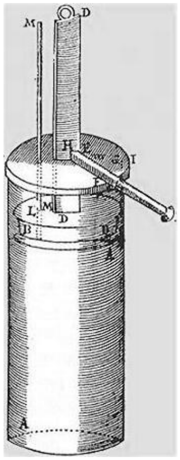
GEOS 24705 / ENST 24705
Problem set #6
Due: Tuesday Apr. 21

Background – some history to inform the PS problems

The early development of engines is complicated by many different legal fights over intellectual property rights.

Thomas Savery, the inventor the first commercially used heat-to-work machine, was a sharp operator. He got a patent for his suction-pumping machine in 1699, and though patents in English law usually lasted 12 years, he somehow persuaded Parliament to extend his patent by another 21 years, so that it did not expire til 1733. That means that when Newcomen, after 14 years of tinkering and development, finally achieved a practical, commercializable, version of his true engine in 1712, Savery insisted that he owned all rights to the concept of raising water by means of steam. Savery's argument prevailed and Newcomen was denied a patent for his new invention. The only way he could get his invention to market was to (reluctantly) partner with Savery to start his business.



Papin, 1690

Savery himself was no intellectual property purist, as he had borrowed most of his idea from a 1662 book by the Earl of Worcester, who received neither credit nor royalty payments. Furthermore, the French theorist Papin had published extensively on possible steam engine designs, including a 1690 description of a piston-and-cylinder steam engine. But still Savery managed to get an "exclusive patent" for the entire concept of "raising water by fire." When Savery died in 1715, the patent was passed to his wife, who transferred the rights to a joint-stock company called “The Proprietors of the Invention for raising water by fire.'' The London Gazette ran an advertisement in August 1716 stating that 'any person desirous to treat with the Proprietors for such engines' should meet with one of the proprietors who would be at a coffee-house in Birchin Lane every Wednesday to discuss terms.

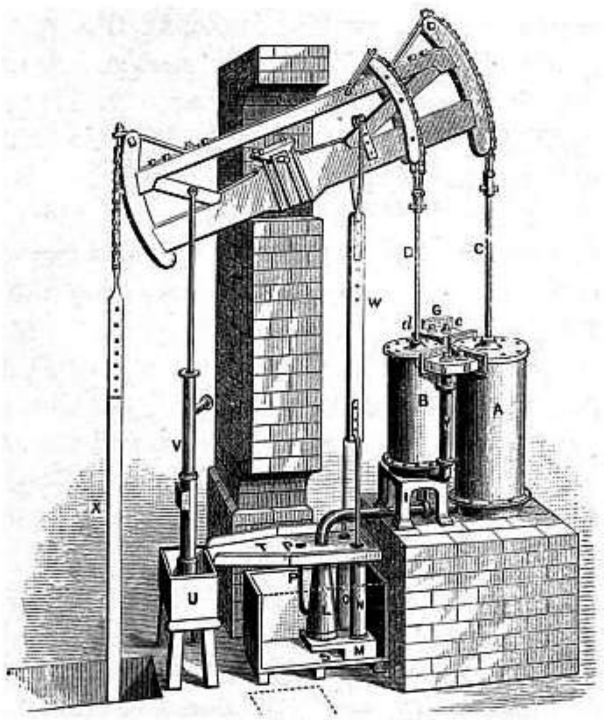
Patent protection may have contributed to periods of stagnation in engine design. There were few improvements in Newcomen's design for decades, other than the important step of automating the valves to make the engine self-acting. (Legend has it that that first advance should be credited to a boy named Humphrey Potter hired to operate the engine valves, who rigged up a system of ropes to do his job automatically, hence the term "potter cord”. By 1718, an engine-builder named Henry Beighton switched the valve control design to the all-metal version you saw in the videos.) Innovation then paused. Wallace writes that this improvement "brought [the engine] into the form in which it continued, without any material change, for more than half a century" (Wallace, *The History of the Steam Engine*).

The golden age for development of Newcomen engines came only in the 1770s-1790s, after Savery's patent had run out, when inventors like John

Smeaton, James Pickard, and John Curr made significant changes. Why were these entrepreneurs working on Newcomen-type engines at such a late date, when Watt had already developed the superior external condenser in the 1760s? Because Watt had of course patented the condenser (in 1769), and not only aggressively defended his patent but refused to license the technology to any competing manufacturers. Inventors could only work on the outdated Newcomen engine, which was in the public domain.

Watt's aggressiveness contributed to several other instances of sub-optimal use of technology.

Pickard tried to open a new market for the Newcomen engine as a driver of factory machinery, and developed a crank mechanism that would adapt the Newcomen engine to convert its linear motion into rotational motion that could turn a driveshaft. Although the crank had been in use for centuries, Pickard in 1780 managed to get a 12-year patent on the broad idea of translating linear motion to rotational motion by means of a crank. Trying to be a tough negotiator, he refused to license his crank to Watt, unless Watt in turn agreed to license his condenser to Pickard. Watt refused, and sold his engines instead with the sun-and-planet gearing that he had developed to get around Pickard's patent. (The gearing worked, but was more complex and less efficient). In the end, you might say that Watt won: he waited out Pickard's patent, and once it expired in 1794 immediately dropped the sun-and-planet gearing for the crank. Pickard on the other hand never managed to get his Newcomen-engine-with-crank system functional for factory use - the power delivered was too jerky to drive machinery.



Another instance of Watt's litigiousness impeding the development of technology happened after Hornblower patented (in 1781) a compound engine: an engine that re-used the exhaust steam from the cylinder in a second, lower-pressure cylinder. (Someone in class proposed this strategy, but Watt himself hadn't thought of it.) The engine went into production briefly, but Watt sued, and the resulting litigation prevented the use of multiple-cylinder "compound" engines until Watt's patent expired in 1800.

The expiration of Watt's patents, as expected, meant a boom in steam engine purchases and a jump in innovation. Once the condenser was in the public domain, manufacturers promptly switched over to that better design instead. The expiration of Watt's patents therefore also meant the end of the Newcomen era.

Existing Newcomen engines did continue to operate long after 1800, though. Watt’s improved efficiency was apparently not sufficient to make it cost-effective for a mine owner to discard a perfectly operational engine and buy a newer model. One of the longest-lived was the Newcomen engine at the Ashton Vale ironworks, built in 1750 and operational until 1900. Wallace writes: "Over its 150 years of use, the South Liberty Engine worked for about 5 hours per day, for 6 days a week. The engine-man who was driving it in 1895 had driven it since he was a boy, his father and grand-father having driven it before him."

The Ashton Vale engine is important because its long life meant that it was the most extensively documented of the early Newcomen engines. You'll use measurements from this engine in some of the problems below.

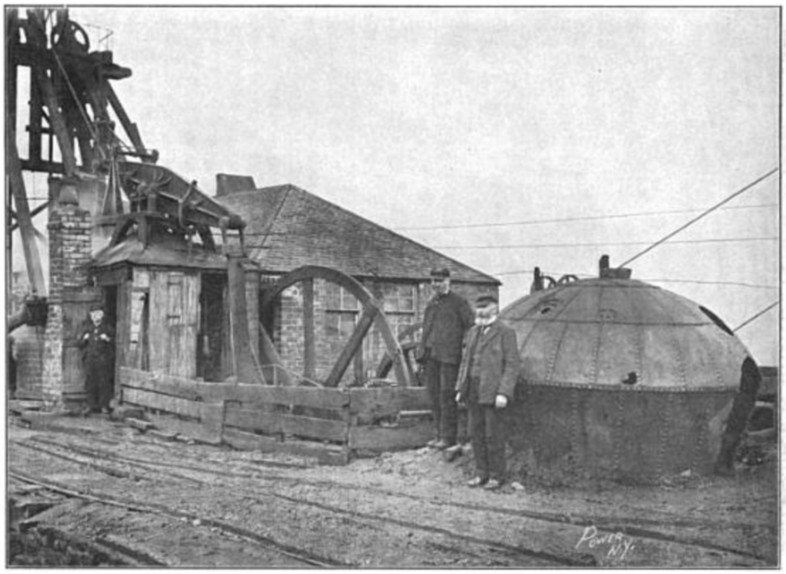


FIG. 2. EXTERIOR VIEW OF ENGINE, ETC. STANDING AGAINST THE HAYSTACK BOILER IS WILLIAM PARK, WHO DROVE THE ENGINE 40 YEARS AGO; AT HIS RIGHT IS TOM SMITH, WHO HAD CHARGE OF ENGINE 60 YEARS AGO AND STILL WORKS AT THE PIT HEAD. IN THE DOORWAY IS DUGALD DON, WHO HAS BEEN IN CHARGE OF THE ENGINE FOR THE PAST 18 YEARS.

Possibly the last Newcomen engines built were at Farme Colliery in Scotland, one in 1810 and two in 1820 (two were rotative “winding” engines to lift coal that incorporated more modern linkages, but used only the force of the atmosphere to drive the piston down). It’s not clear why the colliery built such primitive engines - the 1810 version even had manually operated valves. (The other designs aren’t known). The engines were home-builds, probably to save on costs: the 1810 was designed by a local blacksmith. But they weren’t bad investments: two of them ran reliably for nearly 70 years, and the 1810 engine ran for over a hundred years, til 1923. At article in 1904 (with photographs!) called it “the last survivor of an otherwise extinct type.” (Benjamin Taylor, “A Century-Old Colliery Engine – Last Survivor of the Newcomen Type”, *Power*, p. 134, March 1904, see this link).

You can see the text and diagrams of some of Watt’s patents here. Note that Watt is shamelessly trying to patent a crank in 1781 despite Pickard’s 1780 patent!

Problem 1: Patent litigation

Write an appeal to the English courts, either as Newcomen complaining about the interpretation of Savery’s patent or as Watt complaining about Pickard’s. You can argue that the patent is over-broad, invalid on the basis of prior art, doesn’t apply to your case, or any combination of these. Googling is OK. Just a paragraph, no more.

Problem 2: Physics of the Newcomen engine

The Newcomen engine is called an ‘atmospheric engine’ because the only net force is that applied is by the atmosphere itself during the engine’s downstroke, when atmospheric pressure pushes the piston down. The chain connections cannot transmit any upward force during the upstroke. In this problem set you’ll use some data from the 1750 Ashton Dale engine, reported in a 1903 article and shown on the figures below.

Fig. 4. *Newcomen Engine at Ashton Vale Iron Works, Bristol.*

From a Sketch made in September, 1895. Erected about 1746-60. Dismounted 1900.

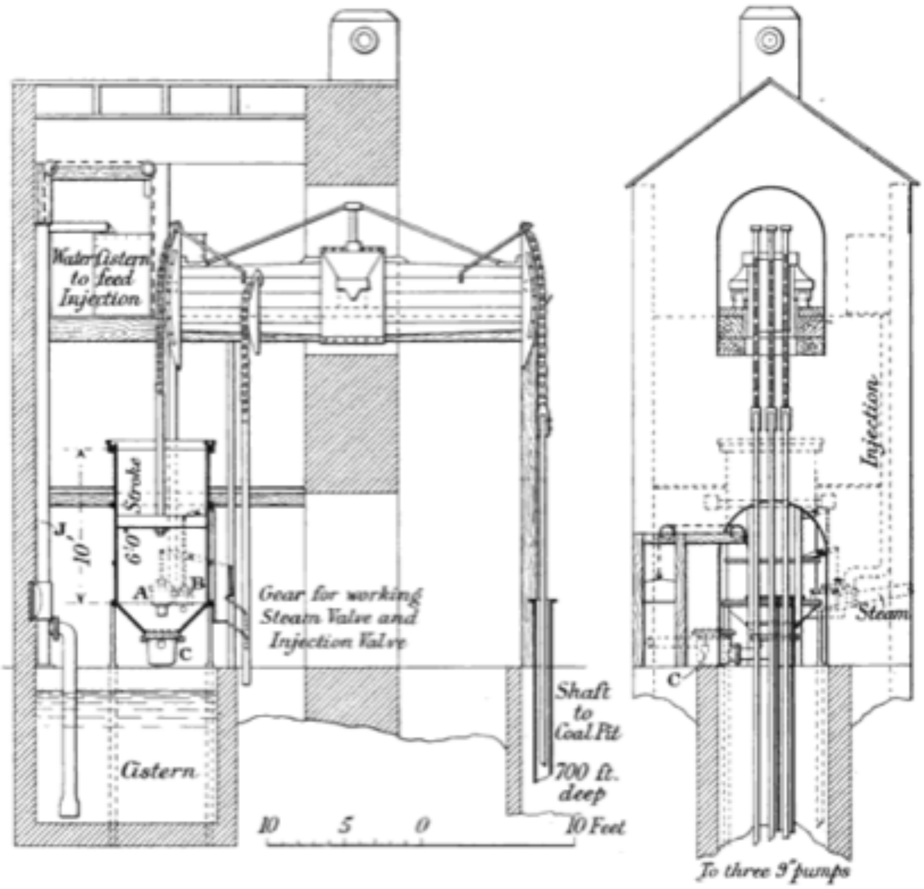
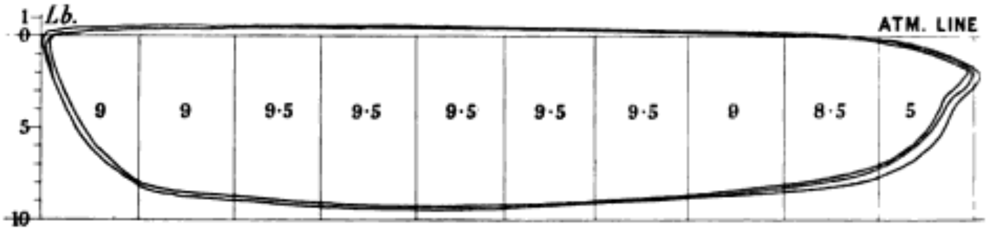


Fig. 5. *Indicator Diagram taken from above Engine, 27th May, 1895.*

Dia. of Cyl. 5' 6"
Stroke 6' 0" about
No. of Strokes per min. 10.

Boiler Pressure 2·3 lbs.
Vacuum Gauge, none fixed.
Time 3 p.m.

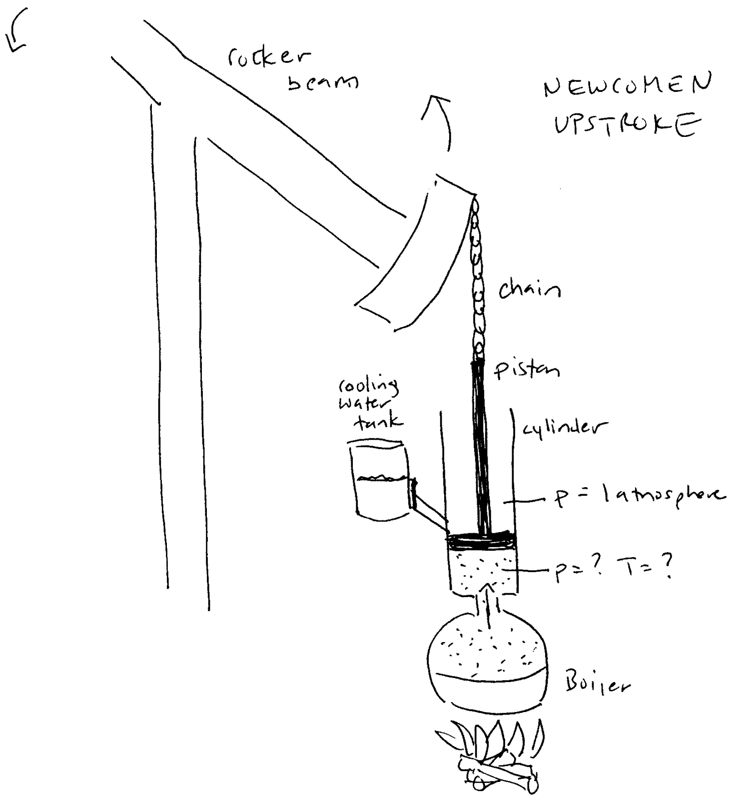


The units of the indicator diagram are given as pounds but what's meant is really pounds per square inch (psi). Atmospheric pressure is 14 psi. In SI units that's ~ 10^5 Pascal, where 1 Pascal = 1 kg m/s^2 per m^2)

Consider the different parts of the engine cycle:

Cylinder fill & upstroke

In the first part of the Newcomen engine cycle, the steam valve is opened and the cylinder is allowed to fill with pure steam (no air, or at least minimal air – mostly just water molecules). The piston is drawn upward by the rocking motion of the beam, increasing the volume of the cylinder, and the steam flows in to fill that volume.



A. What pressure is the steam in the cylinder at, once the valve is opened? First state it based on physical reasoning. (Explain your thinking). Also: what would happen if you tried to increase the pressure in the cylinder?

B. Draw what you would expect an indicator diagram of this stage to look like. Then look at the measured indicator diagram, and clearly mark this part of the engine cycle on it.

C. If the indicator diagram conflicts with your intuition, explain the discrepancy. What real-world issues make the diagram slightly different from what you predicted?

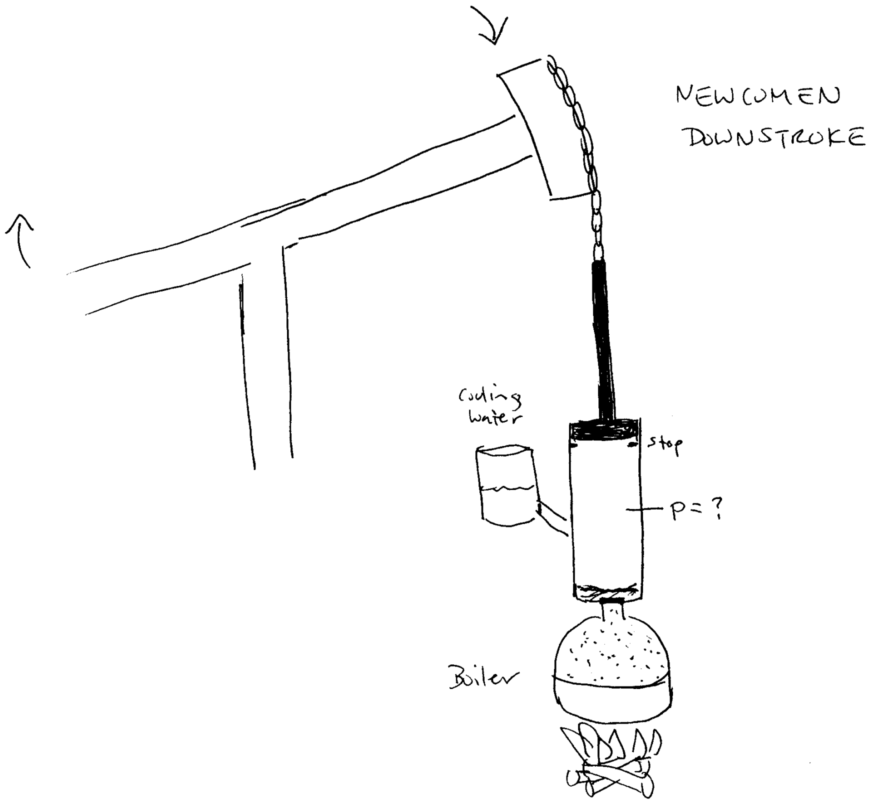
D. What temperature is the steam in the cylinder at? (in Celsius)

We'll call this T_{steam} in the problem. You can likely answer this from common knowledge; if not, consult the reading on steam.

E. The diagram in the slides states that the boiler pressure is above atmospheric pressure by 2.3 pounds per square inch. How is this possible? Explain and discuss. What can you say about the boiler temperature?

Condensation and downstroke

In the second half of the Newcomen engine cycle, cool liquid water is injected into the cylinder and the steam condenses. The piston is then pulled down to the bottom of the cylinder.



F. What would the pressure be if the cylinder had been filled with pure steam and all of it condensed? What would the differential pressure be? (That is, the net force/area on the piston)

G. Based on the indicator diagram, what is the actual pressure inside the cylinder during this stage? What is the net force/area on the piston? Clearly mark this part of the cycle on the indicator diagram.

H. Estimate the maximum work performed over one stroke, in Joules, first in the ideal case of F and then in the actual case of G. Remember that work is force x distance, or, alternatively, differential pressure x volume. (And you know the conversion from pressure in psi to Pascal).

I. Go back to the Newcomen video of the last problem set and estimate the stroke rate of the engine. Compare to the stated stroke rate of the Ashton Vale engine.

J. What is the power output of the Ashton Vale engine? Give your answer in both Watts and horsepower.

K. Newcomen engines actually lost a lot of energy to friction in only had mechanical efficiency of ~ 65% (That is, about 1/3 of their work output was lost to friction). With this correction, what is the max effective pumping power of this engine, in Watts and horsepower?

L. What is the maximum mass of water the engine can pump from the mine per stroke? Remember the work required to lift a mass is m*g*h. The pump is lifting a column of water that extends from the depth of the mine to the surface. (If this is confusing, it can help to draw a diagram.)

M. Why is the diameter (bore) of the lift pump in the diagram so much smaller than the diameter of the cylinder? What would happen if you made the bore of the lift pump much larger? Much smaller?

N. *(Optional)*: Calculate the maximum bore for the lift pump for this engine. Is this value consistent with what you can see by eye in the diagram?

Problem 3: Efficiency of steam engines

Early engineers described the efficiency of pumping engines in terms of “duty”, the foot-pounds of lifting work achieved for each bushel of coal burnt. (Remember that a pound in English units is both a unit of mass and of force - a pound-force is the force that gravity at the Earth’s surface exerts on one pound-mass. A “foot-pound” is the energy required to lift one pound mass a height of one foot against gravity at the Earth’s surface.)

A. What is the “duty” value for a hypothetical perfectly efficient engine? (one in which all chemical energy in the coal was transformed into mechanical work). A British bushel is 8 (imperial) gallons, and each (imperial) gallon is 4.5 liters. You can assume a coal energy density of about 30 MJ/kg. The mass density of coal can vary by x2, but the most common type, bituminous, has a density close to that of water.

B. The duty of the Ashton Dale engine was not recorded, but Smeaton made a survey of Newcomen engines in 1769: *“Smeaton computed the duty of fifteen engines in the Newcastle-on-Tyne district, and found the average duty to be 5.59 millions of foot-pounds per bushel or 84 pounds of coal”*

C. What is the efficiency of these Newcomen engines?

D. ***(Optional)*** Are the engines that Smeaton describes burning bituminous coal? Explain.

E. Chimdi asked in class if the Newcomen engine could allow more coal to be mined than it would take to run the engine in the first place. You would assume this is the case, because if it weren't, no one would buy the engines. But it's always good to check. It's hard to relate the volume of water pumped to that of coal extracted, but you can try assuming a 1:1 relationship. (Same volume of coal extracted as water pumped). With this assumption, and ignoring other energy requirements for mining, what is the "energy return on energy investment" of pumping? That is, **what's the ratio of coal extracted to coal used to power the pump?** You can assume the efficiency from Smeaton and the shaft depth at Ashton Vale. This might sound complicated but it is actually a very trivial problem. Just stay in English units: the units of duty can be very helpful!

The article from which the Ashton Vale diagrams were taken (Henry Davey, "The Newcomen Engine", *Practical Engineer and Engineer's Gazette*, p. 415, Oct. 1903). describes continued improvements in engine efficiency over time, reporting:

"1772. Smeaton made improvements in details, not altering the general construction, and succeeded in obtaining a duty of 9.5 millions"
"1776. Watt corresponded with Smeaton, and claimed 21.6 millions duty for his engines. Smeaton, after making experiments with Watt's engines, laid it down as a general rule that the Watt engines did double the duty of the Newcomen."

Duty improvements are discussed also in Walter, "The Engine Indicator"

"The publication of performance tables in the Philosophical Magazine encouraged competition among mine captains; 'Greatest Duty' was a source of particular pride amongst these Cornish enginemen, and each vied to be at the head of the list. Consequently, Cornwall saw many of the earliest advances at first hand…"
"In August 1816, the old 45-inch Wheal Chance engine was altered from its original single-cylinder Watt configuration to a two-cylinder Woolf compound, Duty leaping from 25·37 million in July to 44·35 in September."

"By 1839, the single-cylinder Cornish Engines, working expansively with high-pressure steam, were returning impressive performances: the 80-inch West Julia machine (120·9hp), with a piston stroke of eleven feet, gave a Duty of 73·94 million, and the Consolidated Mines 80-inch Davey engine (159hp) gave 70·35 million. During this period, steam pressures associated with these huge engines had risen from barely above atmospheric level to 30–40 lb/sq.in"

Similar numbers are reported in a 2004 artice (graph below).

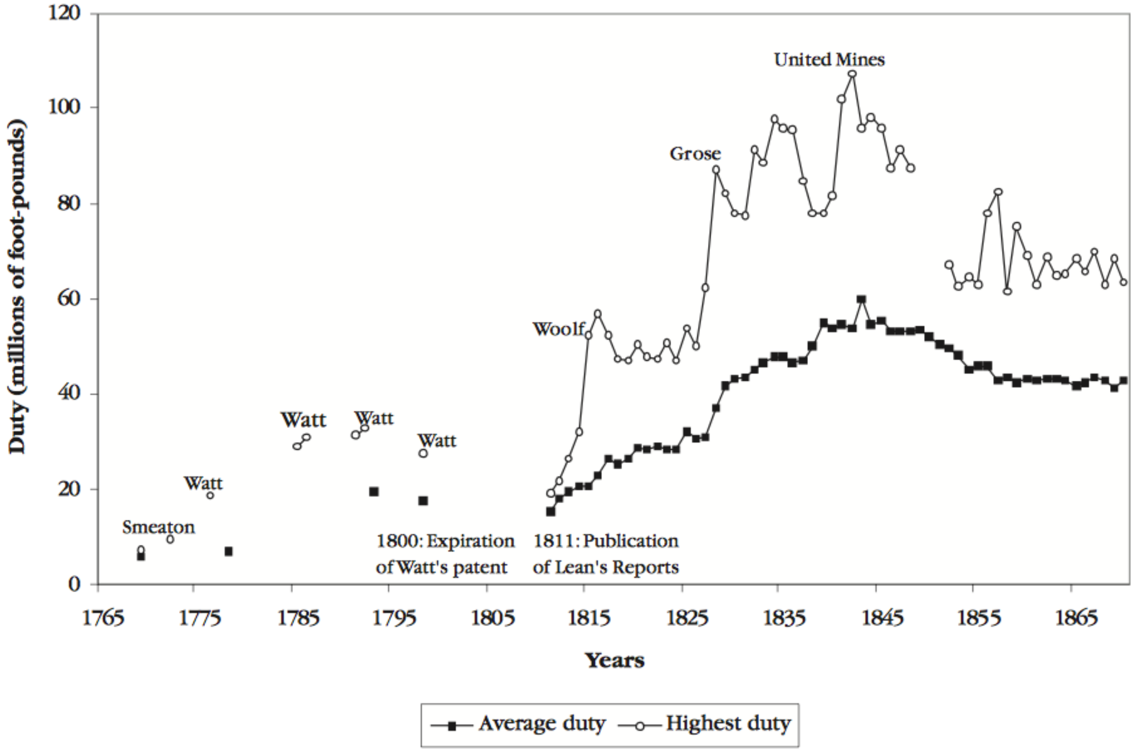


Fig. 1. Duty of Cornish engines.
Sources: Lean (1839), Pole (1844), Dickinson and Jenkins (1927), Barton (1965).

from Nuvolari, "Collective invention during the British Industrial Revolution: the case of the Cornish pumping engine", Cambridge Journal of Economics, 2004.

F. Are the numbers from Davey consistent with the figure from Nuvolari? Plot Davey's numbers on this figure.

G. Are the numbers and figure consistent with the argument that Watt's patents stifled innovation?

H. Vaclav Smil gives a longer-term but rougher version of this figure, along with a figure of the growth in power of engines (below). Plot the power you calculated for the Ashton Vale engine on the appropriate spot on the left panel. Translate the "duty" for each point given by Davey into a % efficiency and plot it on the right panel. Are they consistent?

(Note: since "duty" refers to work after losses to friction, for proper comparison to Smil's "thermal efficiency" you should increase the duty values: if you had 30% losses to friction you'd multiply your "duty" numbers by 1.5. On a log plot you'd hardly see the difference, though.)

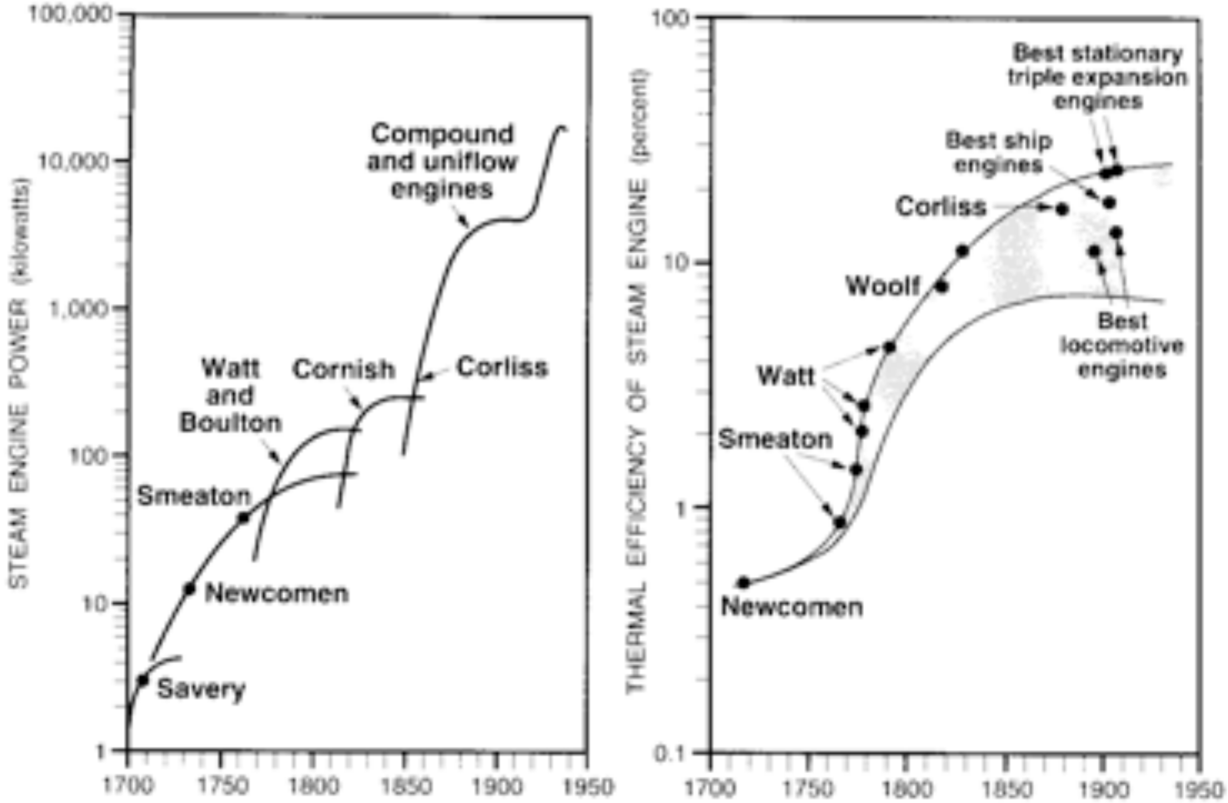


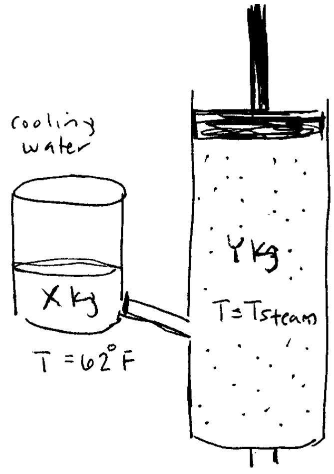
FIGURE 5.3 The rising power and improving efficiency of the best steam engines, 1700–1930. *Sources:* Plotted from data in Dickinson (1939) and von Tunzelmann (1978).

Problem 4: Watt's efficiency improvement

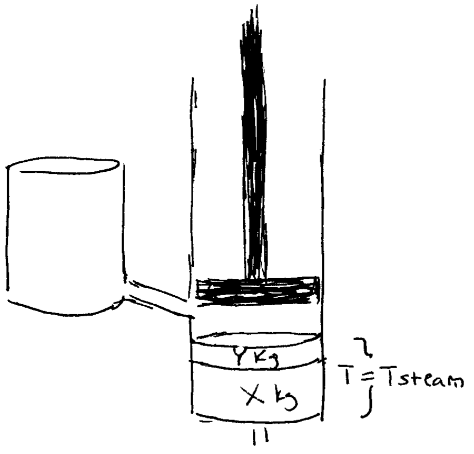
James Watt got interested in steam engines when he was asked to work on a model Newcomen engine. (He was a mechanic working for Glasgow University). He was surprised by how much water had to be squirted into the cylinder on each engine cycle to condense the steam. After some experimenting with a full-scale Newcomen engine, he found that the minimum amount of water he could add per stroke and keep the engine going was 24 kg of liquid water (from his reservoir tank, which was at 62 Fahrenheit or 17 Celsius). That amount of water condensed only one kg of water in the form of steam.

That seemed excessive to him, and he started investigating more systematically.

The picture below shows how condensation should be working in the cylinder. Some mass of cold liquid water (X kg) is added to hot steam (Y kg). If you had perfectly insulated cylinder walls and wasted no energy at all, the temperature of the cylinder itself would never change. You'd condense the steam, releasing its latent heat, and in the process you'd heat up the cold water, but the walls wouldn't change temperature - the only transfer of energy would be between the steam and the liquid water. The end result (if you added *just* enough cool water to condense the steam) would then be X + Y kg of liquid water at T_{steam}.



before condensation



after condensation

A. **For this system, describe what happened to the latent heat that was dumped out when the steam condensed.**

B. **What would happen if you injected liquid water at T_{steam}?**

First, Watt did some careful experiments to determine how much energy he could derive from condensing steam. He made the first definition and measurement of the latent heat of vaporization of water, L_v.

Then, Watt thought about the energy going to heat the cooling water. All material has a characteristic "specific heat", i.e. a characteristic amount of energy required to raise the temperature of a given mass of water. Watt also did enough experiments to effectively derive the specific heat of water vapor. (Though he didn't have standard units to describe it in – the calorie wasn't defined until fifty years later, by exactly this physics, as the amount of energy required to raise 1 gram of liquid water by 1 degree Celsius.)

C. Do Watt's calculation: **how much cooling water (in kg) should ideally be needed to condense 1 kg of steam?** First calculate the energy needed to raise the temperature of 1 kg cooling water from room temperature to T_{steam}. This is how much energy that can be absorbed by each kg of cooling water. Then state the amount of energy released in condensing 1 kg of steam. Then combine to figure out how much cooling water you need.

D. Compare your answer above to the amount of cooling water actually used by the Newcomen engine. **State the ratio of cooling water actually used to cooling water that *should* have been used.**

Watt concluded from his ratio that the Newcomen cylinder was wastefully designed. Some of his cooling water must be cooling the cylinder walls themselves, i.e. pulling energy from them on each stroke. The cylinder was cooling on each downstroke, and then heating up again on each upstroke when steam was re-introduced. That then meant that *extra steam* had to be added to the cylinder on each upstroke, to warm the cylinder back up. The first steam added must be just condensing, releasing its energy to reheat the cylinder. The engine operator was therefore burning more fuel to boil more water than he should.

E. **If Watt could avoid *all* the excess losses he had identified in the Newcomen engine, efficiency should improve by what factor over Newcomen's?** Compare this to Watt's claim from 1776. (See problem 3).

Problem 5: Behavior of gases

In class we derived the equation of state for gases, the ideal gas law:

$$PV = nkT$$

where P is pressure, V is volume, n is the number of gas molecules, k is some constant, and T is temperature.

In preparation for our discussion of the maximum possible engine efficiency, do a simple plotting and thought exercise.

A. What happens if you let high-pressure gas expand freely without any addition of energy? (*adiabatically*) Expansion means the volume increases. What happens to the pressure and temperature of that gas? (If you have no experience with this situation, remember the story from class.)

B. Imagine that instead you want to make that expansion happen at constant temperature. (*isothermally*) Would you have to add heat to the gas or take it away? Explain.

C. Consider an isothermal expansion on a P-V diagram. What equation describes what happens to P? Draw it on the P-V diagram. (We don't care what the start and endpoints are, I'm just asking what the shape is).

D. Now, compare the adiabatic expansion (no energy added) to the isothermal expansion. Let the final volume be the same. Is your final temperature larger or smaller? Is your final pressure larger or smaller? Sketch a guess as to what the adiabatic expansion might look like on the P-V diagram.