronze</td>
<td>922</td>
<td>marine, ornamental</td>
</tr>
<tr>
<td>Aluminum Bronze</td>
<td>954, 955</td>
<td>gears, struts, used where saving weight is critical</td>
</tr>
</tbody>
</table>

Beyond this third step, the possible paths vary widely depending on manufacturing method. This thesis will focus on the sand casting process.

**6.2 Sand Casting Terms**

This thesis will use terms relating to the sand casting process that are defined here [6] [11] [10].

**Mold**

A mold, in the case of sand casting, is comprised of packed sand which forms a cavity, or a void in the shape of the desired part. This mold includes other features (such as sprue, well, runner, gate, riser, vent, etc.) also defined in this section.

**Green Sand**

Green sand is the most common kind of sand used for sand casting. It is comprised of silica sand, bentonite clay, and water. This mixture gains a homogeneous consistency through the act of mulling. A muller is shown in Figure 8.

Figure 8: A muller for green sand casting
Resin Sand

Resin sand is another common kind of sand used for sand casting. It is comprised of a different kind of sand than that in green sand, with an addition of binder and catalyst chemicals that react when combined to cure and harden the resin sand.

Flask

A flask is the box frame in which the sand is packed. Typically there is a top (cope) and bottom (drag) side of the flasks, though it is possible for more than 2 flasks to be used at once depending on part size, available flask size, and desired head pressure. However, this thesis will only discuss parts for which there are two flasks: the cope and the drag.

Parting Plane

The parting plane is the plane at which the cope and drag flasks meet. Also called parting joint.

Pattern

A pattern is an object or a collection of objects fabricated with intentional geometry such that sand can be packed around it, then the pattern removed from the sand without destroying the geometry imposed on the sand. Patterns can be made out of any material easily removed from the sand as well as rigid enough to not deform when sand is packed around it. Common materials include wood, plastic, foam, and wax. In the Pappalardo Apprenticeship, all sand casting patterns are machined out of rigid polyurethane foam.

Sprue

The sprue is the hole in the cope through which the molten metal is poured into the flask. There is only one sprue per flask to avoid problems like weld lines and underfilling of the mold cavity.

Runner

A runner is a channel carved into the mold to direct the flow of metal from one place to the other. Typically in the Pappalardo Apprenticeship, runners are carved into the drag side of the flask.

Gate

A gate is like a specialized runner that directs the flow of metal into the mold cavity itself. Typically in the Pappalardo Apprenticeship, gates are carved into the cope side of the flask. This is above the runners so that the runners are filled with molten metal before the gates and part itself.

Vent

A vent is a hole in the cope leading from the mold cavity out the top of the flask. Vents provide an exit for any gases that accumulate in the mold.

Cold Insulated Riser

A riser is an additional void in the mold that creates a reservoir of molten metal from which the cooling part can draw metal as it cools and shrinks. Risers can be at the
side of a part or directly on top of the part, can come out the top of the flask or be captured inside the flask, can have an insulating tube or not. A cold insulated riser is the formal term for a riser that comes out the top of the flask and has an insulating tube. A hot riser is the formal term for a riser that is captured inside the flask.

Wells are pockets in the drag that sit below features like the sprue and risers. These pockets are used to absorb some turbulence and contain as much slag (defined below) as possible such that the flow of molten metal into the mold cavity is pure and laminar. In the Pappalardo Apprenticeship, these wells are dug out of the drag side after packing using a spoon.

![Diagram of components of a sand casting mold](image.png)

**Figure 9: Diagram of components of a sand casting mold [12]**

**Core**

Cores are pieces that are inserted into mold cavities to create additional void geometries in the resulting part. Cores can be used to create hollow sections, undercuts, or other geometries that could be otherwise difficult to achieve with a pattern alone. While they can be made out of other materials (though uncommon), cores in the Pappalardo Apprenticeship are made out of resin sand.

**Corebox**

To make a core, a corebox is used. This corebox acts as a mold for the core. Coreboxes can be made out of any material from which it is possible to remove the cured resin sand. In the Pappalardo Apprenticeship, coreboxes are machined out of rigid polyurethane foam, typically out of more than one part for easy disassembly and core removal after curing sets.
Coreprint

To locate a core in the correct position within the mold cavity, coreprints are extra bosses included on patterns that result in extra voids in the mold cavity. These extra voids provide space for cores to be supported and located properly in reference to the rest of the mold cavity.

Core Vent

A core vent is a hole leading from the coreprint out the top (or less commonly a different part) of the flask. Core vents provide an exit for any gases that accumulate in the core.

Pattern Shrinkage

Pattern shrinkage refers to the amount which the part will shrink between its frozen size at the metal’s melting temperature and its room temperature size. The design of the pattern typically accounts for this pattern shrinkage (i.e. a pattern will be made a certain percentage larger than the desired part, so that the cooled part is the desired size).

Shrinkage

Shrinkage refers to the amount which the part will shrink between its molten size and its solid size at the metal’s melting temperature. Not to be confused with pattern shrinkage, shrinkage typically is used to refer to defects in the finished part resulting from uneven freezing. Shrinkage is especially prevalent in areas of thick cross-section, for those features tend to freeze at its edges before the centers. The purpose of risers is to help combat shrinkage defects. Figure 10 exemplifies a cast iron part with a shrinkage defect.

![Figure 10: Example of shrinkage](image-url)
Porosity

Porosity refers to the presence of voids in the finished part, caused by pockets of gas that were trapped inside the mold cavity. The purpose of vents is to help combat porosity defects. Figure 11 exemplifies a cast iron part with porosity.

![Figure 11: Example of porosity](image11)

Slag

Slag refers to any nonuniformity of material composition, typically caused by crumbling sand that gets picked up by the molten metal. The purpose of wells is to capture as much slag as possible that joins the metal flow in the sprue, as slag tends to sink to the bottom of these wells. Figure 12 exemplifies a brass part with slag defects.

![Figure 12: Example of slag](image12)
Flash

Flash refers to any molten metal that is able to spread outside of the mold cavity along the parting plane. Typically, the flask halves are clamped together to help provide a tight seal of the cope and drag sides together. Figure 13 exemplifies an investment cast steel part with excessive flash.

Figure 13: Example of excessive flash [13]

Sieve

A sieve is a tool used to sift green sand for the purpose of getting a better surface finish. This tool is shown in Figure 14. It is not necessary to use a sieve to sift sand that is not touching the surface of parts or the parting plane, as the sand chunks will not touch any metal.

Figure 14: Green sand chunks of green sand in a sieve on top of a flask
A rammer is a tool used to manually pack green sand into a flask. This tool is shown in Figure 15.

Figure 15: A rammer in use

Machinability

Machinability is a percentage used to represent a metal alloy's machining speed for same tool wear against a standard “free machining” metal in that same family. For example, copper alloy C36000 is free-cutting brass, and copper alloy C95300 is aluminum bronze, rated at 35% machinability.

Castability

Castability is a number used to represent the ease of casting a metal alloy. Castability is rated between 1, for the most easily casted, and 8, for the least easily casted. This rating takes into account a variety of factors, mainly those which would place at the top alloys that do not require special techniques for gating, risering, melting, or sand conditioning.

6.3 Process for Fabricating a Sand Cast Steam Engine Part

The process for fabricating a sand cast part for a collective Pappalardo Apprenticeship project continues from the process begun in section 6.1 as:

4. **CAD model for pattern making**: With perhaps extremely rare exceptions, sand cast parts cannot be cast in their as-drawn form. The first step is to identify a parting plane, which would create a split in the part for different halves of the overall pattern. The necessity of cores is identified now too, and those features are filled in the CAD,
and coreprints added where necessary. To aid in pattern removal, part overhangs must be removed and side walls must be drafted. Small features such as holes and thin-walled details are difficult to pack, and are typically filled in and/or made much thicker on patterns. Any surfaces that have to be finished to a specific dimension in the final part should have thickness added in the casting. All of this extra added material will be post-machined after casting. After these geometry changes are made, then the entire pattern CAD should be scaled up by a factor corresponding to the pattern shrinkage of the material used.

5. **CAD for cores/coreboxes:** As mentioned in step 3, the necessity of having cores is identified when other changes are made to make the part patterns. After focusing on the pattern, including filling the core volume and adding coreprints, the cores themselves need to be CADed. These cores should include a feature that fits into the coreprints added to the patterns. To make the cores, molds need to be made for the core shape, called coreboxes. These molds are CADed from the core CAD themselves, typically using a “Combine - Subtract” feature of the core from a box shape (representing the corebox stock) in SolidWorks.

6. **Pattern and corebox CAM:** The patterns and coreboxes are machined using a 3-axis CNC mill. The toolpaths for these operations are generated using HSMWorks, a CAM package that integrates directly into the SolidWorks work environment. Each pattern and corebox will have a single job, which can contain multiple operations. Each job definition specifies the expected stock size, and origin/orientation of the part, positioning of the part within the stock size. Each operation contains its own toolpath of a specified type, with specified parameters, run with a single tool, on sections of the part also specified. In general, the operations go from large tool diameter, fast material removal, and coarse step size, to small tool diameter, slow material removal, and high quality surface finish. It is important to note that the virtual tool library from which the CAM operations are based must match the actual selection of tools and tool holders available for the mill.

7. **Pattern and corebox machining:** The machining step realizes the processes, tools, and setup specified in the CAM jobs. First, foam stock of the appropriate size to match what was specified in the CAM job must be cut and fixed to the mill bed. It is helpful to spray a layer of paint on the bottom of the foam pieces to assist in the adhesion to the wood board, as the foam is less likely to chip or break off from the double-sided tape. These foam pieces are then fixed to a flat wood board using 3M Very High Bond (VHB) double-sided tape. This wood board has an additional wood block attached to its underside so that it can be gripped in the mill vise. Proper zeroing of the machine to the stock ensures that the part will be contained within the stock as expected from the CAM job. Fine foam dust is produced when machining the patterns and coreboxes, so it is important to follow the endmill as it cuts with a shop vacuum, as shown in Figure 18.
Figure 16: Applying paint on the bottom of foam for pattern making

Figure 17: A foam block fixtured for machining a pattern

Figure 18: Following the milling tool with a vacuum
8. **Corebox packing:** Typically before packing the flasks, coreboxes are packed first so that the cores have ample time to cure before getting placed in the flasks. Coreboxes are clamped together, if made out of multiple parts as recommended to facilitate removal. To mix the resin sand mixture, first the sand is put in a mixing bowl. 2% of the sand’s weight in binder is added to the sand, then mixing begins to distribute the binder throughout the sand uniformly. 1% of the sand’s weight in catalyst is added last. As soon as the mixture is a consistent color green, the resin sand should be packed by (gloved) hand into the coreboxes promptly, as the sand becomes less workable as it cures. Excess sand pressed on top of the coreboxes can be scraped away using a straight edge, such as a metal bar. Figures 19-22 demonstrate a corebox and resulting core that went into the recirculating engine bed plate.

![Corebox packing](image)

**Figures 19-22: A corebox and resulting core**

9. **Flask preparation:** This is an extensive step that can take several hours. Pappalardo Apprentices performed all packing and pouring steps in the Merton C. Flemings Materials Processing Laboratory at MIT.

   a. **Sand materials:** Most often, the flasks are packed with green sand. Occasionally, resin sand is incorporated on surfaces that touch the metal to alleviate mold crumbling, decrease slag, and improve surface finish. Green sand is used more often due to its easy manipulation, easier recycling, and avoidance of any toxic chemicals.

   b. **Packing:** First, both the patterns and the parting plane should be coated in baby powder to assist in the pattern removal and flask halves separation processes. Either using a pattern board or setting pattern halves on a flat
surface, sifted sand using a sieve is then added into the flask until it covers the whole pattern and parting plane. This sifted sand can be carefully packed by hand, adding more sifted sand where necessary if parts of the pattern or parting plane become exposed. Unsifted sand suffices beyond this point, as it does not touch part surfaces. After adding more sand, a rammer can be used to compact the sand further. Thoroughly compressing the sand is necessary to avoid sand crumbling in the mold cavity that could add to slag defects. When the sand reaches beyond the top of the flask, the excess can be removed using a straight edge, leaving a flat top. After this side of the mold is packed, the flask is carefully flipped over, as shown in Figure 23. Without yet removing the pattern, the other flask is stacked on top, and any additional patterns are located to the patterns from the other side; this locating is typically done with pins. This side of the parting plane as well as the pattern halves are also covered in baby powder. This side can be packed just like the other side, except if there need to be insulated riser tubes, which should be placed in the flask before any packing occurs.

Figure 23: A packed flask half using green sand before pattern removal

c. **Pattern removal:** After both flask halves are packed together, the halves are carefully separated. From each flask half, the patterns can be carefully removed. The patterns can often be difficult to remove, affected by their specific geometries. It is possible and advised to tap on the back of the pattern to listen for its loosening. After the entire pattern sounds loose, wood screws can be screwed into the patterns for ease of pulling. The patterns should be carefully and slowly pulled up out of the flasks, ensuring that the pattern does not twist upon removal. In the case that any sand breaks during
pattern removal, large chunks can be re-attached using an acetone-based glue.

![Figure 24: A flask half after pattern removal](image)

d. Gating/risering setups: The gating and risering setup of sand cast molds are critical to the success or failure of the casting process, and should be different depending on the used metal alloy. Part shapes and sizes as well as flask shapes and sizes can lead towards varying solution setups, though this thesis will outline best practices that should be followed if possible. The general rule is to have the molten metal feed from thick sections of the part to thin sections; this assists in filling of the mold cavity as well as gas venting. This rule helps determine the location of the sprue. Below the sprue, there should be a well to help collect some of the slag and reduce turbulence. From this well and also in the drag side, a runner should lead from this well in a straight line and terminate in another well. Gates are cut into the cope side, and should overlap with the runner then lead in a straight line into the part itself. There can be multiple gates depending on the part geometry. More runners between the part and risers can be cut into either the cope or drag sides. These risers should be located opposite of gates and/or near large cross-sections, which would experience the most drastic shrinkage effects. There can be many risers per part if needed. Vents are then cut into the cope side of the flask at the highest points of the part. These vents help prevent porosity due to lack of gas escape routes. Because these vent holes are typically small in diameter (~\(\frac{3}{16}\))", it is good to place these in excess to avoid possible defects, as they are easily removed in post-machining.

e. Cores: If there are cores involved, a couple more steps are necessary. The resin produces gases when in contact with hot molten metals, so some venting strategies need to be incorporated. If possible, channels in the cores themselves should be carved/cut. These channels should lead into the flask, in which additional channels and vents should be included. These channels can be the same size as typical runners and gates, and the vent (typically one per core channel suffices) can be the same size as a riser (thus larger than
the vent holes that are cut into the mold cavity). The cores can be fixed into the coreprints by adhering with an acetone-based glue.

![Image of a flask half with cores placed and runners cut](image)

**Figure 25: A flask half with cores placed and runners cut**

10. **Pouring:** After flask preparation, the two flask halves should be clamped together. The mold is now ready for pouring. It is important to calculate the required metal needed to fill the mold cavity, sprue, runners, gates, and risers. Any excess molten metal can be easily poured into an ingot and later remelted for another part, so it is common to overestimate without negative consequences. For melting the metal, the foundry uses an induction furnace and an infrared thermometer to keep track of the metal’s temperature. Suggested material pouring temperatures can be various amounts above each material’s melting temperature and should be looked up. After pouring, it is necessary to wait a long enough duration of time to allow a slow cooling rate for the parts. This avoids quench hardening of the metal, a phenomena which can lead to difficult machining later on. If this occurs, the part would need to be heat treated to relax the microstructure and create a more machinable material. Typically breaking out the part after waiting overnight after pouring suffices.

![Image of melting iron in a crucible](image)

**Figure 26: Melting iron in a crucible**
11. **Post-machining:** All of the following needs to be machined after pouring: thickness added, details removed in the cast part, gates/sprues/risers, flash, etc. The initial challenge of this machining is fixturing to establish the first datum, as no part of a casting is flat. Various setups are possible and vary drastically depending on the geometry of the specific part as well as available hardware fixtures. The standard mill vise is rarely sufficient, as it is important to establish several rigid points of contact, typically requiring multiple individual clamping fixtures. The part should be oriented in a way that enables easy access to establish the first datum, from which all others will be referenced. As more flat surfaces are established, more conventional clamping techniques can be used. As with machining non-cast parts, proper speeds and feeds for the material in use should be heeded.

After the post-machining step, the part is completed. Generally, this series of steps can be followed, though it should be altered to suit the individual part and its function. It is important to note that due to the complexity of the total engine assembly, many post-machining steps cannot be done in isolation for each part. Certain sub-assemblies are better made by post-machining certain features together. This distinction leads to some variance in this process and should be determined through inspection of the designs ahead of time.

This thesis will next outline how this series of steps was followed and altered in practice for a couple different parts made in the past year. As mentioned earlier, no two journeys in fabricating a steam engine part look exactly the same, so this thesis will highlight differences between efforts for two parts.

7. **Fall 2017: Column and Gibs**

In the fall 2017 semester, I fabricated three iron parts for the Herreshoff recirculating steam engine: one cast column, and two machined gibs. Since this thesis is focused on the sand casting process, the next section will outline the process for making the column more thoroughly.
7.1 Drawing Interpretation and CAD Model

As mentioned before, each part leads to widely varying fabrication experiences. The primary concentration of time that went into the column was spent interpreting the Herreshoff drawing and making the CAD model of the part.
The column serves the purpose of holding up the cylinders (in combination with the stanchion) from the bed plate, as well as providing a smooth surface on which the bearing crosshead can slide.

The final patterns did not exactly match the part as drawn in the column Herreshoff drawing. That drawing, dated June 9, 1897 as shown in Figure 27, specified an H cross-section throughout the entirety of the column height. However, the assembly drawing, dated June 17, 1897 as shown in Figure 28, instead showed a column with just a T cross-section below the bearing surface. Since this assembly drawing was dated 8 days later than the column drawing, the more recent drawing was ultimately used to create the most accurate part for the assembly. By this point, two versions of patterns had been made, and a flask was packed using one of them. With this new realization, the third and final version of the CAD model and patterns were made to better suit the assembly drawing version of the column. All three patterns fabricated are shown in Figure 29, with the top pattern made as drawn in the column drawing and the bottom pattern made as drawn in the assembly drawing.

Figure 28: The assembly drawing showing the column with a T cross-section [8]
Interestingly, beyond the recirculating engine, future Herreshoff engine drawings showed his further exploration into possible architectures of the columns of his engines. Figure 30 shows the column drawing for a different Herreshoff engine, an electric light steam engine, shows a column with a reversed T cross-section from that drawn in the recirculating engine assembly drawing [6]. This column drawing is dated 8 months after the recirculating engine drawings, indicating that Herreshoff continued amending the exact column form over a significant time period.
In making the patterns from the CAD model, the column gave rise to a simple solution: a parting plane along the plane of symmetry of the part. This would result in mirror image pattern halves that did not require any cores. Figures 31 and 32 illustrate the changes made between the final part model and the cast part model, including eliminating holes, adding thickness to machined surfaces, and scaling to accommodate for pattern shrinkage.

![Figures 31-32: Models of the finished column compared to the cast column](image)

With the parting plane identified, the part was made into a more castable shape by filling in holes, adding thickness to the faces that would be post-machined, and drafting all edges perpendicular to the parting plane.

**7.2 Pattern Manufacturing**

With the CAD model of the patterns made, the next steps are to make that object a reality. In the Pappalardo Apprenticeship, rigid polyurethane foam is used as casting pattern material. Before touching any physical objects or equipment, first CAM needs to be made.

![Figure 33: The column CAM job in HSMWorks](image)
Using the HSMWorks plugin for SolidWorks, a CAM job is defined, as shown in Figure 33. The tool library used in the Pappalardo Apprenticeship exactly matches a selection of tools in Pappalardo Lab, as well as the speeds and feeds for each tool for cutting the rigid polyurethane foam are already built into the tool library. Within the job, a series of operations moved from coarse to fine surface finish. That series of operations was as follows for each pattern half:

1. 3D Adaptive Clearing with ½" flat end mill. 26 minutes and 45 seconds.
2. 3D Scallop with ¾" ball end mill. 2 minutes and 5 seconds.
3. 3D Parallel Pencil with ¼" ball end mill. 33 minutes and 22 seconds.
4. 3D Contour with ¼" flat end mill. 2 minutes and 21 seconds.

After defining the CAM, exporting the job as a .gcd file type makes the toolpaths directly readable by the 3-axis CNC mill. Next the CAM job setup dictated the physical setup of the pattern making. This process carried on as follows:

1. Cut foam to size of the stock specified in the HSMWorks CAM job. In this case, the foam was two blocks sized 4" by 15" by 3".
2. Clean the foam dust off the block using a shop cloth and denatured alcohol. Ensure to let the block dry. Clean the wooden mounting plate similarly.
3. Prevent the foam from scraping off its double sided tape mount by spray painting a layer of clear paint on the bottom of the block.
4. Attach the foam block to the wooden mounting plate using 3M Very High Bond (VHB) double-sided tape. Make sure to attach the foam block in the orientation that aligns with the HSMWorks CAM job setup. First apply to the bottom of the wooden block, making sure to achieve good contact between the tape and the foam. Then put the block on the wooden mounting plate, tapping the foam block with a rubber mallet to ensure strong contact.
5. Zero the mill on the origin of the part as specified by the HSMWorks CAM job setup. Given enough extra material in the x- and y-directions, there is typically no need to use an edge finder or other piece of equipment instead of zeroing the tool by eye. However, the z-direction zeroing should be more precise.

6. Load the .gcd CAM file. Through a USB drive plugged into the mill computer, the .gcd file is then accessible through the mill interface. After opening the file, it can be run.

7. Run the .gcd CAM file, following all directions for switching tools. Since the rigid polyurethane foam creates a fine dust when machined, it is advised to follow the end mill with a shop vacuum as it cuts. Figures 38-41 demonstrate the series of machining operations taken on the column pattern, each using progressively smaller bits and incorporating finer detail and surface finish.

8. Upon completion of the program, next remove the machined pattern piece from the wooden board. Denatured alcohol can help eliminate the bond of the double-sided tape to both the foam pattern and the wooden board.

9. Put alignment pins in the pattern halves so the halves locate properly into each other. This will ensure the pattern halves do not slide apart from each other during the packing steps.
After putting alignment pins into the pattern halves, the patterns are complete.

7.3 Properties of Iron

Iron exhibits uncommon behavior when it freezes. Like water, iron gets larger when it goes from liquid to solid form. This phenomenon, qualified in Figure 42, means that risering for sand casting iron can be minimal. However, it is important to distinguish this freezing expansion from the overall pattern shrinkage, which for iron is still roughly 1% of shrinkage [10]. This pattern shrinkage is a measure of the net shrinkage between the mold cavity size (which matches the pattern size) and the room temperature cast part. While iron expands as it freezes at the melting temperature of approximately 1200 degrees Celsius, the frozen part continues to shrink as it cools down to room temperature, resulting in an approximate 1% shrinkage from the mold cavity size [10].

![Volume change patterns for graphitic irons.](image)

Figure 42: Typical volume change pattern for iron

7.4 Packing and Pouring

Discovered in packing the column flasks, removing patterns with deep pockets can result in chunks of sand grabbing onto the pattern, coming out of the mold when removing the pattern. This occurred for both of the deep pockets in one half of the flask. These sand chunks were tapped out of the patterns then glued in place in the mold, as shown in Figures 43-45.
Because the column is iron, there was significant flexibility in potential risering strategies. Risers enable the mold cavity to draw more molten metal inside as the liquid inside freezes and shrinks. However, due to the atypical solidification expansion of iron, the riser is not typically necessary, with the exception of parts with very thick cross sections. In this case, one uninsulated cold riser was still used as feedback for the metal pourer that the mold cavity had been filled.

The general thick-to-thin gating strategy did not entirely suit this part, which has a thicker section at either end, connected by a thinner section in the middle. Thus, the part was gated in the center with an uninsulated cold riser on either end as feedback that the cavity had been filled to both ends.
The iron was poured at approximately 1370 degrees C, a typical pouring temperature for gray iron [10]. To avoid quench hardening the iron, the part remained in the sand mold for approximately 24 hours. On this first attempt, the part came out void of any visible defects.

Figures 47-49: Pouring, unpacking, and the resulting column

7.5 Post-Machining

Several features from the drawing were eliminated in the castable version: 3 flat machined planes and 10 holes. As with any cast piece, the column began with no trustworthy surfaces: i.e. no perfectly flat, round, or dimensioned features. This leads to some challenges involving proper orientation of the part as well as fixturing.

Proper orientation of the part is critical, especially for long parts such as the column, as a mere 1 degree offset of the part results in a height difference of 0.017” per inch of length. This means that a 1 degree offset of the column would result in a 0.221” height difference between the top and bottom flanges of the part. Thus, thorough orientation of the part is necessary. Typically this is done using a level and averaging the level readings over a large surface of the part.

Fixturing is additionally a critical aspect of the post-machining process, particularly when establishing the first datum surfaces. It is important to not treat any surfaces as perfectly flat, and to instead clamp at many small contact points. Additionally, any cantilevered features could vibrate during machining, resulting in poor surface finishes.

A series of independently adjustable fingers and individual support points fixtured the raw cast iron part. There were 7 of these clamping points in total. To begin establishing datum surfaces on the column, first the sides of the bearing surface were squared to use as a clamping surface for further machining. This fixture and series of steps are shown in Figures 50-51. These planes were none of the 3 flat machined planes required to finish the part, though it allowed more robust clamping method for further operations.
Figures 50-51: Establishing initial datums on the column

Making use of these parallel clamping surfaces, the mill vise next held the part. Custom vise jaws avoided clamping on the ribs between the column back and the bearing surface. A level ensured the part's proper rotation, leaving the bearing surface oriented upwards. This fixture and series of steps are shown in Figures 52-55. In this orientation, the mill was used to machine the flat bearing surface, drill the 6 holes on that surface, and side mill the flat top flange.

Figures 52-53: Custom vise jaws for fixturing the column

Figures 54-55: Machining the bearing surface and gib holes
The next orientation used the flat top flange and the flat bearing surface to orient the bottom bearing surface upwards. The top flange was seated flat on the mill table, and the bearing surface was clamped onto a right angle fixture. This fixture and series of steps are shown in Figures 56-57. This orientation allowed the mill to machine the flat bottom flange to the proper height relative to top flange and to drill the two holes on that surface.

Figures 56-57: Machining the bed plate mounting surface and holes

The last features to machine were two holes on the top flange. To reach these, the part was oriented with the bottom flange seated flat on the mill table and the bearing surface again clamped onto the right angle fixture. With these two holes drilled, the part was completed.

Figure 58: Machining the cylinder mounting surface and holes
8. Spring 2018: Bearing Crosshead

In the spring 2018 semester as part of my senior Pappalardo Apprenticeship, I fabricated one part for the Herreshoff recirculating steam engine: one cast bronze bearing crosshead piece. While the concentration of the time in the prior semester on the column was spent on interpreting the Herreshoff drawing, the bearing crosshead gave a more in-depth look at material casting properties, particularly for copper alloys.

Figure 59: The original power connecting rod and bearing crosshead drawing [8]
8.1 Part and Pattern Design

The bearing crosshead is the linkage that helps convert linear cyclic motion of the piston to rotary motion of the crankshaft. The power connecting rods interface with the bearing crosshead, free to rotate about the cylindrical arms. The dovetail feature on the other side of the bearing crosshead slides along the column and is constrained to only vertical linear motion by the column and gibs. A rod threads into the bearing crosshead, extends vertically, and transfers the matching vertical linear motion to the power piston.

![Figure 60: The bearing crosshead CAD model](image)

The part and pattern design of the bearing crosshead took significantly less time than those stages for the column. This was likely a result of both a more straightforward Herreshoff drawing of the part as well as my prior introduction with casting-related CAD and pattern making steps for the column.

The part was made using two cores, each to fill the cone-shaped void in the ends of the cylindrical feature. The parting plane thus split both the cylindrical feature and the dovetail feature in half along a plane of symmetry. The pattern halves were identical, as were the two cores.

8.2 Pattern and Core Design and Manufacturing

Since pattern machining was exemplified by the column earlier, this section will focus on the unique aspect of the bearing crosshead: the cores. To make the core design, a new body in...
SolidWorks was added to match the inside of the cone-shaped void and stuck outside of the part by a significant bit. That extra length would provide adequate contact as the coreprints, shown in Figure 61.

![Figure 61: The bearing crosshead pattern CAD model](image)

From this core design, the coreboxes were designed by subtracting the intersection of the core body from a rectangular block. While the origin for patterns was one of the bottom corners of the block stock for ease of zeroing, the origin for coreboxes was instead the center of one of the top edges of the block stock. This location is more convenient for coreboxes because they were made out of two clamped pieces of foam for ease of removal of the cured cores. This origin location allowed for more accurate facing of the blocks as well as kept the split lines of the coreboxes along the core centers.

![Figure 62: The bearing crosshead CAM job in HSMWorks](image)
CAM for the coreboxes was done on this part, including the following operations:

1. 2D Horizontal Facing with ¾" flat end mill. 1 minute and 3 seconds.
2. 3D Adaptive Clearing with ¾" ball end mill. 2 minutes and 41 seconds.
3. 3D Parallel Pencil with 3/16" ball end mill. 2 minutes and 44 seconds.

Figures 63-65: Operation toolpaths for bearing crosshead corebox machining

To make the cores, resin sand is mixed and packed into the coreboxes, allowed to let cure for around 10-20 minutes, then removed from the coreboxes. The resin sand mixture contains a fine silica sand, a binder chemical at 2% of the sand’s weight, and a catalyst chemical at 1% of the sand’s weight. After packing and removing from the coreboxes, these cores can sit indefinitely without negative consequence. In fact, the cores continue to harden as they age, to a point of maximum hardness. Thus, cores can either be put into flasks and undergo a metal pour immediately, or they can sit for an extended period of time before going into their flasks.

In this case, the cores were cured in halves, as shown in Figure 66. To connect the half pairs together, an acetone-based glue adheres both sides together. The cores are then fixed into their coreprints also using some of the acetone-based glue.

Figure 66: Cores for the bearing crosshead

8.3 Alloy Selection, Packing, and Pouring (and Repeating)

Parts on the Herreshoff drawings are labeled as “bronze,” “iron,” or “steel,” with no specifications for what type of each. Given that the numerous kinds of copper alloys and their properties, we selected a copper alloy that would best suit the use case of the bearing crosshead: a load-bearing piece with low friction sliding/rotating features. We initially chose
copper alloy C95400, an aluminum bronze, for its high strength and excellent bearing properties [10].

In total, three bearing crosshead pieces were attempted in aluminum bronze, each with increasingly generous risering strategies. Repours were necessary because each iteration saw significant shrinkage defects. A “generous” risering strategy is one that provides extensive risering with efforts to keep these risers hot and full of molten metal, mostly by using insulated tubes or by including hot risers which do not touch the outside air. The second attempt used one insulated riser, though the resulting part still showed shrinkage defects in the center of the knuckle, as shown in Figures 67-68. The third attempt featured a cold insulated riser tube on top of the part itself, on the short cylindrical boss below which we saw the most extreme shrinkage defects. Despite the drastic differences in risering strategies, all three of the resulting cast parts exhibited extreme shrinkage defects, always in the middle of the cylindrical piece and additionally elsewhere for some. Cross-sections of these failed attempts are shown in Figures 69-70, which illustrate the extreme shrinkage in the center of the part as well as near the base of the bearing surface.

Figures 67-68: The second attempt at casting the bearing crosshead

Figures 69-70: Shrinkage shown in cross-sections of failed bearing crosshead casts
Seeing no more room to strategize our risering setup, we looked into switching our alloy. Ranked from most castable to least castable from 1 to 8, aluminum bronze C95300 is rated at the lowest possible rating, at an 8 [10]. This rating matched our casting results, as the shrinkage defects became unavoidable given our equipment access. Instead, we selected copper alloy C83600, a red leaded brass, for its moderate strength and excellent castability, rated at a 2 for castability [10]. We determined that the decrease in strength was acceptable given the use case of the bearing crosshead. Table 2 shows the drastic property differences across different copper alloys, including castability rating.

<table>
<thead>
<tr>
<th>CDA #</th>
<th>Family</th>
<th>Shrinkage Allowance (%)</th>
<th>Melting Point (°C)</th>
<th>Castability Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>836</td>
<td>Leaded Red Brass</td>
<td>5.7</td>
<td>1010</td>
<td>2</td>
</tr>
<tr>
<td>844, 848</td>
<td>Leaded Semi-Red Brass</td>
<td>1.4-2.0</td>
<td>970</td>
<td>2</td>
</tr>
<tr>
<td>854</td>
<td>Leaded Yellow Brass</td>
<td>1.5-1.8</td>
<td>940</td>
<td>4</td>
</tr>
<tr>
<td>858</td>
<td>Yellow Brass</td>
<td>2.0</td>
<td>925</td>
<td>4</td>
</tr>
<tr>
<td>863, 865</td>
<td>Manganese Bronze</td>
<td>2.3</td>
<td>920</td>
<td>4, 5</td>
</tr>
<tr>
<td>872</td>
<td>Silicon Bronze</td>
<td>1.8-2.0</td>
<td>...</td>
<td>5</td>
</tr>
<tr>
<td>875</td>
<td>Silicon Brass</td>
<td>1.9</td>
<td>915</td>
<td>4</td>
</tr>
<tr>
<td>903</td>
<td>Tin Bronze</td>
<td>1.5-1.8</td>
<td>980</td>
<td>3</td>
</tr>
<tr>
<td>922</td>
<td>Leaded Tin Bronze</td>
<td>1.5</td>
<td>990</td>
<td>3</td>
</tr>
<tr>
<td>937, 943</td>
<td>High-Lead Tin Bronze</td>
<td>1.5-2.0</td>
<td>930</td>
<td>2, 6</td>
</tr>
<tr>
<td>953, 958</td>
<td>Aluminum Bronze</td>
<td>1.6</td>
<td>1055</td>
<td>8</td>
</tr>
<tr>
<td>976, 978</td>
<td>Nickel-Silver</td>
<td>1.6-2.0</td>
<td>1165</td>
<td>8</td>
</tr>
</tbody>
</table>

With this new alloy selected, a moderately “generous” risering strategy was used to match that used for the second aluminum bronze attempt: gate into two spots on the dovetail feature and two cold insulated risers on the opposite ends, each feeding into the bearing crosshead at the center and one end of the cylindrical feature. This first red leaded brass pour attempt succeeded, with no shrinkage defects, shown in Figure 71.
The experience with the bearing crosshead taught the importance of researching material properties to select an alloy suitable for both the final use case as well as the manufacturing method. While gating and risering strategies can make a big difference in pour outcomes, those strategies cannot always overcome shortcomings of the material properties of the alloy used.

8.4 Post-Machining

Several features from the drawing were eliminated in the castable version: several flat machined planes, 2 cylindrical features, and 2 holes. To begin establishing datum surfaces on the bearing crosshead, the regular mill vise clamped the part by the knuckle, orienting the flat bearing surface upwards. A level ensured sufficient orientation of the part. To decrease vibrations while cutting, wood wedges tapped into place supported the cantilevered arms.

![Figure 71: The successful bearing crosshead cast in red leaded brass](image)

![Figure 72: Drawing used to assist in machining the bearing crosshead](image)
Figures 73-74: Establishing initial datums on the bearing crosshead

The mill vise held the part by two of these parallel clamping surfaces, placing the faced bearing surface on parallels. In this orientation, four more surfaces were machined flat: the ends of the cylindrical arms and the ends of the knuckle.

Figures 75-76: Zeroing the mill using a center finder

Figure 77: Machining the bearing crosshead arms to length
Then the part was oriented with the bearing surface flat against one of the vise jaws, a side edge of the bearing surface resting on a parallel, and the cylindrical arms vertical. In this orientation, the circular profile of the cylindrical feature on one side was machined, including a fillet that matches the surface of the connecting rods that interface with the bearing crosshead. Due to shifting of the cores during casting, finding the center axis of the cylindrical features that resulted in optimal wall thickness on both ends of the arms took some trial and error. Those measurements are shown in Figure 78, and those machining operations are shown in Figures 79-80.

**Figure 78: A drawing to assist in locating the bearing crosshead center**

**Figures 79-80: Machining the cylindrical profile and fillet on the bearing crosshead**

Using a collet block to hold the finished cylindrical feature on one side, this robust clamping method also enabled accurate orienting of the part and locating of the center of the cylinder. This setup allowed the same operations to run in order to mirror the cylindrical feature. The small hole through the axis of the cylindrical features was also drilled in this setup.
Next, the bearing surface was machined to size, basing the dimension off the location of the cylindrical axis. The part was held with both of the coaxial cylindrical features in collet blocks, keeping them square to each other by clamping them in the vise first on parallels before tightening the collets. A level ensured sufficient rotation of the part in the collet blocks, however, this facing step ensured more precise squareness to the collet blocks. This fixture and machining operation is shown in Figure 83. Then using the bearing surface as a
clamping surface and keeping the collet blocks fixed onto the part, the large hole was drilled and tapped.

Figure 83: Machining the bearing surface of the bearing crosshead to size

Figure 84: The bearing crosshead after machining the tapped hole

The final features to machine on the bearing crosshead were two step-downs to act as relief between the two gib pieces, an aesthetic fillet, and the dovetail profile. Machining these step-downs and fillets came first, holding the part in the same way as it was held for the cylindrical profiles, as shown in Figure 85. This step-down was machined to clear the gap between the gibbs on the column. Pins of 3/8” diameter pins properly spaced the gibbs when mounting to the column, as shown in Figure 86.
Figures 85-86: Machining the step-down on the bearing crosshead to fit the gib gap

To machine the dovetail, the part was held the same way. The mill head was tilted to an angle that matched that of the gibs, using a dial indicator along the face of the gib. This feature was machined to fit the column and gib subassembly. Figures 87-88 show machining the dovetail feature in progress.

Figures 87-88: Machining the dovetail feature on the bearing crosshead

With all of these features machined, filing of any excessive rubbing surfaces helped achieve a proper tight yet low-friction fit between the sliding bearing crosshead piece against the fixed column and gibs.
9. The Completed Recirculating Engine

The recirculating engine is scheduled to be completed at the end of May 2018. It is scheduled to be on display at the MIT Museum Lighter, Stronger, Faster exhibit in the fall of 2018. At the time of submission of this thesis, the engine assembly is in progress, as can be seen in Figure 90.
Acknowledgments

Thank you to the many people who have worked on the project and who enabled progress to happen. Thanks to Danny Braunstein for spearheading this project and for providing an advisory role to the writing of this thesis. Thanks to Bill Cormier and the rest of the Pappalardo shop staff for supporting fabrication in Pappalardo Labs. Thanks to Mike Tarkanian and the shop staff in the Merton C. Flemings Materials Processing Laboratory for providing equipment, oversight, and assistance in casting parts. Thanks to Kurt Hasselbalch from the Francis Russell Hart Nautical Museum at MIT for providing access to the original engine drawings. Additionally, thank you to all of the Pappalardo Apprentices who have contributed to the project over the past two years.
References

8. Original Herreshoff engine drawings provided with permission of Kurt Hasselbalch, curator of the Hart Nautical Collections at MIT Museum.