Recreating Steam Power at WPI

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Recreating Steam Power at WPI

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree in Bachelor of Science
In
Mechanical Engineering
By:

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Professor Robert Daniello
Abstract

Steam power made possible the early growth and success of WPI as an Institution. Beginning in the late 1800’s three large stationary Steam Engines were used to power all of the equipment in the Washburn Shops and provide auxiliary electricity before municipal electrification. Researching original archive photos of the WPI Powerhouse sparked an interest in steam engine technology, the group launched a plan to design, manufacture and construct a 1/5 scale model of the original, Fitchburg-built Putnam Steam Engine, using modern manufacturing practices to recreate the engine in period correct materials. The engine was recreated without original drawings, working only from photos, period books and scaling of original design to ensure that the engine would function properly at a smaller scale. Period correct materials and casting processes were researched to ensure that all components would perform properly and to identify suitable, cost effective modern manufacturing techniques. Major engine components were cast from wood patterns made in the Higgins Labs shop. Various manual and CNC machining techniques were employed. Work commenced in August to build a running scale engine, which was completed and ready for testing in late March. Performance of the finished engine will be discussed. Overall the knowledge gained from completing this engine covers many fields of mechanical engineering and demonstrates the fundamentals of WPI’s motto Theory and Practice.
Acknowledgments

Without the help of certain individuals and organizations, the completion of our project would not have been possible. We would like to thank our faculty advisor Robert Daniello for his support of our project, Arthur Carlson of the WPI Gordon Library Archives, for his help with researching photographs and information pertaining to the steam engines while they were present on campus, Tom Partington for the supply of literature on steam engines and their construction and project materials, Dane Kouttron for access to equipment not available to us at WPI, Bill Grudzinski of the WPI Powerhouse for providing us with steam and the history of the powerhouse, Ian Anderson for supplying us with the wood for the base of the steam engine and James Loiselle for assistance with several CNC lathe operations. We would also like to thank the Fitchburg Historical Society for access to what documents remain of the Putnam Machine Company and Cattail Foundry in Lancaster, PA who were able to pour the castings that made up key components of the steam engines.
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Introduction

From the latter part of the 19th century through the early 20th century, steam was king. Steam was used everyday from transportation to heating and power generation to farming. As the advent of electricity came on, it was often steam engines that would power the generators. Railroads used steam locomotives to carry large amounts of material and people across long distances quickly and efficiently.

The aim of the educational curriculum of Worcester Polytechnic Institute has always been “Theory and Practice” since the founding of the institution. Every graduate of WPI aspires to leave here with the knowledge and practical skills to make their mark on the world around them. This statement was no less true for students who went to this institution during the latter part of the 19th century. Students learned by classroom education and hands on learning in their field. With steam power being a prevalent subject of the time, it should come at no surprise that steam engineering was taught here as part of the original Mechanical Engineering program. Students had opportunities to apply their knowledge in a practical way right on campus. With this in mind, our project goal was to recreate a historically significant piece of machinery while maintaining the concepts of design and manufacturing that contributed largely to the school’s founding. The design we chose replicates a Putnam Machine Company 30 horsepower horizontal stationary steam engine manufactured in 1892.
Background

WPI was founded in 1865 and as an engineering school, practical applied studies that were relevant to the time were taught to students. Prior to the turn of the century, the school had purchased three stationary steam engines. They were purchased to power electric generators for the school, run the flatbelt equipment in the Washburn Shops and also to perform testing on as WPI had a steam testing laboratory in what is now the WPI Powerhouse. At the time, coal fired boilers were used to produce steam to run the engines. From the WPI archives we were able to find the floor layout for the three engines that were put here as well as the flywheel size and rated rotations per minute (RPM).

The school purchased three steam engines from separate companies. The largest of these engines was produced by the Wheelock Engine Corporation and had a 10’ flywheel. The Wheelock Engine Corporation was located where the current Worcester Police Department stands today. The next engine was produced by the Edward P. Allis corporation (taken from the maker plate from the photo of this engine, designated as an Allis-Corliss engine) in Milwaukee Wisconsin and used a Corliss valving system with a 9’ flywheel. The smallest of the engines had an 8’ flywheel and was made by the Putnam Machine Company of Fitchburg, Massachusetts. WPI had other vertical stationary engines in the steam testing lab, however no information on these was available and they will not be discussed further.

As stated previously, these engines were used for testing in the steam engineering lab, to power Washburn shops and to power generators for the school. At the time, steam engine technology was a very relevant topic as steam was a more common power source. The study of
engine design, valving, thermodynamics, steamfitting and boilermaking were all practical fields at that time. Steam engineering was largely applied to the design and construction of locomotives for transportation and stationary engines for power generation. This area of Worcester was also a thriving industrial city at the time and there were several engine and boilermakers located both in Worcester and the surrounding areas. Students were able to use these engines to take measurements and calculate efficiencies with the testing apparatus available in the lab. The engines also demonstrated three different forms of valving design: Putnam rotary cam valve, Corliss valving and Wheelock cam actuated valving.

When researching the engines for the project we needed to analyze the engine with the most information and photographs. We went to the WPI archives to try and find any information on these engines. We found several photographs and a blueprint of the engine bases (included below) but no plans or diagrams of the engines themselves. One photograph (below) had the names of the corresponding engines handwritten below each engine. This was how we were able to identify what company made each engine. After determining that the most visible engine was the Putnam, we contacted the Fitchburg Historical Society to see if they had any records of the company as Fitchburg was where this engine was originally made. They were able to give us access to records and other materials obtained from the Putnam Machine Company and through this and the school photographs, we were able to start designing the engine.
Picture 1: Engine Make Designation (WPI archives)
Putnam Machine Company

The Putnam Machine Co. was founded in 1836 by John and Salmon W. Putnam in Fitchburg, Massachusetts under the name J & S.W. Putnam Co. Their main product was machine tools for industrial scale use for the railroad industry as well as specialty machine tools. They started were incorporated as the Putnam Machine Co. in 1866. The full production of steam engines began in 1855. The main factory building was 469 x 90 feet and was powered by a 70 hp putnam steam engine. There are many patents attributed to the Putnam Machine Co. including both engine, valving and machinery improvements and designs. The Steam engines were designed by Charles H. Brown until he left the company in 1863 (note this was not the end of production for steam engines). In 1913, the Putnam Machine Co. was taken over by Manning, Maxwell and Moore, another large scale railroad equipment manufacturer based out of Bridgeport, Connecticut. The prime purpose for production of steam engines was so that customers purchasing their equipment would have a way of powering it without having to go to another company to acquire an engine. All information for the Putnam Machine Co. was found through the Fitchburg Historical Society.
**Fundamental Steam Engine Design**

A steam engine is a mechanism that transforms the energy of steam into work. Most stationary steam engines of the era were designed on the basis of a four-link slider crank. The parts that made up the link were the fixed base, crank, piston rod and connecting rod. The piston rod connects the piston to a slider block mechanism so that the connecting rod does not have to be directly attached to the piston. (7) The reason for this added linkage is so that the rear end of the cylinder can have a packing seal that seals the gap between the head and piston rod so that the rear of the piston can be pressurized. If this was not in place, the engine could not be double acting due to the movement of the connecting rod. Steam input into the cylinder is regulated by a valving mechanism that will be described later. The general motion of a steam engine is as follows: The piston is pushed from one end of the cylinder to the other by steam. The steam on the end of the cylinder opposite to the pressurized side escapes through the same port and out the exhaust. This reciprocating motion is regulated by the valving on the side of the engine. (5)

Steam Engines can be classified into two types: condensing and non-condensing. The design of the engine for this project is a double acting, non-condensing, slide valve stationary engine. Non-condensing steam engines do not condense the steam after the exhaust. Condensing engines have a chamber after the exhaust that condenses the steam into water to be recirculated into the boiler. Non-condensing engines just release the exhaust steam into the atmosphere. Our engine is a non-condensing (as was the original) engine because boiler construction was not an intended part of the project and for safety reasons it requires special inspection. The double acting designation means that each stroke is a power stroke. (10) However, because of the piston rod being contained in the rear portion of the cylinder during the return stroke, this means that
the overall volume of the cylinder is less than that of the forward stroke. This difference in volume will lead to the return stroke not generating as much power as the forward stroke. For this project, the Goddard Laboratories will be providing 35 psi steam to power the engine for demonstration and test purposes. For safety reasons, we will first be testing the engine under air power to make confirm the timing and fine tuning of the valve train. The accepted general values for steam engines of various types can be found in appendix 17. The designation for steam engines is “bore” x “stroke” which for this engine would be 3” x 4-1/2”. This terminology only designates the size of the engine, not the type or power rating.

Steam engines use weighted and balanced flywheels to keep the momentum of the engine. Regarding stationary engines, these flywheels are often several feet in diameter. For single cylinder engines, this is necessary as there is no other way to get the engine past top or bottom dead center without manually moving it passed either end (which defeats the purpose of the engine). One exception to this is early rocker type engines, such as the one invented by James Watt as a means to pump water, which had a large weight to return the engine to the starting position after the power stroke. (10) The other advantage of having large flywheels was that the engines did not have to run very fast to generate a lot of surface footage on the flywheel face to power flatbelt equipment. Most large engines were not high speed engines (as the Putnam engine originally had an operating speed of 90 rpm). This problem does not exist in twin or multi-cylinder engines as the cylinders are set out of phase with each other so that at least one cylinder is on a power stoke. Steam engines are significantly more torque efficient than internal combustion engines of the same power rating although much less thermodynamically efficient. Unlike internal combustion engines, steam engines do not have a limited power band for optimal
horsepower and torque respectively. The faster a steam engine operates, the greater the horsepower generated. For slower steam engines (stationary engines) large bore, stroke and flywheel compensate for the slower speed. (7)

Steam engine pistons can vary in design but in general are shorter than automotive pistons as to take full advantage of the stroke of the engine. They contain piston rings to ensure both good compression and minimal wear on the cylinder bore. Many variations of piston shapes exist for different purposes. High speed marine steam engines use different pistons than a stationary engine and both are different from those of a locomotive. One common feature is that they are usually secured to the piston shaft by castle or jam nuts that thread onto the piston rod end. Sometimes, there is a taper cut on the end of the piston rod to match with one on the piston. This is done to maintain concentricity between the two and so the piston does not bind by tilting to the side. (7)
**Engine Casting Component Design**

In order to produce a functional engine with a similar appearance to the original putnam engine several considerations were made. Specifically scaling factors were taken into consideration, along with casting design for manufacturability, and design for serviceability, assembly, and fastening. The fifth scale aspect of the engine was determined by analyzing the capacity of all milling and turning equipment that we had access to in WPI’s Higgins Machine Shop to ensure that all components could be made on site. From there we were able to making a close series of designs matching the original engines contours, shapes, and built in design fasteners. Several components including the crankshaft and connecting rods were intentionally left slightly oversized to provide additional strength to key components that would have been to weak in scaled form. All initial designs did not include proper draft angles and casting shrinkage factors until we consulted with Cattail foundry and several casting books to clarify changes needed during the pattern making process. The draft angle needed to allow for proper pattern-mold release is between 2 and 3 degree of inward draft.

![Diagram of draft angle and mold release](image)

**Picture 2: Casting Draft Angles for Mold Release (2)**

The casting shrinkage factor researched for cast iron during cooling is roughly $\frac{1}{8}$" inch (0.125")
per foot of cast piece or about 1.04% shrinkage. During the initial design phases fastener choice were taken into consideration to ensure that all fasteners would be historically correct, and that all fastener points would allow for enough space for wrenches and other service tools. For assembly purposes we decided to include alignment dowel pins for all cast components to ensure that all linkages and connecting rods and bears would be aligned properly.
Thermodynamics of a steam engine and Steam Properties

A steam engine is a form of heat engine that uses steam as the working fluid (compressed air can substitute for steam, however it does not have the expansive properties of steam and will produce much less power). The most ideal form of steam to be used for steam engines is dry saturated steam or superheated steam. Breaking this down further, saturated steam means that the temperature of the steam is the same temperature as water boiling at the same pressure. Dry steam is steam that contains no moisture. If the steam contains moisture, it is known as wet steam. Dry steam is ideal for steam engines as water will not condense in the engine and hydraulic the cylinder. This is why there are compression reliefs. These are left open until no water is present in the steam engine. For steam properties at certain temperatures, see the steam tables in appendix 5. Another type of steam is superheated steam. This occurs when saturated steam is separated from water and heat is added, raising it above the saturation temperature and thus guaranteeing there will be no water present. This process is generally accomplished by having high pressure steam expand to a lower desired pressure. The weight per cubic foot will decrease as the temperature increases. The quality of steam is the measure of the amount of moisture in steam. Steam of high quality should have no more than 3% water in it or 97% steam by weight. For example, the quality of steam with 2% water would be .98. \[ Q = 1 - m \] where \( Q \) is quality as a decimal and \( m \) is the percentage of water as a decimal.

Steam engines may share some of the same parts as an internal combustion engine, however they function very differently. There is no combustion within the engine itself, rather a separate boiler is needed. Steam engines need to be warmed up to operating temperature before optimal running conditions can be achieved. This is so the thermal expansion of the engine
components will not dramatically change during operation and cause a failure (as different materials expand at different rates).

There is a device known as a steam indicator that can draw out a diagram for the expansion, cutoff and release of steam for the engine. This device works by having a spring loaded valve piped into both ends of the cylinder. The valve is connected to a pencil that draws a line on a rotating cylinder for the revolution of the cylinder. This device forms a graph that shows the exact expansion and cutoff of the steam during a full cycle. This device was useful for gathering data from individual steam engines when they were studied for idealizing efficiency. A graph similar to the one shown in appendix 18 is generated for the cycle. (7)
Valve Design

Steam engines use an array of valving designs to deliver steam into the cylinder and cut off the admission at the proper times to take advantage of steam expansion within the cylinder. Early engines used conical lift valves much like that of an internal combustion engine. This design was soon replaced by the D-valve. All discussion of steam valving will relate to stationary steam engines, although similar valving designs were used on locomotives. The design of the valving on the steam engine varies based on engine application, engine speed, desired output, engine design and desired economy. There are multiple patents and designs for this valving that were used in stationary engines. The ultimate goal of the valving is to minimize the admission of steam to the cylinder and maximize the expansion of steam to push the cylinder. These principles are used in both single and double acting engines of the condensing and non condensing type (these terms will be discussed later). Three common valving types of stationary steam engines are D-slide valve or-D valve (which is the simplest valving type, although not the most efficient), rotary cam valve and Corliss type rocker valve. The rotary cam and Corliss type valving offered the most steam efficiency as the cutoff for the steam is more controlled and faster acting. (7)

The Putnam engine that our project is based upon used a Putnam patented (pat. US14125A) rotary cam valving system of which there is only a patent for, however no original detailed blueprints for the valve timing exist or were obtainable within the scope of the project. Another issue with using rotary cam valving is that the scaling of the valve construction is not proportional to the scaling of the engine. On the full scale engine, this valving system, while efficient, was of the smaller size. Scaling this down even with proper plans would not allow proper admission of steam to the cylinder for the engine size and therefore would be extremely
difficult to duplicate. For simplicity of both construction and analysis of the engine we have constructed, a simple D-slide valve was used in place. Using this design, the admission, cutoff, valve lap and valve port size could be calculated. Below is a diagram that was constructed given the width of the steam port, stroke of the piston, and length of piston travel when steam is cut off from the start of the stroke, calculate the outside lap and travel of the valve. See appendix 2 for the procedure and final diagram.

The D-slider has laps on the outside and inside in order to take advantage of steam expansion. Valve lap is defined as the distance on the D-slider that extends beyond the valve port when it is in mid-position. The added material on the D-slider allows for steam expansion within the cylinder during the stroke of the engine. If there were no valve laps, steam will enter the cylinder for the full length of the stroke and no expansion will occur. The engine can run like this, as most early (1860 era) engines did, however no steam expansion is utilized and the engine will be very inefficient. To correct this, an extension of the slider or outside lap is added to add a cutoff of the steam to the stroke. Inside lap increases the compression in the cylinder by closing the exhaust sooner. (8) There is no inside lap for this engine as the lap was insignificant relative to the size of the engine and would offer minimal benefits if any at all. Larger engines, for example 15” x 22” (bore x stroke), only have about 1/32” inside lap. (7) Inside lap is necessary on larger steam engines to increase the compression in the larger bore cylinder and cushion the cylinder at the end of the stroke. Lead is the amount the D-slider opens the intake port before the piston reaches top dead center which for this engine is 1/16”. (7) See appendix 15 for lead diagram.
The cutoff of the engine was determined to be at 75% of the stroke. What this means is that steam is admitted for 75% of the intake stroke and is allowed to expand for the last 25%. This takes advantage of the expansive properties of steam to maximize the economy of the engine. The D valve has a tradeoff for simplicity, while it is simpler, it lacks the adjustability of cam and rocker valve designs.

The components that make up a slide valve are the intake ports (one at either end for steam admission to each side of the cylinder), an exhaust port, the D-slider, and connecting rod. The D-slider regulates steam admission to each side of the cylinder by way of an eccentric cam attached to the crankshaft. There are intake ports present for admittance of steam on each side of the piston so that steam pressure acts on both sides of the piston. This design for a double acting steam engine offers a more balanced motion of the engine as well as a slightly higher efficiency. Single acting steam engines rely heavily on the flywheel to keep the momentum as there is only one impulse per rotation. (7)

The steam chest is attached to the side of the engine and contains the valving mechanism for slide valve engines. The D-slider moves within the steam chest and is held against the valve seat by the steam pressure. Traditionally, a steam chest is part of the cylinder body of the steam engine. For the engine constructed for the project, we decided to make it a separate piece both to make sure the ports of the engine are in the proper location for the allotted clearance at the end of the cylinder as well as being able to lap the valve seat so that the slider block can have better surface contact with the face of the valve seat. The pressure in the steam chest holds the slider valve against the valve face. This is applicable to all vertical and horizontal slide valve engines. In some instances, retention springs are mounted to the steam chest or slider to keep the slider
centralized. This spring system is common on larger engines where the slider is heavier and is designated as the American valve. (7)

As we were not using the rotary cam valve design that was designed by Putnam for our steam engine design, we needed to calculate the port sizes, lap lead and travel of the valve. For this, a diagram can be drawn given certain known variables about the engine itself (see appendix 2 for the diagram). For the valve port design, the following dimensions can be used to determine port size: Given the diameter of the cylinder (D), you can calculate the width (L) and length of the input and exhaust ports (S and E respectively). The dimensions are $L = 0.75D$, $S = 0.15D$ and $E = 0.33D$. The thickness of the walls between the exhaust and intake ports is $\frac{3}{4}''$. This was determined based on the necessary valve travel. See diagram of valve ports for reference. (5)

For the regulation of the valve an offset or eccentric cam is used. The rule for the cam timing relative to the crankpin is 90 degrees plus the angle of advance. The angle of advance can be calculated with the formula found in the appendix 4. (10) This offset cam allows for rotational motion to be transformed into linear motion but not the other way around. The eccentric cam on the engine is constructed from bronze with a steel insert in the middle. The hole for the crankshaft is drilled offset the center the exact travel of the valve in one direction, which in this case is 1”. This will allow the valve to travel 2” in total.
Lubrication

Friction can cause wear which can lead to premature part failure or efficiency loss due to the worn surfaces or damaged components. For lubrication of external moving parts, gravity feed drip oilers will provide lubrication. These are containers that hold oil and have a needle valve flow control to deliver drips of oil at given intervals. This can be adjusted based on the speed and size of the moving part by turning the adjustment screw at the top. The difficulty arises when lubrication needs to be applied to the internals of the engine itself under steam. The drip oilers will not work because the drip oilers are rated not for pressurized applications.

The lubrication issue is addressed by directly applying lubricant into the cylinder with the steam. This can be done by means of mechanical injectors, hydrostatic lubricators or displacement lubricators. The mechanical lubricator offers the best lubrication because it is able to inject the same amount of oil to the system for every stroke of the cylinder. This is also the most complex mechanism and requires the addition of more moving parts. These were used largely on locomotives due to increased reliability. Hydrostatic lubricators and displacement lubricators are similar in function with the main difference between these two types is that the hydrostatic lubricator has a designated condenser dome to aide in the condensation of the steam thus having the condensation displacement. (5)

For this engine, we will be using a simple hydrostatic lubricator inline with the steam input line that will deliver oil to the cylinder. It is a Lunkenheimer No.1-A plain type lubricator. The designation of plain type refers to there being no sightglass to view the level or drip of oil coming out of the lubricator. This also makes regulating the flow of oil more difficult as the flow can not be seen, however there are fewer failure points as there is no sightglass. The hydrostatic
lubricator design is simple but effective in delivering oil to the cylinder. Steam oil is poured into a reservoir that is inline with the steam input to the steam chest. The reservoir is sealed and the steam is admitted. This pushes the atomized oil out of the lubricator housing through a nozzle and into the steam chest with the steam. When the lubricator needs to be refilled, the steam is shut off, water is drained out of the lubricator and then it can be refilled. A simple valve controls the amount of steam that is admitted as well as the flow of oil. The disadvantages to this design is that it can not be refilled while the engine is under pressure and the admittance of oil to the steam can be inconsistent. The steam oil that is used is a high viscosity oil generally designated as 600W oil. The high viscosity is necessary so that the oil does not thin out excessively and provide no lubrication to the piston or D-valve.
Seals and Gaskets

As stated previously in Fundamental Steam Engine Design, this is a double acting engine. Both sides of the cylinder must be sealed in order to retain steam pressure during the cycles of the engine. For the front cylinder head, this is attained by a thin copper gasket (.020”) along with the cylinder head itself. For the rear cylinder head, there must be a packing seal between the head and piston rod in order for the rear side of the cylinder to maintain pressure. This is achieved with a graphite impregnated rope that is coiled and compressed against the piston rod by an adjustable brass stuffing box.(6) The graphite rope is rated for 2500 psi and 1200 degrees F. The graphite within the rope helps lubricate the cylinder rod as it moves. However, because this seal is not perfect and motion needs to occur, a minute amount of steam will escape and some compression will be lost, however this is expected and acceptable.

The steam chest has a similar seal requirement for the connecting rod attached to the slide valve. This stuffing box will serve the same function as the one for the cylinder, however this stuffing box will be made of bronze because it will also act as a guide for the rod connected to the slide valve. The same graphite rope will be used in this stuffing box as the one for the cylinder. To seal the steam chest against, a copper gasket of the same thickness mentioned above was used.
**Manufacturing Stage 1: Pattern Making**

After completing the initial design, the main components to be cast were modified outside of the solidworks assembly. The engine cylinder which has the most complex geometry was change to model a split pattern casting, with the parting line located directly on the center of the cylinder bore. The existing flat faces on the model were than drafted inward to provide the proper pattern release. Additionally, semi-circle bosses were added to either end of what would be the cylinder bore to make a cavity indent in the sand mold to hold a cylinder core box, which would cast the cylinder with an existing undersized hole. The cylinder core box pattern was made using a 2” inch diameter pipe which would be used to make the cylinder of sand to sit in the mold during casting.

![Picture 3: Cylinder Casting Core Box (4)](image)

The other split pattern castings include the main flywheels and the crankshaft crank throws. With parting lines at the centerline of the circumference of each part. This enables the spokes to be easily released from the mold on the parting line. The remaining castings were
made as single side drop castings. The large rear end casting and the pillow-block bearing supports were cast using that same method because of there basic tapered shapes.

After the pattern shapes were changed in the model assembly in solidworks the pattern making process began. Using the built in Solidworks Camworks add in, we were able to generate g-code CAM toolpaths to make the intricate pattern shapes using various extended router bits on a HAAS TM-1 3 axis CNC milling machine. Our patterns were made by laminating large billets of standard size douglas fir construction lumber, purchased at a local lumber yard. We then adapted fixture plates to the bottom of the billets to act as hold down surfaces to use on the milling machine. Once the billets were made and fixtured to mill’s table, we utilized standard 3 axis area clearance roughing tool paths to remove the bulk of the material from the the billets with a large extended shank 1” inch router bit. In order to finish the surfaces of the patterns we utilizes a z-level surfacing tool path that adapted different scallop heights to achieve the best optimal surface finish in the least amount of toolpath time. We used an extended shank ½” ball nose router bit to blend the curves for the patterns and remove any roughing toolmarks. The finished machined patterns were than sanded, and blended using hardening wood putty. The wood was than sealed and painted with a standard lacquer. The patterns were than coated in a parting agent powder to aid in pattern release from the sand molds at the foundry.
Manufacturing Stage 2: Casting

Once the pattern making process was complete we made the journey from WPI to Cattail Foundry in Lancaster, PA, an Amish run foundry specializing in making vintage engine and tractor castings. We initially discussed how we designed the patterns and how our core box would be used to provide an existing 2” cylinder through hole. We then toured the foundry and discussed the process of mold making and how the riser and casting gates were made in the sand mold to control the flow and handle the shrinkage during the cooling process. The casting process starts in the mold making shop where the patterns are compressed in sand mold and the core boxes installed. The gate and riser are then added to the mold. Once the patterns were removed from the molds the iron was ready to pour at about 2800 degrees fahrenheit from the coal fired furnace. After about 4 weeks were able to pick up the castings and exchange pay them for their casting services. The 4 sets of engine we cast weighed in excess of 2500 lbs.

Picture 4: Several of the Castings being loaded after picking them up from Cattail Foundry
Manufacturing Stage 3: Finish Machining Rough Castings

After all of the castings were brought back to WPI the machining processes began. Using a large diameter carbide indexable face mill, all intended flat surfaces were faced to remove the rough casting scale and provide a near mirror finish on all mating components. This proved to be a challenge because the exterior casting scale contained sand and hard scale which shortened the carbide insert lifetime. Coolant also could no be used extensively because the cast iron chips harden into large chunks when mixed with water. We used negative rake CNMG 432 carbide inserts in a Kennametal KSM style 5” face mill on a large Induma horizontal milling machine to achieve optimal surface finished for the cast components. This process was used on the engines rear base, on the cylinder mounting face and bottom surface, the cylinder on both the bottom and rear mounting face as well as the steam chest mounting surface, and the top and bottom of the pillow block bearing support. The cast crankshaft crank throws were turned to diameter and faced on a 13” swing engine lathe to provide smooth thrust surfaces and remove any casting scale. A kennametal DNMG 431 style lathe tool and insert was used to machine the cast iron to achieve a good surface finish at around 80 SFM (Surface Feet per Minute) and handle the cast iron hardness. The crank throw bore was drilled, bored and reamed to a slight clearance fit with the main crankshaft.

The next major machine required on the casting was the cylinder bore, which consumed the most time to machine. Using a single point carbide lathe tool fixed in a homemade 1-¼ steel boring bar, the cylinder surface was line bored on the Induma horizontal milling machine. The process proved to be very challenge with an overall cylinder length cut time of about 25 minutes,
and about 15 cuts to get the cylinder bore to size from the cast core size of 2” rough undersized. Because the initial cast hole was not remotely round, the interrupted cutting and abrasive scale was very hard on the carbide tool, causing the tool to be re ground and honed nearly every pass. The cylinder bore size was bored to 3.25” to allow for a press fit continuous cast sleeve with a 3” bore size for the finished cylinder. The liners enable the engine to be rebuildable in the future and provide a safer continuous cast sleeve rated for pressure. The sleeves are also easily available from any racing engine catalog, and were originally designed to be used in a 1996 Chrysler Firepower V8 engine. After the cylinder liners were bored to finished size, they were honed using a Sunnen style cylinder hone to achieve optimal surface finish and cross hatching for oil retention.

The remaining machining operations required involved drill and threading various hole patterns for the engine to secure the cylinder head, valving system and the base to cylinder. The rear cylinder area was undercut to recess the rear head to allow clearance with the back casting. All hole patterns were spaced to optimize holding forces to contain pressure for the cylinder heads. All threaded holes were tap cut using spiral fluted taps to extract any chips during tapping. Dark thread cutting oil lubricant was used to insure clean cut threads and lower cutting friction. The ribbing on the cylinders was the last machine component strictly used cosmetically to match the original engines. The original engines used them for cooling and stress release on the cylinder walls however on our scale engine, the wall thickness are much thicker limiting the function of cooling associated with the ribbing. All processes discussed above will be displayed in the appendix.
**Manufacturing Stage 4: Machining Billet Components**

Although the main large components were cast at a foundry, many of our smaller components were machined out of billet materials including cast iron durabar, 1045 steel, 4140 steel, 932 bearing bronze, and common leaded brass. Many of our billet machine parts machined using various HAAS 3 axis CNC Mills and a HAAS CNC Turret Lathe. Our offset cam components were machined from cast iron durabar using surfacing tool paths, the remaining bore was turned on the manual engine lathe. Our valve body components were machined using similar surface techniques to mimic cast surfaces and have similar curves to that of early model engine components. Our main connecting rods were turned on a HAAS ST-30 CNC Turret lathe using both right and left handed carbide tooling to achieve both curves and the double tapered center section. The remaining can linkages and straight connecting rods were turned on the manual lathe and all threaded components were single point cut using the engine lathe. The pistons were also made on the manual lathe using various grooving and boring tools. All processes discussed above will be displayed in the appendix.
Manufacturing Stage 5: Finish work, Tags, and Fasteners

Our last stage of Machining included a lot of finish work to make period correct fasteners with dome head features, square fasteners, and all of the machine tags on the engine. Many of our fasteners were machined using billet hex stock to replicate the beauty polished dome head fasteners. Other standard bolts were turned to look like older bolts with dome heads. We made the domed shape on the heads using a handground HSS (high speed steel) form tool on the lathe. The ribbing on the cylinder was machined in a vertical fashion using a rotary index table on the horizontal mill to position the ribbing equally apart. A ½” carbide endmill was used to traverse in the z axis on the mill allowing for an equal length rib that cosmetically matches the ribbing on the original engine.

Our machinery tags were made using 1/8th” inch thick brass plate with machined boss letters to match what the original tags would have looked like. The tags were than painted and polished to mimic old putnam machinery tags. The front cylinder head also featured a finely machined WPI Arm and Hammer Logo in the heart representing the old machinery tags made on campus in the washburn shops prior to World War II. This embellishment added no function to the engine, however it shows the pride taken in manufacturing a good running product, with talented craftsmen putting all of their hard work into each individual component, before machines built everything.
Manufacturing Stage 6: Assembly and Alignment

After all component machining and manufacturing was completed, the assembly process began. The piston and rings were assembled in the engine and installed with assembly oil along with the primary linear connecting rod. From there the rear cylinder and graphite packing seal was installed, ensuring that the motion of the piston was free with minimal resistance. The rear end of the engine was installed to the cylinder using bolts and dowel bins. The main slider block and connecting rod guide were then installed using several fasteners and adjustment screws to control tram and side to side movement. The rotary connecting rod was then pin to the slider block and secured with a taper pin. The crank throw side used a bronze oil bushing and 1” crankpin secured with a taper pin. The bearings flywheel and offset cam were then installed and connected to the valve block on the side of the steam cylinder. Adjustments were made to the valve system using feeler gauges and an adjustment screw with locking jam nut. After all components were assembled the engine was run with liberal amounts of oil to ensure proper lubrication.
Machine Fixturing

One of the major challenges when machining rough castings is fixturing a part that has no flat surfaces and is too large to fixture in a standard machinist vise. In order to solve this problem we designed and built a two-piece vise that bolts to the table of any milling machine on WPI’s campus. It utilizes the mills table as a vise mounting surface which enables us to clamp the castings sizewises without putting excessive downward forces on uneven points which could cause the castings to buckle.

Picture 5: Homemade Two-Piece Vise

Also in order to tram uneven drafted surfaces a ruler and dial indicator technique was used to ensure that the castings would be parallel to the defined cylinder features. This technique was adapted from a WWII era tool and die machinist handbook. All billet machined components were fixtured using standard machinist vises, accompanied with soft jaws, or standard 3 and 4 jaw chuck on all lathe operations.
Importance of Tolerances

Tolerances are extremely important to the proper function and prolonged life of any mechanical component. During the design phase of building the steam engine, types of fits were examined to ensure proper performance of certain components. For example, when installing the cylinder sleeve the proper press interference was made to ensure that the press in liners do not move at all during standard engine operations. The designed interference fit was 0.0025” to ensure a press fit of about 25 tons compressive force required to move the fit between the casting and the liner. Other important fits include babbitt bearing slip fits. The crankshaft main bearings have 0.0015” clearance to allow for an oilite surface on the nickel tin coated babbit bearings. Length tolerance were also critical for the main connecting rods, because there is no adjustment for elongating the connecting rods. Each connecting rod was measured within 0.001 of each other ensuring continuous equal stroke. The lapped slider block for the linkage between connecting rods had a 0.0005” clearance between the bronze slider blocks and the base cast component to ensure perfect linear guiding without allowing any sideways deflections from the other connecting rods. Flatness and cylindrical concentricity are other important factors to consider when building a steam engine. All gasket mating surface for the cylinder heads and valve system relied on soft copper compression gaskets which were waterjet cut, to ensure coverage full contact on only milled surfaces. The other vavling components were made flat by surface grinding all components down to a flatness tolerance of +/- .00005” to ensure no steam leaks and proper sealing on all components. The cylindrical concentricity of the cylinder bore was tested using a starrett bore indicator and corrected accordingly using a 280 grit sunnen hone.
to provide a smooth surface optimal for engine compression and for a smooth ring mating surface. Improved tolerances on our engine enable us to achieve higher compression ratios due to improved surface finishes. Also tighter tolerances on wearing surfaces prolongs the life of the engine and allows for more consistent timing and overall aid the balance of the running engine.
Material Science and Analysis

When designing the engine, several material groups were used to ensure smooth power transfer without enormous amounts of friction wear. In the 1800’s many machine companies used babbitt bearing and bronze on cast iron surfaces which have proven to span the test of time. However we wanted to take the materials portion of our project a step further. We began by testing all of our castings by testing samples using a photo spectroscopy machine to conduct an elemental analysis of the gray cast iron we received from cattail foundry. After receiving the data we were able to show that our gray iron castings were within acceptable range of provided material literature making it safe to assume the structural and strength properties of the castings.

Picture 6: Spectroscopy Data for the Castings
We further examined the castings by completing a rockwell B hardness test, and found a rockwell hardness of B48 which is acceptable for grey iron castings with no heat treatment. We also conducted several tensile tests on casting blanks we machined and surface ground into dogbone shape tensile testing samples. The samples were then tensile tested at the UMASS Amherst Material Science Lab with assistance from professor Robert Daniello on an Instron machine.

Picture 7: Tensile Testing Sample
The cast iron sample broke at just over 4kN which is acceptable for and The data is displayed as follows.

Picture 8: Stress Strain Curve
Testing

For testing purposes, compressed air was used in place of steam to determine the correct valve placement and engine timing. After finishing the valve ports and steam chest components, a temporary linkage was made to connect the valve slider to the eccentric cam. We were then able to set the proper calculated angle of advance and appropriate lead for the valve relative to top dead center of the piston. We fitted a ⅜” air line providing 90 psi at an estimated 15 cfm through a ¼” npt valve to the steam chest. The engine was set slightly after top dead center as to open the valve enough. The engine is set to rotate the flywheel in the counterclockwise direction (when viewed from the non steam chest side). On steam engines, this can be changed in two ways. For reversing engines, a draft valve is used to change the position and stroke of the valve during the motion of the engine. (8) What this valve does is change the cutoff position of the valve to increase or decrease the time steam is admitted. This draft valve is common on locomotives because they have to run at high speeds. This allows the engine to run faster or slower without the need for a transmission by adjusting steam admission to conserve steam. At higher speeds where less torque is needed, the draft valve can be closed to shorten the time of the stroke of the valve and the opposite can be done to achieve torque at slower speeds. The second way to reverse flywheel rotation only applies to non reversing engines. The only way to change the direction of the flywheel rotation is to reverse the direction of the eccentric cam relative to the crank pin. In the case of this engine, the crank would have to be offset 118 degrees in the other direction. (7)
For this engine, the predicted Horsepower is 4.5 at 330 rpm. At 55 rpm, this engine produces .68 hp and was calculated using the PLAN method described in appendix 11 assuming 35psi. These numbers are approximations and the engine is assumed to have no pressure loss and the engine is ideal (no heat loss). As this is impossible, actual numbers will be slightly lower than this. (7)
Operation and service of a non-condensing slide valve engine

This is an instruction guide of how to properly start, run, stop and store the scale steam engine. The process described hereafter is similar to the process used to start and stop the original engines. The engine should have a small amount of steam flowing into the steam chest and cylinder with the drain open to allow the engine components to get to operating temperature. This should be for about 10-15 minutes prior to operation. (6) With the engine still not under steam, the lubricator valve should be opened slightly as to allow the oil to warm up and be admitted to the steam chest. Drip oilers should be placed in the upwards position to allow oil to reach bearings. All parts not affected by lubricator should be liberally lubricated with steam oil or machine oil. To start the engine, a quick opening of the throttle valve to push the cylinder over top dead center, after, the steam/air can be reduced as the momentum of the flywheel will take over. The engine should be started slowly and gradually brought to operating speed. If only dry steam is being emitted from the drain valve, the valve should be closed. To stop the engine, the steam simply has to be shut off and drains opened. The engine should be turned over a few times by hand as to clear water from the cylinder and the lubricator valve should be closed. For long term storage, cylinder and valve components should be free of water and debris. A generous coating of oil should be applied to all machined surfaces and inside the cylinder to prevent rust. To apply oil to the inside of the cylinder, spray light oil inside steam/air input input valve and down exhaust, then run engine for a short period of 1-2 minutes or a few revolutions by hand.
After this, intake and exhaust fittings should be plugged as to prevent dust and debris from getting into the steam valve body. (6)
Analysis of steam cylinder

Prior to the construction of the cylinder and pressurized components, we performed an analysis on the deformation of the cylinder and heads using Solidworks simulation software. The cylinder heads were treated as solid plugs and the cylinder was put under 150 psi (intended operating pressure is no more than 75 psi steam) with 14 psi outside pressure. The following stress and strain models were generated. We found that within the designated operating pressure that there would be no safety concern given this design. Another important factor to note is that the cylinder heads are treated as solid plugs and are not on the final design. For the model, the maximum displacement will occur on the cylinder heads at the direct center and at 150 psi, the displacement will be 0.0002”. This will never occur as the packing seals on the engine will fail long before the cylinder or heads will. If the pressure in the system of the engine becomes a concern, a pressure release valve can be added inline with the intake pipe to prevent the pressure entering the engine to ever reach a pressure higher than the release valve.
Picture 10: Stress intensity at 150 psi

Picture 11: Displacement of cylinder material at 150 psi
**Terminology**

**Steam Engine:** A heat engine that converts the expansion of steam into work. The steam pushes a piston back and forth. The work is converted from linear motion to rotational motion by means of a connecting rod, crankshaft and flywheel.

**D-slider Valve/Slider Valve:** The simplest and oldest form of steam valve that has been used for many steam applications due to simplicity. This design consists of a steam chest with a steam inlet and exhaust port and a D-slider to regulate steam admittance and exhaust to and from the cylinder respectively. An eccentric cam is used to control the movement of the D-slider over the steam ports.

**Rotary cam Valve:** Steam Engine valve gear that utilizes a gear connected to the crankshaft of the engine to drive a cam that controls the movement of cylindrical valves that regulate the input and exhaust of steam. This definition refers to the Putnam patented rotary cam valve used on their full size steam engines.

**Corliss Valve:** Similar to the function of a rotary cam valve with the main difference being that a cam is used to drive a rocker mechanism that controls four different valves. Two of these valves are input valves on the steam chest side and the others are exhaust. The valves are cylindrical and run perpendicular to the cylinder on the top and bottom. This type off valve gear was used on a large number of engines due to the steam efficiency increase. The Corliss design is very complex when compared to the simple slide valve design. See patent US747109A for full description.

**Hydrostatic Lubricator:** This form of lubricator was developed as a replacement for the displacement lubricator. Although it operated under the same principles, key changes were made
to improve the functionality. A sight glass and separate condensing chamber were added so that the level of oil can be monitored and the steam condenses faster. See patent US 1156133A for the description lubricator developed by the Detroit Lubricator Co.

**Displacement Lubricator:** The most primitive type of lubricator developed in England to lubricate steam engines and locomotives. This uses an oil reservoir that is connected to the steam inlet pipe before the steam chest. Steam enters the oil chamber and condenses. The water displaces the oil and forces it back into the steam line to be pushed into the steam chest and then the cylinder. This provides sufficient lubrication to the cylinder and piston to reduce wear as well as increase compression.

**Cylinder:** The section of the steam engine where steam expansion produces power by pushing a piston. The linear motion of the piston is transformed into rotational motion.

**Valve Lap:** The distance on the D-slider that extends beyond the valve port when it is in mid-position. The added material on the D-slider allows for steam expansion within the cylinder during the stroke of the engine.

**Lead:** The distance between the edge of a valve port and the edge of the valve when the piston is at top dead center. For this engine the lead is 1/16”.

**Drip Oiler:** Gravity feed oil reservoirs that drip oil onto surfaces for lubrication. The rate of oil flow can be adjusted based on the application by turning an adjustment knob on the top of the oiler.

**Crankshaft:** the main shaft of the engine through which rotational motion is transmitted from the crank throw to the flywheel. In the case of the steam engine, the eccentric cam to regulate valve motion is also connected to this shaft by a key.
**Condensing Engine:** Exhaust steam from the engine is condensed and returned to the boiler to be reused. This allows for an increase in steam efficiency due to less need to refill the boiler with water. Another key aspect of this type of steam engine is that the hot exhaust steam is used to preheat water going into the boiler which means that it requires less fuel to heat the water in the boiler.

**Non-Condensing Engine:** Exhaust steam from the engine is not condensed and goes into the surrounding air through an exhaust pipe.

**Bore:** The diameter of the steam cylinder.

**Stroke:** The total travel of the piston in the cylinder.

**Valve Port:** The pocket in the steam chest where steam enters or exits the cylinder. These are designated as intake and exhaust ports respectively.

**Steam Oil:** A highly viscous oil with the designation 600W with an ISO 460 viscosity rating.

**Cutoff:** The time when steam is no longer admitted to the cylinder to allow for steam expansion. This is regulated by valve lap. The cutoff for this engine is at approximately ¾ of the stroke.

**Eccentric Cam:** A circular disk that has a hole offset a designated distance from the center. This allows for half a revolution of the shaft to move the associated rod the diameter of the circle created by the offset of the cam. This is commonly referred to as the throw of the eccentric cam. The eccentric on this engine is offset 1” which gives the valve travel as 2” (1” in each direction).

**Angle of Advance:** Angle due to lap plus angle due to lead of the valve. This angle is after 90 degrees on the eccentric relative to the crank. For this engine, the angle of advance is 28 degrees past 90 or 118 degrees between the cam and crank.
**Stuffing box:** The apparatus that holds in the graphite rope packing material around the piston rod. Made from brass or bronze, it consists of two pieces. The graphite packing material is coiled around the shaft and compressed when the cap is tightened.

**Graphite Packing:** Graphite impregnated rope that is designed to provide a seal around a moving or rotating shaft.

**Flywheel:** A flywheel is a large wheel attached to one end of the crankshaft. The mass of the flywheel is used both to provide momentum to keep the engine running and run flat belt equipment off of. This was common practice to transmit power from the engine to a piece of equipment or generator.

**Indicated Horsepower:** The calculated horsepower based on given dimensions of the engine, mean effective pressure and measured rpm of the flywheel. This was traditionally measured with a steam indicator. See Appendix 3 for calculations.

**Mean Effective Pressure (M.E.P.):** The average pressure pushing the piston forward during an entire stroke in one direction minus the resisting pressure. It can be estimated by the formula in Appendix 3
Sources


(11) Students of Worcester Technical Institute, "The WPI Volume 11 Issue 3, May 18 1895"

Appendices

Appendix 1: Engine specifications and dimensions

Bore and Stroke: 3” x 4.5”

Working Pressure Steam: 75 psi

Test Pressure Air: 90 psi

Max RPM: 330

Min RPM: 55

Calculated Max Indicated Horsepower at 330 RPM: 4.46

Calculated Min Indicated Horsepower at 55 RPM: .677

Lubrication: Hydrostatic Pressure Feed

Valving: D-Valve

Cutoff: 75% of stroke

Angle of advance: 28°

Engine Type: Non Condensing, Double-acting

Appendix 2: Valve travel and lap diagram (8)

Note that the top diagram is the one for the scale engine, the photographs following it are taken from pages 36-37 of One Thousand Pointers For Machinists & Engineers as instructions for creating the diagram starting with example 22. This method for the diagram can be used on any
size slide valve engine.
center of the line $y_2$, and through $s$ and perpendicular to the line $y_2$, draw the line $AB$; if the latter line is drawn accurately it will always pass through the center $c$. The distance between the points $s$ and $c$ will be the amount of lap required, and in this example it is $1\frac{7}{8}$ inch.

It sometimes occurs, in designing a new locomotive, and often in designing stationary or marine engines, that only the width of steam port and point of cut-off is known, and the lap and travel of the valve is not known. In such cases both of these can be at once determined by the following method:

Example 23.—The width of the steam port is 2 inches; the stroke
of piston, 30 inches; steam to be cut off when the piston has traveled 24 inches from the beginning of its stroke; find the lap and travel of the valve.

Fig. 20. Draw any circle, as $A B M$, whose diameter is larger than what the travel of the valve is expected to be. Through the center $c$ draw the diameter $y z$, and, since the stroke of piston is 30 inches divide $y z$ into 30 equal parts. Steam is to be cut off when the piston has traveled 24 inches; therefore, through point 24 draw a straight line $g k$ perpendicular to the diameter $y z$, intersecting the circumference $A B M$ in the point $g$. Join the points $y$ and $g$ by a straight line; through the center $s$ of the line $y g$ draw a line $A B$ perpendicular to $y g$. So far, this construction is precisely similar to that shown in Fig. 19, and in order to distinguish this part of the construction from that which is to follow, we have used dotted lines; for the rest full lines will be used. It will also be noticed by comparing Fig. 20 with Fig. 19 that, if the diameter $A B$ had been the correct travel of valve, then $c s$ would have been the correct amount of lap. But we commenced this construction with a travel that we know to be too long; hence, to find the correct travel and lap, we must proceed as follows: Join the points $B$ and $y$. From $s$, toward $B$, lay off on the line $A B$ a point $b$; the distance between the points $s$ and $b$ must be equal to the width of the steam port plus the amount that the valve is to travel beyond the steam port, which, in this example, is assumed to be $\frac{1}{4}$ of an inch. Therefore the distance from $s$ to $b$ must be $2\frac{1}{4}$ inches. Through $b$ draw a straight line $b y$, parallel to $B y$, intersecting the line $y g$ in the point $y_s$. Through the point $y_s$ draw a straight line $y_s x$, parallel to the line $y x$, and intersecting the line $A B$ in the point $c_s$. From $c_s$ as a center, and with a radius equal to $c_s b$, or $c_s y_s$, describe a circle $a b y_s$. Then $a b$ will be the travel of the valve, which, in this case, is $7\frac{1}{4}$ inches, and the distance from $c_s$ to $s$ will be the lap, which, in this example, is $1\frac{1}{4}$ inch.

Appendix 3: Mean Effective Pressure

M.E.P. = $0.9(C(p+14.7)-17)$ where $p$=input steam pressure in psi gauge and $C$=cutoff constant from table in appendix 14. For this engine, M.E.P. = 28.1 psi for 35 psi input pressure and $\frac{3}{4}$ stroke cutoff (constant is .97).
Appendix 4: Angle of Advance

$$\text{AOA} = \sin^{-1}((\text{lap} + \text{lead})/\text{radius of eccentric}).$$

$$\text{AOA} = \sin^{-1}((.407 + .0625)/1) = 28 \text{ deg}$$

Appendix 5: Steam Tables (taken from *The Steam Engineers Handbook* (6))
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Appendix 6: Corliss Engine Patent US747109A
Appendix 7: Displacement Lubricator Patent US 1156133A
Appendix 8: Putnam Rotary Cam Valve Patent US14125A
 UNITED STATES PATENT OFFICE.

CHAS. H. BROWN and CHAS. RICHARDS, OF HOPKINTON, MASSACHUSETTS, ASSIGNS TO THE PUTNAM MACHINE CO.

MEANS FOR REGULATING AND WORKING STEAM-VALVES AS CUT-OFFS.


To all whom it may concern:

Be it known that we, CHAS. H. BROWN and CHAS. RICHARDS, both of Hopkinton, in the county of Worcester and State of Massachusetts, have invented a new and improved Method of Regulating Cut-Off of Valves by the Governor, whereof the following is a full, clear, and exact description, reference being had to the annexed drawings, of which one is a side elevation of an engine with the steam improvements attached; Fig. 2, a plan of the same; Fig. 3, a section through the steam valve upon the line X, Y, of Fig. 2; Fig. 4, a section upon the front of the valve; Fig. 5, a plan of our valves; Fig. 6, a vertical section upon the line B, C, of Fig. 1; Fig. 7, a horizontal section upon the line B, C, of Fig. 1; Fig. 8, a vertical section upon the line E, F. G, of Fig. 1; Figs. 9, 10, 11, 12, 13, are sections through the valves upon various lines of Fig. 6, as indicated on the drawings, which will be referred to hereafter.

Our invention consists in a new and peculiar method of connecting the balance out of steam engines with the governor, by which the steam may be cut off at any point of the stroke according to the amount of work upon the cylinder, the parts for effecting this being simple, effective, and not liable to get out of order or require repair.

To enable others skilled in the art to make and use our invention, we will proceed to describe the same, so far as we inspect of carrying it out, referring generally to the parts of the engine, and describing more particularly the specific improvements which we have added thereto, giving, lastly, the operation of the whole combined, assuming the drawings H, I, to be the cylinder Z, the steam valve Q, the safety valve P, the connecting rod K, the crank shaft H. The latter carries a cog wheel L, which engages with a gear M, upon a short shaft W, which is a geared wheel upon the shaft X, which goes with the wheel Y upon the shaft Z, which latter carries the cone that admits the steam and exhaust valves.

The connection between the governor and the apparatus which admits the valve is will now be described: T is the envelope of the governor, upon which slides the other Q, in the manner shown by the dotted lines upon the top of the rod V, which slides freely in a vertical direction in the guides W and Z, attached to the frame externally to the main body, being the axis attached to the shaft a, which vibrates in the bearing B, projecting from the frame of the engine.

The other shafts B, C, are attached to the shafts a, and vibrating with it.

The steam valves are best seen in the section, Fig. 4, 5, 6, 7, and 11, which show the parts of the boiler as they appear after the primary and secondaries have been cut off, but for the sake of the Beverley, due to the very close of the shafts a, B, C, which causes the cylinders to be raised from their seats, and steam is admitted to the cylinders.

In proportion as the balls of the governor Governs, the rod V, is raised, and the balls of the levers b, are withdrawn from the shafts in the bottom of the valve stems p, thus carrying the shoulders f, further from the circles of revolution of the cam a. The levers b, are arranged with reference to the governing and the cam a, and when the balls are at their highest point, the shoulders f are withdrawn (as in Fig. 10), so that the cammoves without leading the levers, and the needle valves are not opened. When the balls are in any other position, the shoulders of the lever b, are more or less over the cam a, and at the 110 later revolve, the levers are raised, and the needle valves are kept open for a longer or shorter space of time. The eccentric M then cuts off sooner or later, in proportion as the balls are more or less distant. The levers 183 a, are caused upon the under side so that they may be moved down gradually as the cam revolves.
Appendix 9: Putnam Frame Improvement Patent US191716A
Appendix 10: Steam Governor Patent US236029A

(Model)

F. HEYER.
Steam Engine Governor.

No. 236,029.
Patented Dec. 28, 1880.

Fig. 1

Fig. 2

Witnesses.
Franz L. Oersted
J. M. Barty.

Inventor.
Frederick Heyer
R. F. Van der Moer, architect.

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Appendix 11: Indicated Horsepower Calculations

The indicated horsepower of the steam engine can be calculated by the formula

\[ I.H.P = \frac{P}{L \cdot A \cdot N}{33,000} \]

where P = mean effective pressure in psi (Note: this is not the working pressure of the engine), L = length of stroke in feet, A = area of piston in square inches, and N = revolutions per minute. For this engine, the I.H.P = \( \frac{(28.1 \cdot 0.375 \cdot 42.4 \cdot 330)}{33000} = 4.46 \) hp at 330 rpm. At 55 rpm, this engine produces .677 hp.

Appendix 12: Excerpt from The WPI Vol. 11, Issue 3 from May 18, 1895 which contains an interesting anecdote regarding one of the steam engines. (11)

“IT DIDN'T WORK On his arrival early Friday morning, the engineer noticed that the front door of the hop was wide open and rightly guessed that something was up. Everything was apparently in good order, however, till the engine room was reached. Here a chair, with legs upward, was situated on one of the pillow-blocks, the iron cap of which was missing. This is an iron block weighing about twenty-five pounds and is held in place over the box of the flywheel shaft by two large bolts. The only explanation to be obtained for the strange and sudden disappearance is that some of the students finished up the celebration of Thursday's sports by a little sport of a different kind, the supposition being that '96 was the party interested, the idea being to stop operations at the Shop the next morning and thereby gain a loaf. But it didn't work! In less than five minutes after the gong sounded the engine started up. Mr. Humphrey had rigged a temporary wooden cap which well answered the purpose. Had the box which lies just beneath the cap, and is made up of four quadrants been taken, in all probability the '96 men would have had a morning's rest. Saturday morning the missing link was found just outside the Shop door, but was not put back to its old place till Saturday night.”
Appendix 13: Valve Port Size diagram and calculations

Appendix 14: Mean Effective Pressure constants (6)

**Constants used in Calculating M.E. P**

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<th>Cut-off</th>
<th>Constant</th>
<th>Cut-off</th>
<th>Constant</th>
<th>Cut-off</th>
<th>Constant</th>
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Appendix 15: Slide Valve Diagram from *Steam Engine Design and Mechanism*
Appendix 15: Valve Lead Diagram from *Steam Engine Design and Mechanism*

Valve lead is designated as distance ab in the diagram.
Appendix 16: Table of eccentric cam angle relative to the crank position (7)

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<th>Kind of Rocker-Arm</th>
<th>Angle Between Crank and Eccentric</th>
<th>Position of Eccentric Relative to Crank</th>
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<td>Ahead of crank</td>
</tr>
<tr>
<td>Over</td>
<td>Reversing</td>
<td>$90^\circ - \text{angular advance}$</td>
<td>Behind crank</td>
</tr>
<tr>
<td>Under</td>
<td>Direct</td>
<td>$90^\circ + \text{angular advance}$</td>
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Appendix 17: Accepted running pressures for given steam engine types (7)

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<td>150 to 200 or higher</td>
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<td>Quadruple-expansion</td>
<td>200 or higher</td>
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<td>Locomotive</td>
<td>160 to 210</td>
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Appendix 18: Cylinder pressure diagram relative to cam position (7)
Supplementary Photographs
Making the Patterns
Machining the Cylinder
Machining the Crank Throw
Cylinder Ribbing
Cylinder facing and hole patterns
Machining the main base
Mating the base and cylinder for the first time
Flywheel Machining
First rough fit
Pressing in cylinder liners
Machining taper on flywheel
Surface Grinding slider block bodies
Machining slider block
Rockwell Hardness test of casting
Cylinder head recess machining
Machining and fitting front cylinder head
Flywheel runout test
First fit on finished base
Grinding and machining connecting rods
Fitting connecting rod, slider block assembly and piston rod to flywheel and base
Machining the piston
Taping rear cylinder head for packing seal
Machining and grinding steam chest cover
Machining valve ports for steam chest
Machining D valve
First Assembly
Machining valve ports
Completed steam engine under Mechanical Engineering display in Higgins Laboratories