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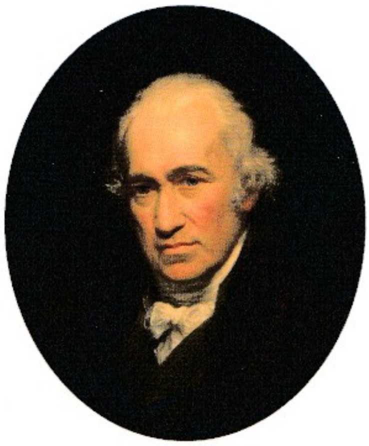

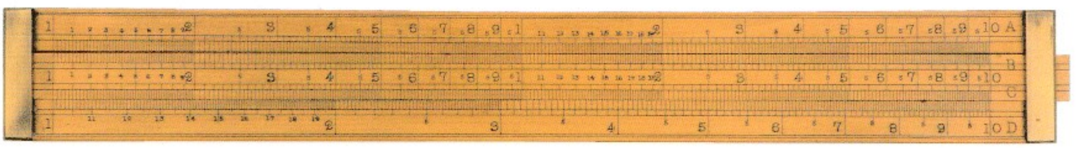

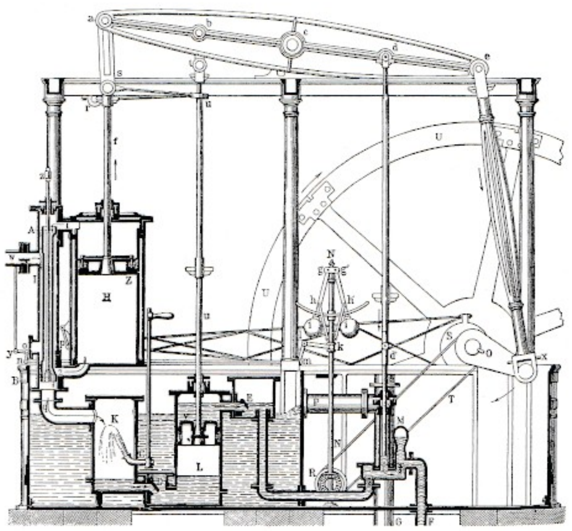

Steam Engines & The Soho Slide Rule

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The Design of a Steam Engine By Means of the Soho Slide Rule

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In the Industrial Revolution of the 18th and 19th centuries in England, the steam engine played an important role. People were no longer dependent solely on their muscle power and that of animals or on the power of wind and water. The steam engine is available as an additional new source of energy without any time limit. It increases productivity and enables new technologies.

Over the same period, the system of units, metrology, and the formula-based recording of physical laws and interrelationships were developed to such an extent that problems of a physical-technical nature arising in the design and construction of machines could be solved mathematically.

These new methods were necessary because new tasks were posed by the identification of acting forces, by the dimensioning of components, or by the estimation of the expected engine power. Another new goal was to determine and optimize the efficiency, i.e. the ratio of coal consumption to achieved power. Ecological and social considerations did not play any role.

Two types of calculation aids were used: a logarithmic slide rule, and numerical tables with one or two inputs and their calculated results. The logarithmic slide rule designed for engineers was new, whereas numerical tables were already in use as multiplication tables or conversion tables. Now the use of these tables was extended to solutions in the fields of geometry and technology.

Soho Slide Rule and Steam Engine

Slide rules that already existed for navigation, taxation, or for trade purposes were not considered useful for mechanical engineering as they were considered to be too imprecise. Therefore, starting in 1775, the entrepreneur Matthew Boulton and the engineer James Watt introduced improved slide rules, the so-called Soho type, for the design of their steam engines at their factory in Soho, near Birmingham.[1]

John Farey Jr. provides information on the origins of the Soho slide rule in his extensive 1827 treatise[2] on the history, design and construction of the steam engine. Farey worked as a consultant mechanical engineer and patent attorney.

Farey wrote about this on pg. 536:

> „The lines upon sliding rules have been combined in various forms, to suit the purposes of particular calculations; but that which has been found most convenient for the use of engineers, was arranged by Mr. Southern, under the direction of Mr. Watt, expressly for the use of the engineers of Messrs. Boulton and Watt's manufactory at Soho, and is in consequence called the Soho rule."

"Mr. Southern" was John Southern, an employee of Boulton & Watt. He was regarded as a very good mathematician and also helped with the calculation of machine components.

From that time forward, the slide rule became an indispensable tool for engineers. Numerous publications gave instructions for its use in mechanical engineering. From a technical point of view, the slide rule is one of the most striking symbols of the Industrial Revolution.

The original Soho slide rule (Figure 1) has four scales. Three identical scales, A, B and C, extend over the range 1-10-100, whereas the fourth scale, D, extends over 1-10. Multiplication, division, as well as squares and square roots are possible with a single adjustment of the slider. The scales have a length of 10 inches. The back is either blank or has a table of gauge points.

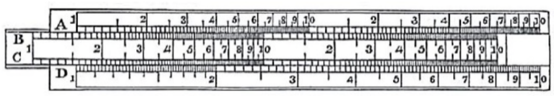

FIGURE 1: Soho Type Slide Rule

In addition to the design of steam engines, Farey also deals extensively with the slide rule and the variants of its design. On pg. 566 under *Directions to Engineers for the choice of a Sliding Rule* he gives hints for its selection and suggests his own arrangement of scales.

After the Soho slide rule had become known, it continued to exist in its original version for several decades. It can be found, for example, in Routledge

1808,[3] where he adopted the Soho scale arrangement and divisions on his joint Engineer's Improved Sliding Rule.

Instructions for the use of the slide rule, which were intended to make it known in Austria, also show the original scale arrangement and name the source too.[4] In the same period, variants of the Soho slide rule appeared because technicians endeavoured to adapt this slide rule to their own requirements by changing the scales or by introducing new scales.[5]

The Design of a Steam Engine

Before I show examples of the calculations for the design of a steam engine, I would like, for clarification, to explain briefly the construction and mode of operation of early steam engines. See Figure 2.

The first usable steam engine was built in 1712 by the English blacksmith Thomas Newcomen. An open cylinder, in which the piston moves up and down, is mounted above the steam boiler. This piston movement is transmitted via a beam, also called a balancier, to the pump rod on the other side. As the piston moves upwards, the cylinder is filled with steam. When the piston reaches the upper position, the steam supply is interrupted and the steam is condensed by injecting cold water. The pressure below the piston drops and the atmospheric air pressure moves the piston downwards, lifting the pump rod again. Since the air pressure acts on the piston, this type of machine is called an atmospheric steam engine.

Vertical water pumps were driven by the movement of the linkage, because the mines frequently reached groundwater level during the mining of coal and ore.

From 1765 onwards, the engineer James Watt made steady progress improving Newcomen's steam engine. As a result of Watt's work, the condensation of the steam now takes place outside the cylinder, preventing heat loss. In addition, the piston is pushed by the pressure of the steam itself, in early versions from one side, later from both sides. This pressure is higher than the air pressure, which means that greater forces can be achieved. Watt initially retained the beam for power transmission, but later converted the movement of the piston into a rotary movement of a flywheel by means of a connecting rod. With a rotary motion, it was now also possible to drive industrial machines requiring continuous motion, such as cotton spinning machines, mills, and others.

At the same time, the steam engine, including the boiler, was continuously improved and adapted to economic and technical requirements.

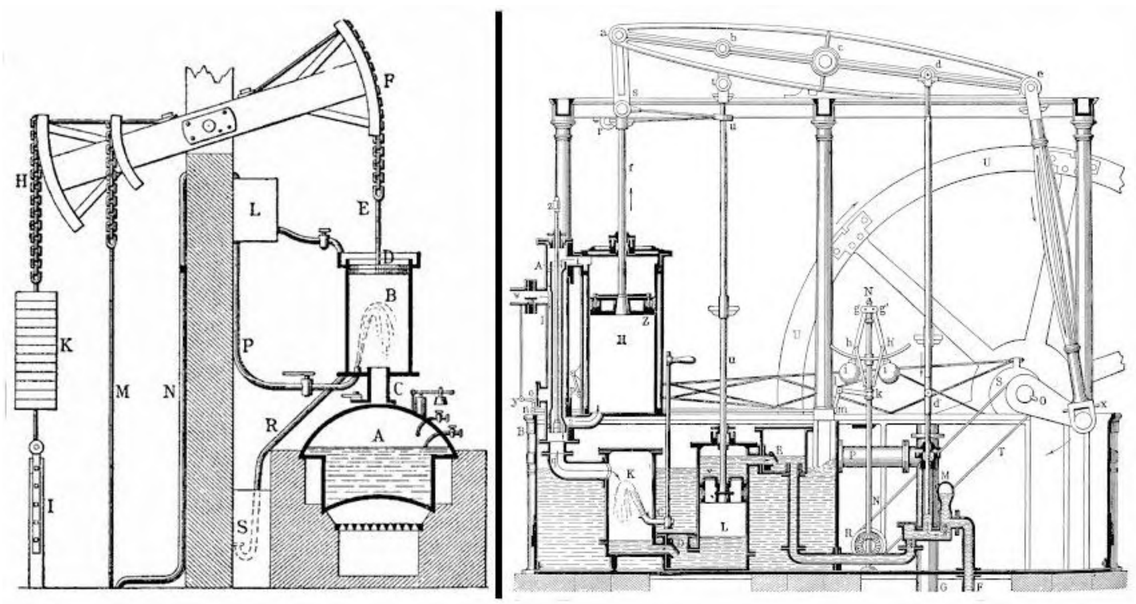

FIGURE 2. Steam Engines from Newcomen (left) and Watt (right)

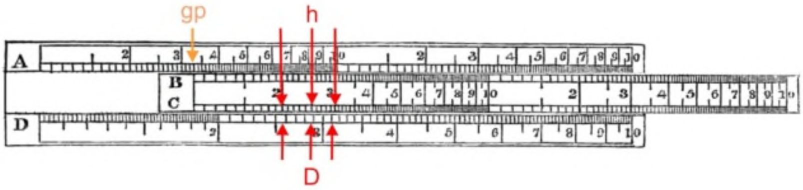

FIGURE 3. Setting the Slide Rule for the Design of a Steam Engine for a Water Pump

The design and mode of operation of a steam engine depends on the specific task it is required to perform. In the early years of steam power, the engines were bespoke power units, with no two alike. The size, weight, and strength of each component of each engine had to be calculated.

The above-mentioned treatise by John Farey and several other contemporary publications provide information on the methodology of the calculations. I have selected four tasks from the numerous examples of slide rule calculations in the literature to illustrate the approach of the engineers and the advantage of using the slide rule.

Design of a Steam Engine for Water Pumps

As already mentioned, the initial use of steam engines was to pump water out of mines. With the vertical movement of the piston, transferred to the other side of a beam, the water in pipes was pumped step by step to the surface. If the friction is initially neglected, the force exerted by the steam on the piston must be at least as great as the weight of the raised water column.

Routledge, in 1830, gives the following task in his manual for the engineer's slide rule on pg. 41: if the steam pressure *p* is a constant 10 lbs/in^2, the height of the water column *h* is 20 yards, and its diameter *d* is 16 inches, how large must the diameter *D* of the piston be?

In an attached table for the pressure *p*, the user searches for the diameter *d* and finds the gauge point 327. Gauge points denote a number; they represent previously calculated numerical values.[6] 327 is found on scale A and placed opposite the beginning of scale B. Opposite the height *h* on scale C, the diameter *D* of the piston can be read on scale D: 25 1/2 inches. Figure 3 shows this setting.

The selected gauge point covers the vapor pressure *p*, the diameter of the water column *d*, the specific gravity of water, and the conversion of yards into inches. It replaces multiple calculations with intermediate values. The numerical value of the gauge point is given, as usual, only as a sequence of digits, with no decimal point or units.

Routledge points out that on the scales C and D not only can the result of this problem be read, but all relations between the height of the water column and the piston diameter. He illustrates this in an arrangement shown in Figure 4.

against 15 ⎫ ⎧ **22,1 inches**
20 ⎪ ⎪ **25,5**
yards upon C, 25 ⎬ **are** ⎨ **28,5 diameter**
30 ⎪ ⎪ **31,3**
35 ⎭ ⎩ **33,8 upon D ;**

FIGURE 4. Variations of Variables on the Slide Rule for the Problem Shown in Figure 3

In a single position of the slide rule, the engineer can read the dependencies from height to diameter and then define the dimensions of the engine. This is not the only advantage of the slide rule, but a significant one. We find the same principle in the next example.

Loading of the Beam

The force of the piston is transmitted to the pump rod or to a connecting rod via a beam which acts as a two-sided lever. The early beams were made of oak wood, which was later replaced with iron. The dimensions of the beam were initially based on experience, a method which was later replaced by simplified calculations based on data obtained from experiments.

Farey demonstrates calculating examples for this. In one of these the arrangement of the slide rule, here with inverted slide, is shown in Figure 5. Farey likes to use inverted scales. His opinion on this is *"The sliding rule may have its slide inverted, and, in many cases, this is the most convenient mode of performing calculations by it."* The representation of the task by a section of the arranged scales and their highlighted values corresponds to the customary manner usual at that time.[7]

Soho Rule, Slide inverted, all four lines.	A One-4th length of beam feet.	Exam.	A	(25 ft. ÷ 4 =) 6·25	
	Ↄ Weight on the middle pounds.		Ↄ	Weight 32 368 lbs.	
	ꓭ Breadth of the beam inches.		ꓭ	Breadth 24 inc.	or 21
	ꓷ Depth of the beam inches.		D	Depth 29 inc.	31

FIGURE 5. Setting for Calculating the Load Capacity of a Beam

From the length of the beam and its load, a constant *C* is determined with both scales A and inverted C. Because $b * d^2 \equiv C$ applies for the dimensions of a beam with breadth *b* and depth *d*, the engineer can immediately read off all combinations of permitted dimensions *b* and *d* in the same position of the slide rule at the scales B inverse and D without repeated calculations.[8] With further considerations, such as the deflection of the beam, he then makes his choice.

Determination of Performance

With steam engines being built in different sizes, a specification of an engine's performance must also be calculated. Power is defined as *work / time* or *force * speed* with the force acting on the piston, i.e. *steam pressure * piston area*. In those early days, calculations resulting in values measured in units of lbs*feet/min were not immediately understandable whereas comparison with the output of a horse was meaningful.

After several tests with horses, the numerical values of their performance were 22916, 27500 and 32000 or 33000 (*pounds avoirdupoise 1 foot high in 1 minute*[9]). These results and the comparative measure itself were discussed. It was argued that horses could not maintain their performance permanently and that the value 33000 was too high, yet that is the value that Boulton and Watt chose, and it has remained the standard definition of horsepower, in terms of mechanical work, to this day. It was agreed to use horsepower (HP) as the unit for steam engine power.

Farey takes up this topic, beginning with a statement of the procedure for the calculation. This is followed by a graphic representation of the setting of the slide rule for calculating the power from *33000 * HP = force * motion* shown in Figure 6. Here he uses an inverted slider again and thus converts two multiplications into two proportions. The practical example is based on a double-acting machine with a force on the piston of 3070 lbs, a piston stroke of 5 feet and 21 1/2 double strokes per minute (2 * 5 * 21 1/2 = 215). This engine has a theoretical output of 20 HP.

Input variables of the calculation can be easily varied on the slide rule; further intermediate calculations are not necessary. The use of a gauge point in the calculation of the power is also present. I have given an example of this in an earlier article.[10]

In the early times the methods of calculating the engine power differed. In the previously mentioned book, *Roberts's Mechanic's Assistant*, the author points out in the title that he lists the correct method for calculating power. The calculation considers all influencing variables, namely pressure of the steam, area of the piston and the average piston speed taken from piston stroke and number of strokes. He also provides auxiliary tables that facilitate the calculation or estimation of variables for machines and their components. Auxiliary tables have always been a popular calculation aid. Figure 7 shows one of his tables. It gives the mean piston speed as a function of the piston stroke for real machines. There is no room here for discussing the values and their dependencies.

Length of Stroke in Feet	2	3	4	5	6	7	8	9
No. of Double Strokes	43	32	25	21	19	17	15	14
Feet per Minute	172	192	200	210	228	238	240	252

FIGURE 7. Auxiliary Table for the Average Piston Speed

Roberts' reference to the correct calculation of power probably stems from the fact that simplified methods based on unspecified assumptions with the aid of the slide rule are given in the literature. They can therefore hardly meet all requirements.[11] It should be mentioned that Roberts describes a slide rule which, with scales A, B and C, resembles the Soho type, whereas the D scale ranges from 4 to 40 and is called the girt-line.

Sliding Rule. slide inverted.	A Force in pounds.	33 000 lbs.	Examp.	A	3070 lbs.	33 000.
	Ↄ Motion ft. per min.	Horse-power.		Ↄ	215 ft.	20 HP.

FIGURE 6: Setting of the Slide Rule for Calculating the Power

The Hyp.Log. Scale for the Expansion Steam Engine

A major redesign is the expansion steam engine. In this case, the piston is not under constant pressure of the steam over the entire piston stroke, but only at the beginning of the working movement. Then the inlet valve closes and the steam expands with decreasing pressure. The pressure curve as a function of the piston position standardized to $p = 1$ at the beginning is shown in Figure 8.

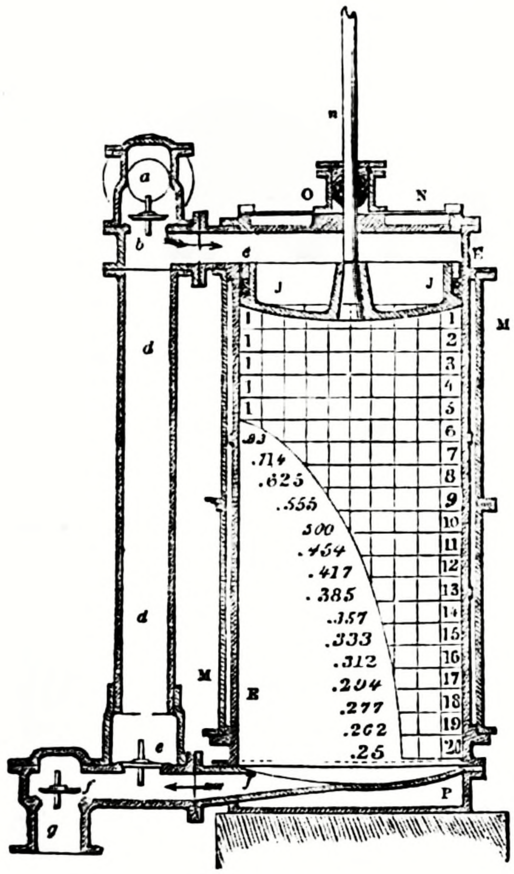

FIGURE 8. Pressure Curve in the Cylinder of an Expansion Steam Engine

In order to calculate the performance of such an engine, an average steam pressure is required which performs the same work during the piston movement from one dead center to the other as with a real pressure curve. In his treatise[12] on p. 13, engineer Thomas Dixon presents an improved slide rule which, in addition to the usual scales A, B, C and D, carries additional scales. One of them is marked with HYP.LOG^S. This scale gives the natural logarithms ln(x) to numbers x on a base scale (Figure 9, 2nd and 3rd scale from top) and serves to determine the mean pressure in the cylinder during expansion. Its use is based on two assumptions. The real drop in pressure is equated to that of an ideal gas with $p*V$ = const. and therefore corresponds to a hyperbola. Furthermore, during expansion, the work per area unit up to x times the initial volume with $p = 1$ initially corresponds to ln(x).

In the example calculations, Dixon demonstrates the use of this scale with expansion machines. In the simplest case such a calculation consists of four steps and is too extensive for a reproduction here. He expressly points out that calculations of this kind with a Soho slide rule, i.e. without the HYP.LOG^S scale mentioned, are not possible.

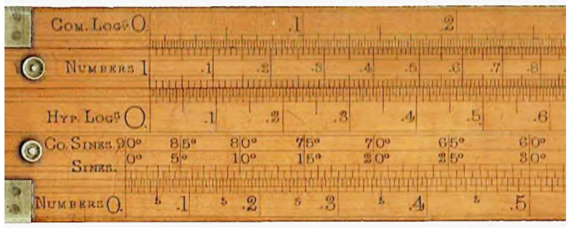

FIGURE 9: Slide Rule type Dixon, left Section of one Side

Currently this is the earliest use of the scale ln(x) on a slide rule known to me.

The other scales of his slide rule give the values of the angle functions, the logarithms to base 10 (marked with COM.LOG^S, Figure 9, scale on top) and the third powers.[13]

This example, like the introduction of the Soho slide rule itself, demonstrates that the computational tasks needed during the design of steam engines have influenced the arrangement of the engineer‘s slide rule.

Sources of Figures

Figure 1: Farey 1827, p. 537.

Figure 2: Meyers Konversationslexikon, *Bibliographischen Institut, Leipzig und Wien, 4th ed. 1885-1892, vol. 4. p.* 472 (Figure left), p. 460 (Figure right).

Figure 3: created by the author.

Figure 4: Routledge 1830, p. 42.

Figure 5: Farey 1827, p. 611.

Figure 6: Farey 1827, p. 440.

Figure 7: Roberts 1833, p. 15.

Figure 8: Bourne, John, *A Treatise on the steam-engine in its application to mines, mills, steam navigation, and railways,* London 1851, p. 12.

Figure 9: Photo E. Dean Butler, reproduced here with his kind permission.

Notes

1. Wess, Jane, *The Soho Rule,* Journal of the Oughtred Society, 6:2, Fall 1997.
   Wyman, Thomas, *Soho Steam Engines The First Engineering Slide Rule and the Evolution of Excise Rules*, Journal of the Oughtred Society, 22:2, Fall 2013.

2. Farey, John, *A Treatise on the Steam Engine: Historical, Practical, and Descriptive*, Longman, Rees, Orme, Brown, and Green, 1827.
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3. Routledge, Joshua, *Instructions for the engineer's improved sliding rule...*, 1808, 7th ed., London, 1830.

4. Schulz von Strassnicki, Leopold Carl, Anweisung zum Gebrauche des englischen Rechenschiebers…, Wien, 1843.
   Burg, Adam, Über die Einrichtung und Anwendung des bei den englischen Mechanikern und Maschinenarbeitern gebräuchlichen Schieberlineals (Sliding rule), mit welchem sie sämmliche auf ihre Arbeiten Bezug habenden Rechnungen sehr leicht und schnell ausführen, Jahrbücher des Kaiserlichen Königlichen Polytechnischen Institutes in Wien, Vol. 16, 1830.

5. Rudowski, Werner H., *Variants of Soho Slide Rules*, Journal of the Oughtred Society 24:2, Fall 2015, p. 6.

6. For gauge points see Weiss, Stephan, *Gauge Points and their Advantages*, Journal of the Oughtred Society, 27:2, Fall 2018.

7. Weiss, Stephan, *The Methodology of Teaching a Logarithmic Slide Rule in Historical Sequence*, Journal of the Oughtred Society, 26:2, Fall 2017.

8. The calculation of the constant C also includes the material of the beam, here oak, as well as empirical values from built machines and tests. Experts will recognize approaches to the section modulus here.

9. Roberts, Peter, *Roberts's Mechanic's Assistant; or Universal Measurer, containing a Collection of Tables of Measures, Weights and Powers, with a correct Method of Calculating the Horse Powers of a Steam Engine, New ed.* 1819, 6th ed., Leeds, 1833, p. 14.

10. Weiss, Stephan, Journal of the Oughtred Society 27:2, 2018, s. a. Farey 1827, p. 575.

11. See examples at Coulson, S., *Coulson's Treatise on his newly invented Engineers' and Mechanics' Slide Rule,* Stokesley, 1842, p. 243f.

12. Dixon, Thomas, *Treatise on the Arrangement, Application, and Use of Slide Rules*, Bradford 1875.

13. Wyman, Thomas, *The Thomas Dixon Engineer's Slide Rule*, Journal of the Oughtred Society, 5:2, Fall 1996, p. 68.
    S. a. International Slide Rule Museum: Aston And Mander Makers - Dixon Style Slide Rule. URL https://www.sliderulemuseum.com/Rarities.htm (last visit Dec. 16 2018).