AC 2012-4707: THE NEWCOMEN PUMPING ENGINE: A CAPSTONE DESIGN PROJECT

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The Newcomen Pumping Engine: A Capstone Design Project

abstract

The purpose of this article is to describe the undergraduate mechanical engineering capstone design project of building an operating and instrumented scale model Newcomen Engine. Thomas Newcomen built the first successful steam engine in 1712. His design was built in large numbers from 1712 until about the 1820s and continued to be used until about 1930. Today's engineering students should be aware of this significant historical development as part of their education. The design project described in this article is an excellent capstone design project that integrates fundamental knowledge of mechanical engineering with historical perspectives.

introduction

The year 2012 marks the 300th anniversary of the first successful reciprocating steam engine. This breakthrough was a pumping engine built by Thomas Newcomen of Dartmouth, England, at the Coneygree Coal Works, about 9 miles northwest of Birmingham.

In celebration of such an important invention, which can be classified as a turning point in steam technology, a design/build project was conducted at the U.S. Naval Academy to construct an operating and instrumented, scale Newcomen steam engine model.

This article describes the design process and modeling efforts already conducted, as well as to be conducted over the course of this project. As of the date of this writing, all calculations and values are theoretical, but as the design comes together, the values and calculations will be refined and collected through testing and analysis of the operational model Newcomen engine. This paper explains the steps taken in the design process leading up to where the project stands currently, as well as the steps that will be taken to further develop an operational engine, in view of performing an exergy analysis of the model engine. Developing and documenting this level of analysis is a significant goal of this project.

background

The purpose of this section is to familiarize the reader with a synopsis-level history of the Newcomen engine. The definitive book on this topic is *The Steam Engine of Thomas Newcomen*, by L.T.C. Rolt and J.S. Allen.[1] The reader is encouraged to refer to this excellent book for a more detailed history of the Newcomen engine.

The beginning of the 18th century was an extremely important time for the advancement of the steam engine. Many scientists who are familiar to us today contributed to the development of practical steam power, but one individual who stands out was Thomas Newcomen (1663-1729), an ironmonger by trade. Newcomen was the first to develop a working steam engine based on the principles and designs of the engineers and scientists before him, notably a steam piston-cylinder device demonstrated, but never commercialized by Denis Papin. Papin acknowledged difficulty in finding shops with the skill to produce pistons and cylinders of the size and precision needed to perform useful work. Being an ironmonger gave Newcomen a distinct practical advantage, because he was able to use his knowledge of the fabrication of iron tools to develop his engine. Further, his partner John Calley, a plumber and glazier by trade, brought complementary practical skills to the project. The two men took seven years to develop a properly working engine.[1]

Newcomen's first commercial engine was installed in 1712 at the Coneygree Coal Works, Tipton, West Midlands, England. The main use of this engine, and the Newcomen engines that followed, was to raise water from mines so that miners could extract coal, metals, and minerals from deeper portions of the mines which had been flooded with groundwater. The engine, especially in its original form, was extremely inefficient, but was very capable of pumping large quantities of water from previously unattainable depths. Rolt and Allen report that some Newcomen pumps dewatered mines more than 900 feet below the ground surface.[1]

general operation of the Newcomen steam engine

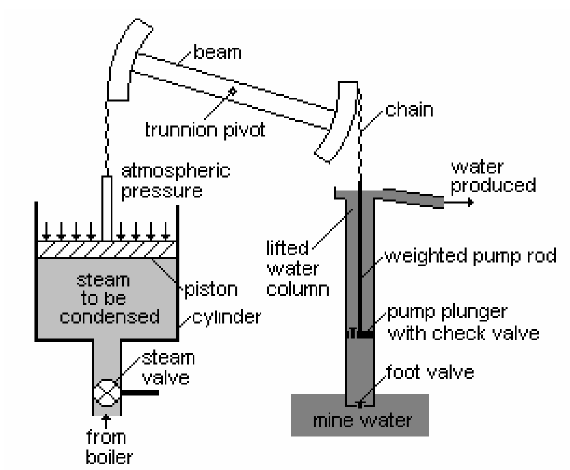

Figure 1 – Newcomen Engine Simplified Schematic

The purpose of this section is to familiarize the reader with the operation of a Newcomen water pumping engine.

As shown in Fig. 1, the basic configuration of the engine consisted of three main parts: (1) the steam piston and cylinder; (2) a rocking beam; and, (3) the reciprocating water pump. The piston and cylinder provided the motive force by condensing steam, which created a vacuum in the cylinder. Atmospheric pressure on the top of the piston then caused the piston to move. The rocker was used to transfer power from the piston to the pump, which raised the water from the mines.

A more complete configuration of Newcomen's design is shown in Fig. 2.

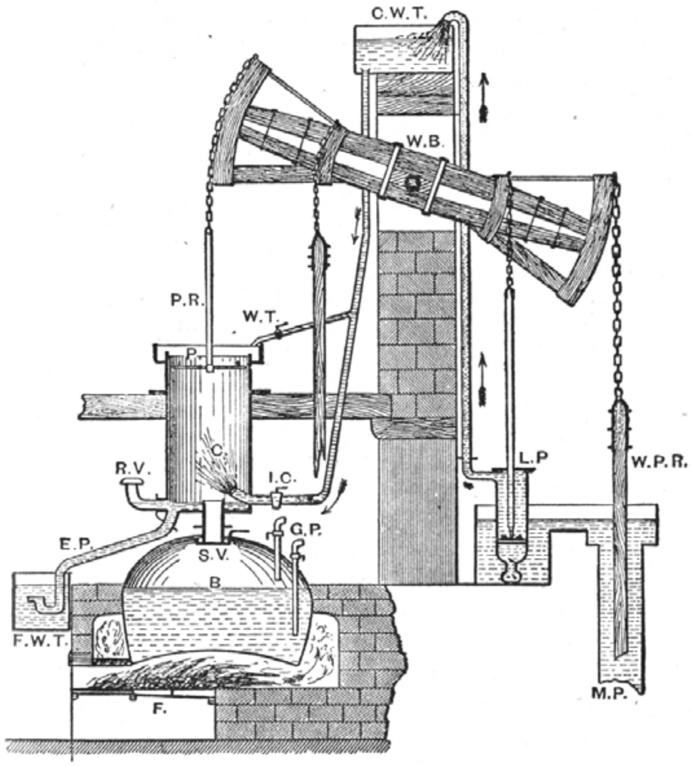

Figure 2 – Newcomen General Engine Configuration [2]
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Steam entered via the steam valve (SV) while the piston (P) rose in a “non-work” reset stroke. The main pump (MP) side of the beam was weighted so that the engine required steam pressure only at, or slightly below, atmospheric in order to raise the piston. The work portion of the cycle commenced with the piston at the top of its stroke and the cylinder full of steam. Water from the cold water tank (CWT) was sprayed under gravity flow directly into the cylinder (C) to condense the steam and create a vacuum. The atmospheric pressure pushed the piston down in the work stroke. Steam was then admitted to the cylinder from the boiler to reset the cycle. Condensate and spray water drained and gases in the cylinder were purged out via an “eduction pipe” (EP) to the feedwater tank (FWT). A “clack valve” (not shown in Fig. 2, but installed at the eduction pipe discharge in the FWT) prevented drawing the drained water back into the cylinder during vacuum conditions. The piston incorporated a water-aided seal, hence the pipe to supply sealing water via the water tap (WT).[2]

As shown in Fig. 2, the Newcomen engine was fitted with some clever auxiliary systems to provide for the overall operation of the engine. A secondary lift pump (LP) filled the CWT. The hot water in the FWT was used to refill the boiler as needed. In addition, a plug rod connected to the main beam (un-lettered, but to the right of the main cylinder in Fig. 2) was adapted to trigger the valve events of the cycle. This early version of automation allowed reasonably steady operation of the engine after it was started by the engineman.[2]

Based on historical data of Newcomen steam engines, it has been calculated that the first engine produced about 4.6 hp as measured in water produced, with an overall efficiency from fuel to water produced of about 0.8%.[3] However, further development in these steam engines by John

Smeaton between 1765 and 1772 increased the engines' efficiency to around 1.4%, a noteworthy increase. Even after the more famous, and more efficient, Boulton & Watt engines were developed in the 1770's, the simpler and very reliable Newcomen engines continued to be built for the purpose of pumping water from coal mines up until the 1820's. Coal mines had a ready supply of unsellable "slack coal" as the fuel which influenced the decision about which technology to use. The last operational Newcomen engine was retired around 1930.[1]

design process overview

The project followed the methodology set forth in *Engineering Design – A Project-Based Approach*, by Dym and Little.[4]

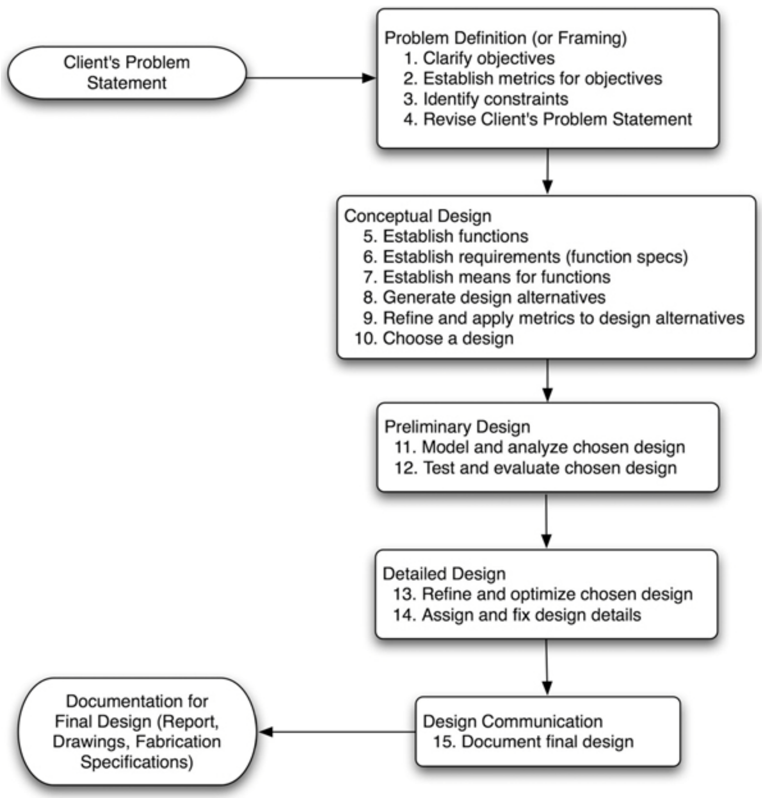

Figure 3 – A Prescriptive Model of the Design Process[4]

Dym and Little present various tools to address these major steps and how we used them on this project will be described.

The problem statement we ultimately derived was to "Design, build, instrument, and operate a replica Newcomen engine in order to demonstrate the technology and to gather empirical data for analysis." The problem statement needed to be complete, yet succinct. It provided focus to keep the project on track. When at several points our project began to go astray, looking back at the problem statement gave us direction.

Next, it was important to determine the customers of the project. This is a broader list than just who requested the product. The more obvious customers of the Newcomen Steam Engine were

Mechanical engineering students. Engineering students benefit from this project because it can be used as a demonstrator in the classroom to better understand thermodynamic processes and mechanics. Other less obvious customers of the project were the lab technicians who will be in charge of operating and maintaining the engine in the future, professors associated with the project and who intend to author papers on the results, and the broader engineering community and historians who will be able to use the information collected from this apparatus to better understand the amazing technology built 300 years ago. A list of customers was created as shown in Fig. 4.

Customers
Project Mentors
Future Mech E students
Thermodynamics Teachers
Lab Technicians
Historians
Engineering Community

Figure 4 – Customer List

The next step in the design process was to create a list of needs. Because the list was made early in the design process, it tended to be somewhat general and just gave an overview of components and services required to create an operating engine. As shown in Fig. 5, the "needs list" did not need to cover every detail of the project. Some items on the list were not even used.

Needs list
Access to machine shop services
Cart for mobility
Steam Generator
Piping
Insulation
Temperature and Pressure Gages
Steel stock
Water Sprayer and Tanks Check Valves

Figure 5 - Needs List

determining objectives

After the problem statement was set and the project began to take shape, it was important to determine the objectives of the project to act as the key requirements and constraints. Dym and Little use an "objective tree" to help shape the objectives of the project. An objective tree helps determine what the main objectives are, and what objectives are subcomponents of the larger objectives. It is also important to assign metrics to each objective as a way to measure whether the objectives are being met. The objective tree of our Newcomen engine is shown in Fig 6.

Reliable	Authentic	Measurable	Affordable	Interchangeable
Operational	True to Original Design	Instrumentable	Scalable	
Repeatable		Demonstratable	Mobile	
Durable				
Maintainable				

Operational-Power(kW)
Repeatable-# of replications
Reliable-# of cycles/operations
Durable- drop height, m
Maintainable-$$/year-hours of maintenance/hours of operation
Scalable-inches/foot
Affordable- dollars
Measurable-Power(kW), Efficiency(%), Heat Loss, Temperature, rotational velocity (rpm)
Instrumentable- number of instruments
Demonstratable- MTBF cycles per failure
Authentic-# of parts replicated, number of actual materials used
True to Original Design- surrogate, how close to original did we get
Interchangeable - number of pistons that can be switched in or out
Mobile- time to move and set up again, s

Figure 6 – Objective Tree

The main objective was then used to determine what was most important when designing the engine. A piecewise comparison chart was used to rank the objectives as shown in Fig. 7. All of the main objectives were sequentially paired and compared to develop the rank of their importance.

	Reliable	Authentic	Interchangeable	Affordable	Measureable	Totals
Reliable	x	.5	1	1	0	2.5
Authentic	.5	X	1	1	.5	3
Interchangeable	0	0	x	1	0	1
Affordable	0	0	0	X	0	0
Measureable	1	.5	1	1	X	3.5

Figure 7 – Piecewise Comparison Chart

The final tool used in the initial design process was the "house of quality" (HoQ), shown in Fig 8. A HoQ combines all of the design tools previously shown. In the "who" column, the HoQ ranks the importance of the objectives with respect to the customers. The body and "roof" of the house of quality set metrics with units to determine whether the objectives are being met and how well they are met. The "Now" section of the HoQ ranks the objectives versus products similar to the design. For example, we used the Newcomen engine at the Henry Ford Museum Engine as a comparison unit. It is a full scale display of one of the historic engines, but is no longer operational and cannot be analyzed for operating data.

Newcomen Steam Engine

	mass	volume	number of measurements	efficiency	power	volume of water/steam	Temperature	Pressure	#cycles till failure	% original parts	authentic material	# of cycles without fail	maintenance hours	price	steps to operate
volume	9														
number of measurements	1														
Efficiency															
Power			3	3											
Temperature		9	3	3	3										
Pressure			3	3	3	3									
r of interchangeabl	1		3	3	3	3	3								
cycles till failure			3	3	3	3	3	3							
% original parts	3		1												
authentic material	3			1	1		1			9					
Cycles without fail									9		3				
maintenace hours										3	3	9			
price	3	3	3	1						3	3	1	1		
steps to operate												3	1		
"+,-,="	-	-	+	+	+	=	=	=	+	+	+	+	-	-	-
units	kg	m^3	#	%	W	m^3	kPa	s	cycles	%	%	#	hours	$	#

What	Engineer Community	Commander Carr	Historians	Lab Techs/USNA	mass	volume	number of measurements	efficiency	power	volume of water/steam	Temperature	Pressure	#cycles till failure	% original parts	authentic material	# of cycles without fail	maintenance hours	price	steps to operate	Newcomen Mem. Engine	BC Living Museum Engine	Henry Ford Museum Engine
Mobile		9		9	9	9						9			3					3	3	3
Measurable	9	9	9				9	9	9	9	9		3			3	1		3	1	2	3
Authentic	9	9	9					3	3	3	3	3	3	9	9			3		1	1	1
Operational	9	9	1	6				3					3			9	6		9	1	1	2
Reliable		9		9									9	3	3	9	9		9	3	3	3
Affordable		9			1	1	3				1			6	3		3	9		3	3	3
Demonstratable	9	9	3	9	3	3	1					3		3	3				9	1	1	2

Figure 8 – House of Quality

<u>design</u>

In order to begin designing an operational model Newcomen steam engine, the function of the engine had to be completely mapped. The "black box" functional decomposition approach was used. The inputs to the engine were found to be steam, spray water, and signals to the control valves. The outputs of the engine were condensed steam, mechanical work, and various instrument measurements. The functional decomposition used for the project is shown in Fig 9.

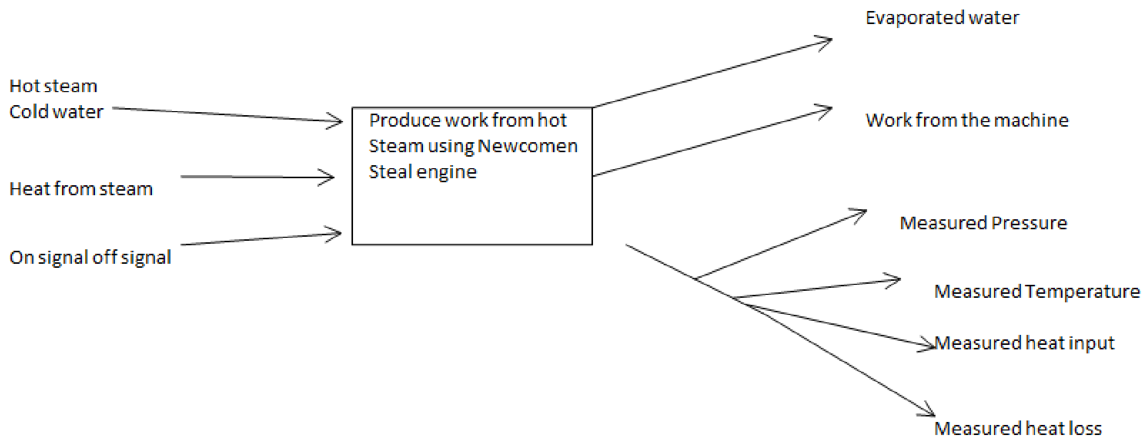

Figure 9 – Functional Decomposition Chart

After all of the functional requirements and energy flow interactions in the Newcomen were explicitly documented, the next task was to map the design space. Dym and Little teach the most direct way to map the design space is through the use of a "morph chart." To employ a morph chart, all of the different features or components of the design must be determined. For the Newcomen engine these included: steam source, cylinder size and material, valve types, rocking beam design, and output method. Figure 10 shows the morph chart mapping the complete design space for our Newcomen Engine.

	Wooden Rocker	**Steel Rocker**	**Pulley System**		
Cylinder size	7 feet 10 inches 21 inches diameter 1 inch thick	3 Feet High 8 inch diameter .32 inches thick	2 feet High 6 inch Diameter .28 inch thick		
Steam production	Coal heating water tank	Steam Generator	Burner		
Water sprayer	Water nozzle and pressurized water tank	Pump that sprays water from tank	Water nozzle and gravity		
Cylinder Design	Regular cylinder Flat bottom	Funneled Bottom	Multi holed flat bottom		
Energy output method	Shock Absorber	Water lifter	Water Spinner		
Cylinder material	Copper-Nickel Brass	Copper-tin Brass	1040 Carbon Steel	Cast Iron	Stainless Steel
Check Valves	Standard Check Valve	Leather Check Valve			
Piston Sealant	Water Rope with water on top	Lubricated O ring			

	Wooden Rocker	Steel Rocker	Pulley System		
In take timings	Controlled by rocker	Controlled by timer	Controlled manually		

Figure 10 –Morph Chart

Four design concepts were created by using different combinations of component options from the morph chart. The design features of each design concept were picked with the idea of embodying a certain important design objective, such as having an operational and resilient engine or having an authentic engine. The four final design concepts for the model Newcomen Steam engine are shown in Table 1.

Design	Cylinder mat'l	Cylinder bore, thickness and height	Cylinder bottom	Stroke-to-cylinder-height ratio	Water sprayer	Piston seal	Rocker material	Output mode	Check valve
Design 1	Cast iron	8 in .32 in 36 in	Flat	2/3	4-foot tank	Wet rope and water seal	Wooden 2 x 4	Water raiser	Leather
Design 2	Stainless steel	6 in .28 in 24 in	Funneled	1	Pressurized tank	Lubricated O-ring	Steel rod	Water spinner	Modern
Design 3	1040 steel	6 in .28 in 24 in	Flat	11/12	4-foot tank	Lubricated O-ring	Steel rod	Shock absorber	Leather
Design 4	1040 steel	8 in .32 in 36 in	Funneled	2/3	Pressurized tank	Lubricated O-ring	Steel rod	Water raiser	Modern

Table 1 – Design Concepts

The completion of the conceptual design work introduced four main design concepts, each with different design elements. The four design concepts were plausible solutions to the problem statement of the Newcomen Steam Engine. In order to decide which of the four designs most satisfied the objectives of the capstone project, a Pugh chart was created in which the six design objectives were weighted and each design was scored on how well it satisfied the objectives. The Pugh chart created for the project is shown in Fig. 11. The weightings attached to each objective show the importance of the objective compared with other objectives. The most important objectives were operational and measurable.

Objective	Criteria	Importance (1-4)	Design 1	Design 2	Design 3	Design 4
Mobile	-Largest Dimension	2	2	3	3	3

Objective	Criteria	Importance (1-4)	Design 1	Design 2	Design 3	Design 4
	-Weight					
Measureable	-Ability to Instrument -Accuracy of Output Method	4	1	2	3	4
Operational	-Does/Doesn't work -Number of Cycles without Adjustment	4	2	4	4	4
Reliable	-Number of Cycles until Failure	2	2	4	2	3
Authentic	-Number of Authentic Components -Authentic Materials Used	3	4	1	2	3
Affordable	-Cost of Components -Cost of Maintenance	1	3	2	4	2
Total			**35**	**43**	**48**	**55**

Figure 11 – Pugh Chart

<u>project management</u>

Our Work Breakdown Structure is shown in Fig. 12.

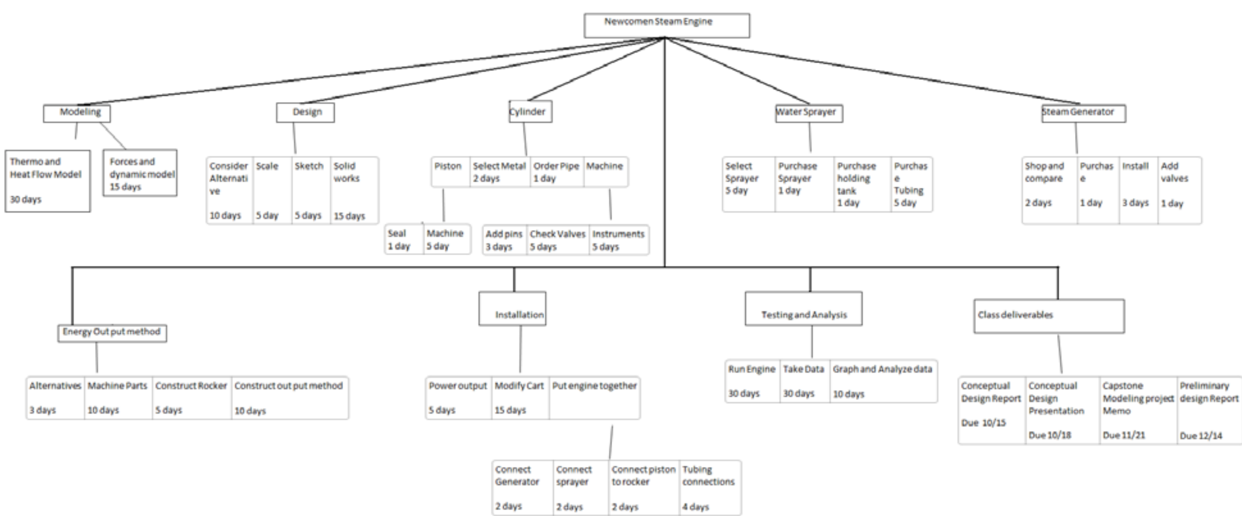

Figure 12 – Work Breakdown Structure

Our Gantt chart is shown in Figure 13.

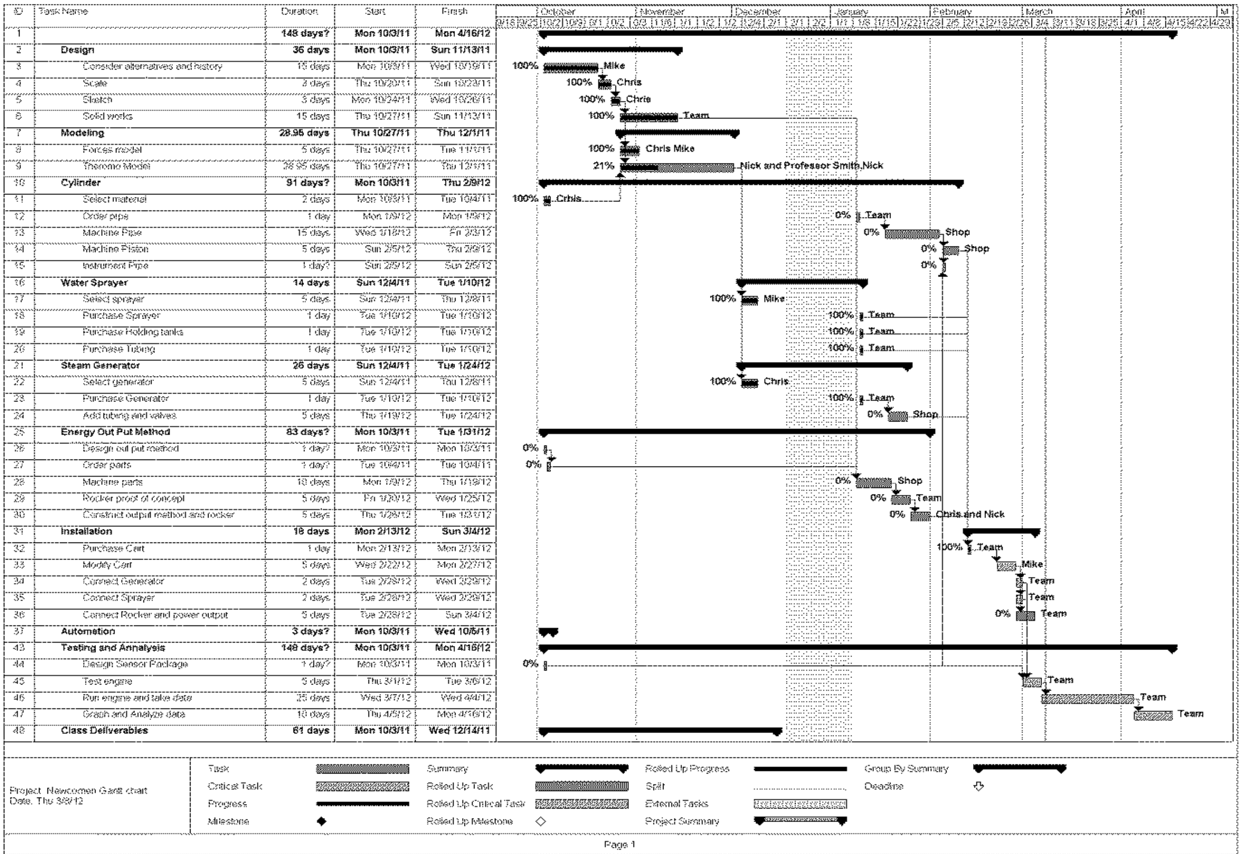

Figure 13 – Gantt Chart

The group also filtered the Gantt chart to show higher level activities for quick reference. This list outlined the construction stages to completion. The major phases were the construction and testing of the piston-cylinder, the rocker system construction, connection to the power output device, and testing, installing instruments and controls, and finally the fully operational engine.

Date	Activity
01/27	Complete Purchase of Cylinder and Steam Generator
02/03	Complete Purchase of Cart, Rocker System and Output method Apparatus
02/10	Construction of Piston-Cylinder and Steam System
02/17	Manually Operated Piston Cylinder System
02/24	Construction and Attachment of Rocker and Cart
03/02	Construction of Output method
03/20	Attachment of Output method
04/06	Completion of Automation of System
04/13	Instrument the System
04/16	Begin Data Collection and Analysis
05/05	Presentation of Final Report

Figure 14 – Steps to Completion

The budget of the project is shown in Fig. 15. Some of the total real cost of the project is not shown because the faculty and staff offer in-kind support for projects without charging to our real budget. Our shop technicians aided in construction and the machine shop supplied some stock and fabricated parts that were needed for the design. Additionally, professors provided expert consultation and theoretical analysis for the project.

Item	# of units	Cost per unit	Total cost
Raw materials			
Stainless steel pipe	48 inches	$9.49/inch	$371.52
¼ in copper tubing	20 ft.	$8.67/20 ft.	$8.67
Aluminum plate	6 ft.	$41.98/6 ft.	$41.98
8/4 Hard Maple Wood	5 ft.	$5.95/foot	$29.75
Parts			
Cart	1 cart	Estimate	$145
Steam generator	1 generator	Estimate	$1000
Spray head	1 head	$8.49/head	$8.49
Centrifugal pump	1 pump	$209.27/pump	$209.27
Water lifter	1 lifter	Estimate	$250
Instruments			
Thermocouple	3	$23.41/thermocouple	$70.23
Pressure Transducer	1	$752.63/transducer	$752.63
Total Cost			
			$2887.54

Figure 15 – Project Budget

modeling and calculations

Once the design process had progressed to the point that visualizing the configuration became easier, the next step was to use engineering skills to analyze the impact of the operating conditions on the machine – the forces, stresses, and temperatures that each component would need to withstand. Theoretical values allowed for adjustments and decisions to be made on all components such as dimensions and material selections. Fig. 16 shows our parametric evaluation facilitated sizing the piston.

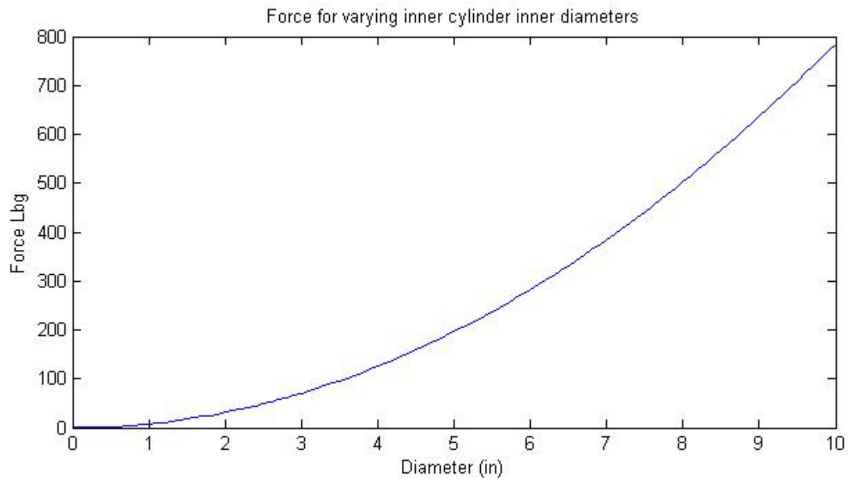

Figure 16 - Force vs. Diameter

The force applied to the piston varies with piston diameter and differential pressure applied to it. A 4-inch diameter piston was selected as the optimum dimension which allowed for sufficient force to be produced, but not so great that the mechanics of the rocking beam and power absorber had to be overly large. The achievable vacuum pressure was assessed to be around 5 psia, or around 10 psi below atmospheric. This number was assumed based off of historical data researched in an early stage of the design process.

One component that was also evaluated by calculation was the rocking beam. The force generated by the piston is an input to this calculation. We then determined the amount of bending stresses in the beam at critical points. This helped determine the material of the beam as well as the dimensions.

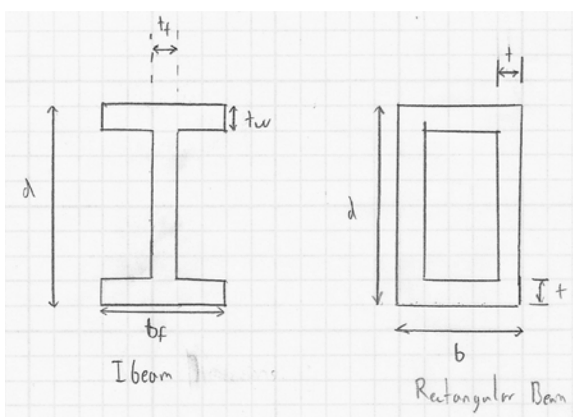

Figure 17 – Beam Cross-Section Alternatives Considered

The geometry of the stroke also impacts the height of the apparatus. A rectangular wooden rocking beam was chosen as the best design because it met the minimum requirements for material strength and it also gave the engine a more authentic look. Another consideration was that the wooden rocker was lighter as well as cheaper as compared to a steel solution.

determination of piston-cylinder friction

An extremely important empirical modeling project that was conducted was determination of the friction that would need to be overcome between the piston and the cylinder wall. The piston-cylinder interaction is a balance between sealing against leakage of air into the cylinder at vacuum and minimizing friction which would inhibit the piston motion. Another purpose this modeling was to determine, once again, if an authentic design could be used, or if modern day materials were necessary for the operation of the engine. Figure 18 shows the apparatus used to test the piston for frictional forces.

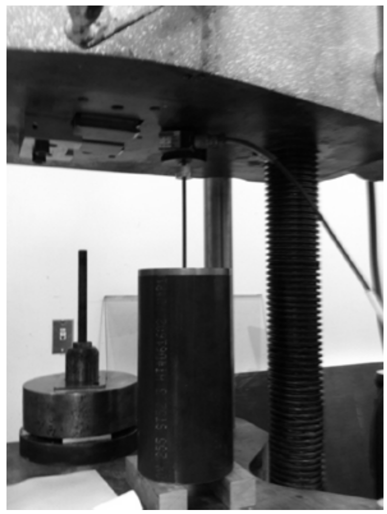

Figure 18 – Piston-Cylinder Friction Testing in an Instron Machine

The authentic design used a water-saturated rope to create the seal around the piston. When scaling the engine, we realized that friction would not scale proportionally. An alternative was (1) to use Delrin rings to create the seal and (2) to ensure the surface finish on the cylinder interior was polished. This design minimized the contact area and thereby reduced the coefficient of friction between the wall and the ring. Fig. 19 shows the piston.

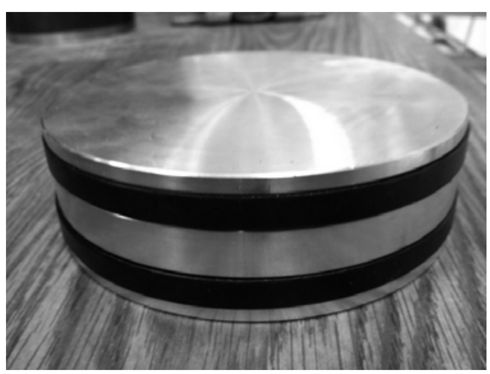

Figure 19 – Aluminum Piston with Delrin Rings

A stainless steel cylinder, two aluminum pistons, graphite rope and Delrin rings were used to test the hypothesis. Fig. 20 shows the results of the force tests for each of the piston seals.

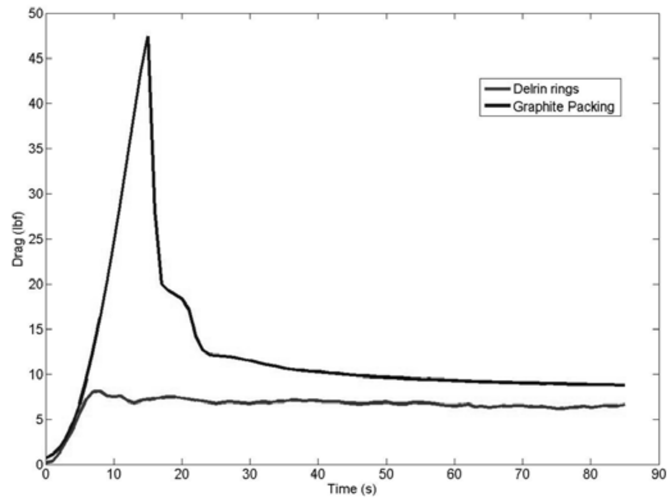

Figure 20 – Drag Friction for Piston-Mounted Delrin Rings

Piston seal	Static friction force (lbf)	Kinetic friction force (lbf)
Graphite Rope	47.4	8.12
Delrin Ring	5.42	4.06

Table 2 – Friction Drag Results

Table 2 summarizes the results of the piston seal modeling. The graphite rope and the delrin ring performed as predicted. The amount of friction necessary to overcome in both cases was negligible compared to the estimated 100 lb_f to be produced by atmospheric pressure pushing on the top of the piston. Something important that was taken into consideration was the static friction force. Because the engine runs slowly (approximately 12 cycles per minute) and the piston momentarily stops at the top and bottom of each stroke, it was important that the static coefficient of friction not be too high because it must be overcome twice per cycle. It was also important that the static and kinetic friction forces were close in magnitude as well so that there would be no sudden bursts of speed at any point. Similar friction forces would allow for the engine to run smoothly. It was evident then from this test that the modern alternative was the best option for the piston.

Another important consideration when choosing the piston seal was that it created as close to a watertight seal as possible. Testing was done simply by filling the cylinder with water and applying a pressure to test for leaks. Further testing on this matter was done after the fact using the same testing apparatus. The size of the ring was adjusted as required to create the best seal.

calculations

Multiple calculations were used throughout the design process to analyze important metrics such as force applied to the piston, or mass of steam required to completely fill the cylinder. These calculations and their results are summarized in Table 3.

Number	Description	Calculation	Output/Use
Rocker			
1	Length of the Rocker		Required beam length for full stroke through 60 degrees of rotation
2	Moment on Rocker		Bending Stress
3	Bending Stress on Rocker		Material of Rocker
4	Second Moment of Area of Rocker		Shape of Beam
5	Factor of Safety of Rocker		Material of Rocker
6	Max Deflection in Rocker		Material of Rocker
7	Shear Stress in Beam		Material of Rocker
Piston/Cylinder			
8	Max Force on Piston		Moment Produced in Beam
9	Net Piston Force		Work Input
10	Sum of the Moments		Required Weight on Power output
11	Sum of the Forces		Required Weight on Power output
Thermodynamics/Fluid Dynamics			
12	Mass of Water Vapor		Theoretical amount of water required to condense steam
13	Mass of Steam		Max amount of steam in cylinder
14	Mass Flow Rate of Steam		Mass flow of steam into cylinder (Power required by steam generator)
15	Power		Required power to heat steam
16	Bernoulli's Equation		Flow around pump system
17	Height of Condensation in Cylinder		Used to find volume of condensation
18	Volume of the Cylinder		Used in mass of steam, P-V diagram, volume of condensate
19	Volume of the Condensate		Determine pooling in cylinder bottom
20	Mass of Water Total		Theoretical amount of water flowing out of cylinder

Table 3 – List of Calculations

the final design concept

After determining the problem statement, setting objectives, designing the engine, modeling key components of the project and properly managing the project, a final design concept was created. The entire design process up until this point was building up to coming up with what the team considered the best approach to building the model Newcomen Steam Engine. Objectives set the scope of the project. Careful design considerations honed the design from four concepts down to one concept that best fit the scope of the project. Modeling key components of the design concepts helped determine specific materials and components that would be used in the final design. For example, now the specific piston and rocking beam could be purchased with confidence that they would be sufficient in building an operational engine. Fig. 21 shows the final design used in constructing the engine. Table 4 outlines the components implemented.

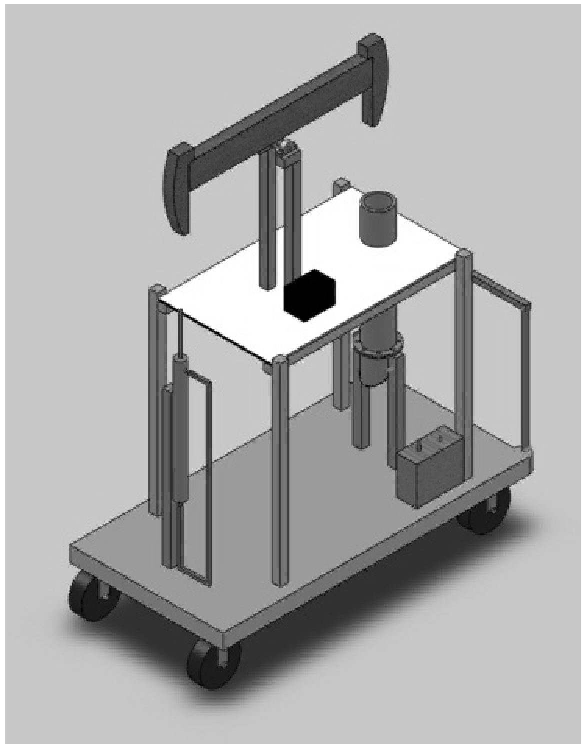

Figure 21–SolidWorks Drawing of the Final Design

Cylinder material	Cylinder inner diameter, thickness and height	Cylinder bottom	Steam production method	Water Sprayer and Plumbing	Piston seal	Rocker material and cross section	Output method	Valve type
Stainless Steel	D= 4 in t=.5 in h=30 in	Detachable funneled bottom	Electric steam generator	Conical spray nozzle with Rickover water supply	Three delrin rings Aluminum piston	Oak rectangular height = 5 in width = 2 in	Water pump and cycling system	Modern solenoid Valves

Table 4 – Final Design Specifications (partial list)

producing an operational prototype

Once all design considerations were accounted for, final design with dimensions had been determined, and parts received, the engine was assembled. There were many factors that needed to be adjusted in the commissioning process. At first, the steam valve and the water sprayer were operated manually. After basic functioning was confirmed, the engine was automated through the use of solenoid valves for steam and water spray and a computer-based control system.

The engine was designed with adjustability in mind. Components such as valves and weights were used to allow for post development adjustments. Eventually after trial and error of the engine physically running, all of the issues were eliminated. After all, that is how they did it 300 years ago. Our design considerations, calculations, and models could only get us so close to the actual functional requirements of the engine.

prototype system features

Besides the main features of the engine (piston-cylinder, rocking beam, and power output method), the total design was built on a cart to provide for mobility. The device had to fit through a standard 36-inch wide door and onto the building elevator. That restricted the dimensions and made weight another, but slightly less important factor. A commercially available steel cart with 6-inch heavy duty casters was procured. The framing for the structure was unit-strut to allow for ability to customize the support structure. This was bolted to the cart.

The steam generator was a commercially available unit that provided for the code-required safety elements. The steam generator must be connected to a source of water. This feature was provided for with hose connections. We wanted to be able to run this device without special electrical power required, so a unit was selected that would work in a 20-amp 110 volt circuit. The spray water also required connection to a pressurized water source. This was hose connection to building potable water.

The piston-cylinder system was constructed second because it was the most involved portion of the design. A four inch inner diameter stainless steel honed cylinder was purchased. The cylinder was honed to ensure smooth movement of the piston. An aluminum piston with three delrin rings was machined from a block of aluminum stock. This piston was similar in design to the piston used in the seal modeling activity except that its height was increased to prevent the piston from locking up and a third ring was added for additional stability in the cylinder. The cylinder was designed to be two and a half feet tall and the bottom was cut on a slant to form a funnel drain from the cylinder. A flat plate was welded to the bottom of the cylinder to ensure it was properly sealed. The cylinder was also cut into two sections with bolted flange connections. The bottom half, including the slanted section was affixed to the cart. The top portion of the cylinder was removable which allowed for rearrangement and repair of the instrumentation in the cylinder and on the cylinder wall.

The steam generator was attached to the cylinder with an insulated rubber hose and a check valve to prevent water from returning to the generator. The cylinder connection was also located above the expected water level. Finally, the conical spray nozzle was attached to building potable water system via a hose. After all of the parts were joined properly, the piston cylinder was tested. The piston was raised to top dead center position, and the cylinder was filled with steam. Then the spray valve was manually activated, condensing the steam. The rapid condensing of the steam created a vacuum in the cylinder which allowed for atmospheric pressure to push the piston down, as expected. The drain water successfully drained. After this test was run multiple times, the sprayer mass was adjusted to the correct level.

The next design element was the rocker and support systems for the engine. The rocker was a three foot long 2” by 5” oak beam. A wooden arch was attached to each end of the rocker ensuring that the chain would always stay aligned with the piston and output method. The support system for the rocker was comprised of strut channel securely mounted to the upper portion of the cart. The rocking beam was attached to the support structure by a steel shaft and pillow bearings. The structure incorporated mechanical stops to prevent the rocker from travelling too far at either end of the stroke. This prevents piston ejection and piston bottoming.

Finally, the chains were attached to the rocker arcs. The output side was left unattached but the piston cylinder side of the rocker was attached to the piston. The piston movement tests were again performed with the added resistance of the rocker weight. This test also showed that the rocker support system and the cylinder position in the cart were steady and aligned. The use of unit strut for the framing allowed for additional bracing to minimize wracking.

The final design element was the water pump and cycling system output method as shown in Fig. 22. This design was completely different than any of the original power output concepts. After taking another look at our previous designs, we believed we could do better. The concept behind the improved output method was by measuring the differential pressure and flow rate in a pump loop with adjustable resistance. The pump selected was an off-the-shelf reciprocating oil pump, altered to attach to the chain and rocking beam.

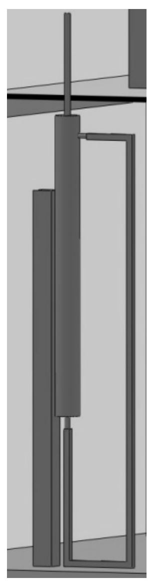

Figure 22 – Water Pump Power Output System

Finally, the entire engine was run with the piston-cylinder system powering the pump and the mechanical work being translated through the rocker. Calibration was necessary to determine the proper amount of weight to be added to the power output side, as well as the duty cycle and timing of the steam and spray valves.

After the engine was sufficiently tested and found to be basically operational, the instrumentation package was attached to the engine. Thermocouples were installed at specific points throughout the cylinder. They were inserted into the steam space and attached to the outside of the cylinder to determine heat transfer through the cylinder walls as affected by the axial position of the piston. A thermocouple was also placed in the drain pipe to measure the temperature of the drained water. A pressure transducer was connected to the cylinder. A differential pressure transducer was added at the lowest point within the cylinder. The purpose of this pressure transducer assembly was to determine the inventory of water pooling in the bottom of the cylinder.

Flow meters were introduced into the steam inlet and the spray water inlet to determine the mass flow rates into the cylinder. Finally, a linear position sensor was attached to the rocker in order to determine the piston position. These systems were connected to a laptop computer with a data acquisition and control system that documented the temperatures, pressures, flows and position over a period of operation and controlled the steam and spray valve timing. Adjustability is a combination of manual throttling and computer-controlled valve timing.

thermodynamic analysis

The final portion of the objective will be to run thermodynamic tests on the engine once it is operational. Through the use of the instrumentation package, data can be collected on what is actually going on from a thermodynamic standpoint. Other important data to be collected is position of the piston, flow rate of the steam and spray, flow rate of condensation out of the cylinder, temperature, and pressure. Pressure and position will be used to plot an actual *P-V* "indicator" diagram using our data acquisition system.

Power output will be measured in the power absorption unit. The pressures and rate of flow of the water being pumped will be converted to work and power values. Measuring the thermodynamics and mechanics at various points will allow determination of the various efficiencies of the engine. The versatility of the engine with its instruments and controls package is intended to allow for future research on the variables of steam and spray timing and insulation of the cylinder can affect the various efficiencies.

Something else we plan to investigate are the effects of scaling on the performance and how the use of different materials effects the overall performance of the engine. So many things can be learned about this historic technology. We speculate that the potential exists for this technology to be used again, perhaps in third world applications. For example, one of the key needs of many parts of the developing world is clean water. As an external combustion engine, a Newcomen engine only requires a sufficient fuel source to boil water at low pressure. The technology has proven rugged, reliable, and capable of pumping water from great depths. A Newcomen pumping engine might be useful in replacing contaminated surface water with deeper groundwater than can be accessed with current systems available to these parts of the world.

lessons learned

Note that, due to the production schedule of this paper overlapping with the progress of this senior design project, we have written this paper as if the activities were all completed, but some are actually in progress. As of this writing, we are in the process of assembling components and testing fit-ups. Yet, we have enough of the system in-hand to project some significant lessons.

As our instructors forewarned us, a wide variety of lessons come from the experience of capstone design. As an engineering design experience, this project illustrated the principle that the act of design requires mentally visualizing what and how the various parts of an integrated system must fit together to function. The fundamental skills learned in our earlier courses had to be adapted to the specifics of our configuration. Project management is especially important. The wide variety of activities necessary to bring this project to fruition demanded a disciplined and systematic approach in order to complete it within the time allotted of one academic year. We realized that the combination of optimism/wishful thinking and inexperience made our scheduling a bit unrealistic. Communication and coordination between team members is vital. Programming some contingency time at the end allows time for rework when certain elements reveal unanticipated results. We deliberately put off designing the instruments and controls portion of the project and had a very steep "learning curve" when we finally were ready to address this vital aspect of the project. So, while our scheduling had to be adjusted, at least we had a reasonably complete sequence. This forced us to focus on things that we otherwise might have missed altogether. And there is nothing like an impending deadline to focus a distracted mind.

conclusions

The Newcomen steam engine played an extremely important role in the development of steam technology and launching the industrial revolution. Learning about historical developments in engineering provides perspective to today's students. The development of an operating model of the engine to demonstrate and to analyze the technology is an excellent capstone design project for engineering students. Even if no more future development is to come from the Newcomen steam engine, a lot can be learned about engineering in general by studying and attempting to replicate the magnificent machines of the past. We hope that other schools will pick up this challenge and welcome follow-on contact to assist in launching this type of effort.

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