The Slide Rule and the Steam Engine Indicator

Bruce E. Babcock, Ph.D.

Near the end of the eighteenth century, advances in the use of the slide rule for manipulating data were paralleled by advances in the use of devices for collecting data. One of the instruments that played a major role in the ever-increasing need for accurate data was known as a steam engine indicator. Today, instruments that perform a similar function on internal combustion engines are often called engine analyzers.

The relationship between the slide rule and the steam engine indicator is evident in Figure 1, which shows four advertisements from inside the front cover of the 1916 edition of C.N. Pickworth's *The Indicator Handbook.* The advertisement for British slide rules is most appropriate alongside advertisements for Pickworth's Power Computer and steam engine indicators made by both Crosby and Dobbie, McInnes. Pickworth's Power Computer was a specialized slide rule used to determine the indicated horsepower of steam, gas, and oil engines.

James Watt's Indicator

An engineer named John Southern, an employee of James Watt, invented the steam engine indicator in 1796. There does not appear to be any record of this instrument being patented; instead, it was considered such a valuable device that its existence and the details of its construction were a closely guarded industrial secret for at least 20 years. Figure 2 shows the construction of the original indicator. The instrument in the figure is a replica built by the author from detailed information provided by Mr. Ben Russell, then Assistant Curator of Mechanical Engineering and now Curator of Mechanical Engineering at the Science Museum in London, England.

In use, the indicator was attached to the cylinder of the steam engine so that the pressure of the steam in the cylinder acted against a piston and thus against a spring inside the vertical cylinder of the indicator. When the steam valves opened and closed, the pencil moved up and down as the pressure of the steam in the engine's cylinder rose and fell. At the same time that the pencil was moving up and down with changes in the pressure of the steam, a string attached to the beam of the engine or to a valve rod caused a piece of paper attached to the board to move horizontally as the engine's piston moved in the cylinder. The result of the simultaneous movement of the pencil and the paper caused the pencil to record the pressure in the cylinder at every point in the travel of the piston. All steam engine indicators built over the following 140 or more years functioned on this same principle.

Figure 3 shows an idealized indicator diagram and the valve events that are recorded.

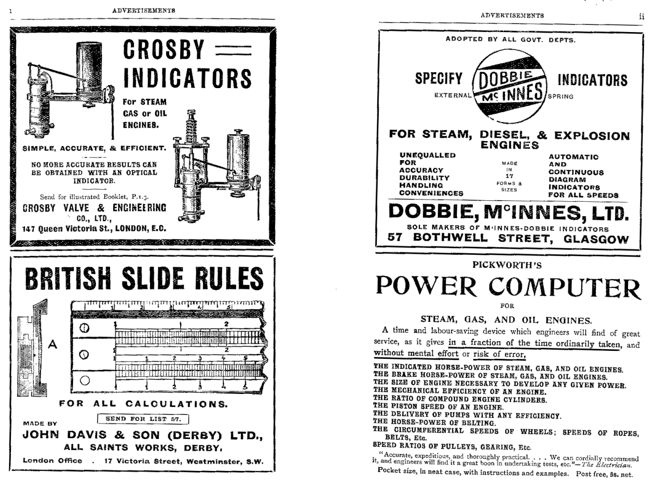
Even though the function of the steam engine indicator remained unchanged, the methods of achieving this function evolved. As the use of the indicator made possible advances in the speed and efficiency of steam engines, these advances made obsolete the very instruments that had made them possible. The early Watt indicator was not effective at speeds greater than about twenty revolutions per minute. Above that speed the inertia of the wooden board distorted the shape of the diagrams, making them meaningless.

Macnaught's Indicator

The first major advance in the design of the indicator occurred between 1825 and 1830 and is attributed to John Macnaught from Scotland. Macnaught eliminated the wooden board and replaced it with a lightweight brass cylinder, known as a paper drum, around which the paper was wrapped. Rather than sliding back and forth, the drum simply oscillated as the engine's piston moved. This design allowed the indicator to be used on engines running as fast as forty revolutions per minute. An example of a Macnaught indicator can be seen in Figure 4. Figure 5 is an illustration from the 1834 instruction book for the indicator shown in Figure 4. This illustration shows a Macnaught indicator installed on a beam engine in much the same way a Watt indicator would have been installed. The pressure of the steam in the early engines was so low that the steam connection on the bottom of this indicator is tapered but not threaded.

Richards' Indicator

As the speeds of steam engines continued to increase, the practice of connecting the pencil directly to the piston of the indicator became impractical, in that the spring would bounce up and down, drawing lines that were meaningless. This was a major problem for Charles Porter, who was developing his high-speed Porter-Allen steam engines in the 1860s. In 1862, Porter turned to C.B. Richards of Hartford, Connecticut, and asked that he develop an indicator that could be used at speeds far beyond the capacity of the Macnaught indicator. Richards' solution was to replace the relatively weak spring in the McNaught indicator with a much stiffer one and then to multiply the movement of the piston rod so that diagrams of equal height could be obtained with the stiffer spring. A major problem in amplifying the movement of the piston is that the pencil must move in a straight line, not in an arc. To solve this problem, Richards adapted a design that James Watt had used to achieve linear movement of piston rods at the ends of engine beams. This arrangement can be seen in Figure 5. A Richards indicator from the late 1860s or early 1870s is shown in Figure 6.


1 ADVERTISEMENTS

CROSBY INDICATORS
For STEAM GAS or OIL ENGINES.
SIMPLE, ACCURATE, & EFFICIENT.
NO MORE ACCURATE RESULTS CAN BE OBTAINED WITH AN OPTICAL INDICATOR.
Send for illustrated Booklet, P.1.3.
CROSBY VALVE & ENGINEERING CO., LTD.,
147 Queen Victoria St., LONDON, E.C.

BRITISH SLIDE RULES
A
FOR ALL CALCULATIONS.
SEND FOR LIST 57.
MADE BY
JOHN DAVIS & SON (DERBY) LTD.,
ALL SAINTS WORKS, DERBY.
London Office . 17 Victoria Street, Westminster, S.W.

ADVERTISEMENTS ii

ADOPTED BY ALL GOVT. DEPTS.
SPECIFY DOBBIE McINNES INDICATORS
EXTERNAL SPRING
FOR STEAM, DIESEL, & EXPLOSION ENGINES
UNEQUALLED FOR ACCURACY DURABILITY HANDLING CONVENIENCES
MADE IN 17 FORMS & SIZES
AUTOMATIC AND CONTINUOUS DIAGRAM INDICATORS FOR ALL SPEEDS
DOBBIE, McINNES, LTD.
SOLE MAKERS OF McINNES-DOBBIE INDICATORS
57 BOTHWELL STREET, GLASGOW

PICKWORTH'S
POWER COMPUTER
FOR
STEAM, GAS, AND OIL ENGINES.
A time and labour-saving device which engineers will find of great service, as it gives in a fraction of the time ordinarily taken, and without mental effort or risk of error,
THE INDICATED HORSE-POWER OF STEAM, GAS, AND OIL ENGINES.
THE BRAKE HORSE-POWER OF STEAM, GAS, AND OIL ENGINES.
THE SIZE OF ENGINE NECESSARY TO DEVELOP ANY GIVEN POWER.
THE MECHANICAL EFFICIENCY OF AN ENGINE.
THE RATIO OF COMPOUND ENGINE CYLINDERS.
THE PISTON SPEED OF AN ENGINE.
THE DELIVERY OF PUMPS WITH ANY EFFICIENCY.
THE HORSE-POWER OF BELTING.
THE CIRCUMFERENTIAL SPEEDS OF WHEELS; SPEEDS OF ROPES, BELTS, Etc.
SPEED RATIOS OF PULLEYS, GEARING, Etc.
"Accurate, expeditious, and thoroughly practical. . . . We can cordially recommend it, and engineers will find it a great boon in undertaking tests, etc."—*The Electrician.*
Pocket size, in neat case, with instructions and examples. Post free, 5s. net.

Figure 1. Pickworth.

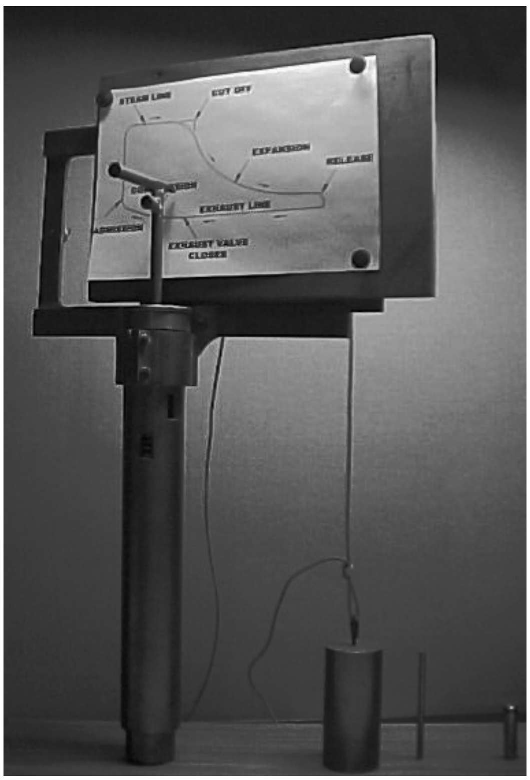


Figure 2. Watt Indicator.

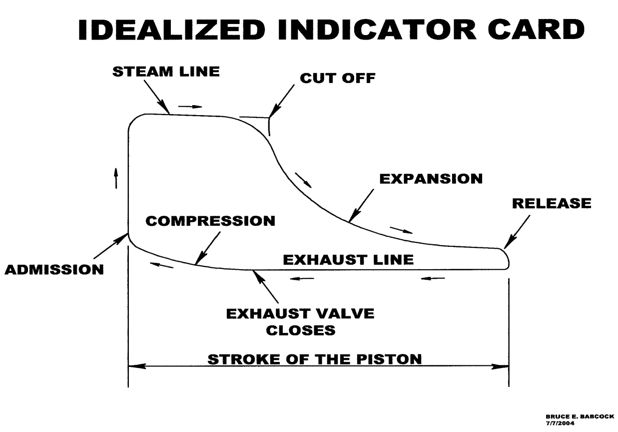


Figure 3. Idealized indicator diagram.

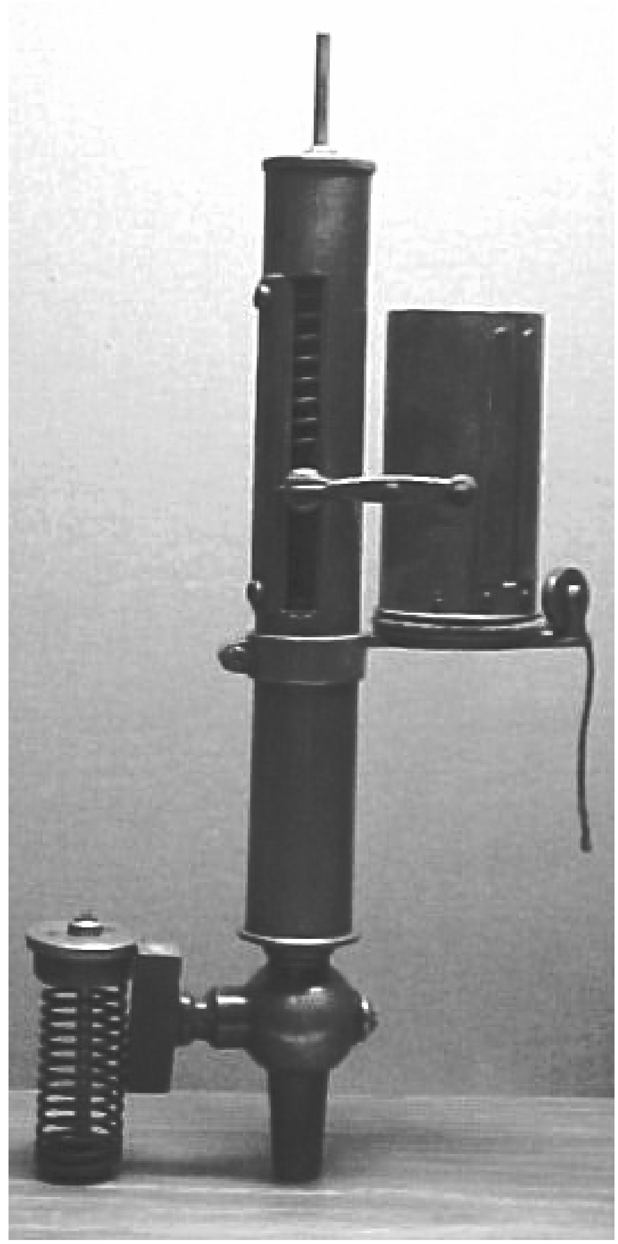
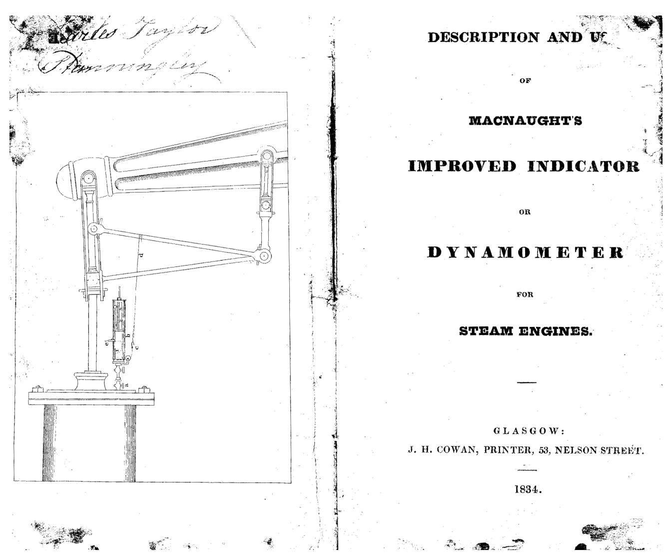


Figure 4. Mcnaught indicator.


DESCRIPTION AND U
OF
MACNAUGHT'S
IMPROVED INDICATOR
OR
DYNAMOMETER
FOR
STEAM ENGINES.

GLASGOW:
J. H. COWAN, PRINTER, 53, NELSON STREET.
1834.

Figure 5. Mcnaught booklet.

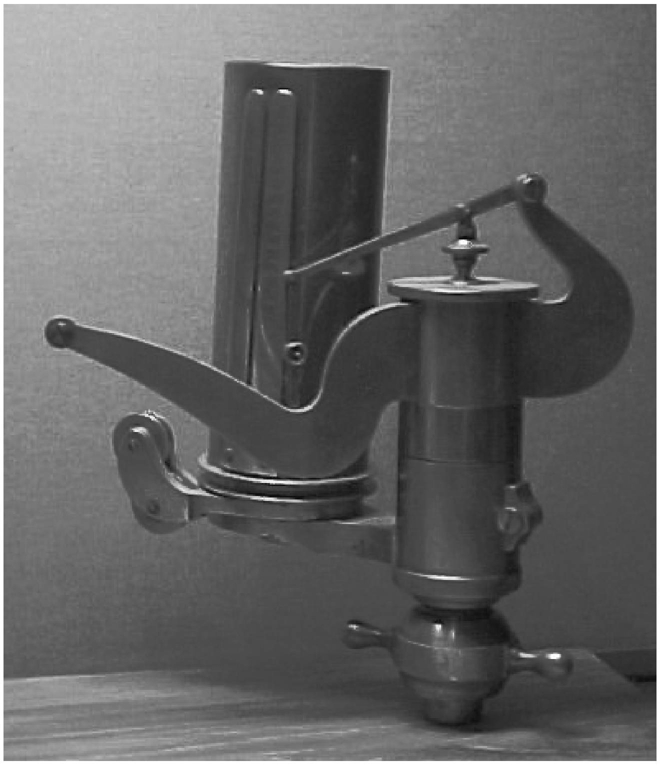


Figure 6. Richards indicator.

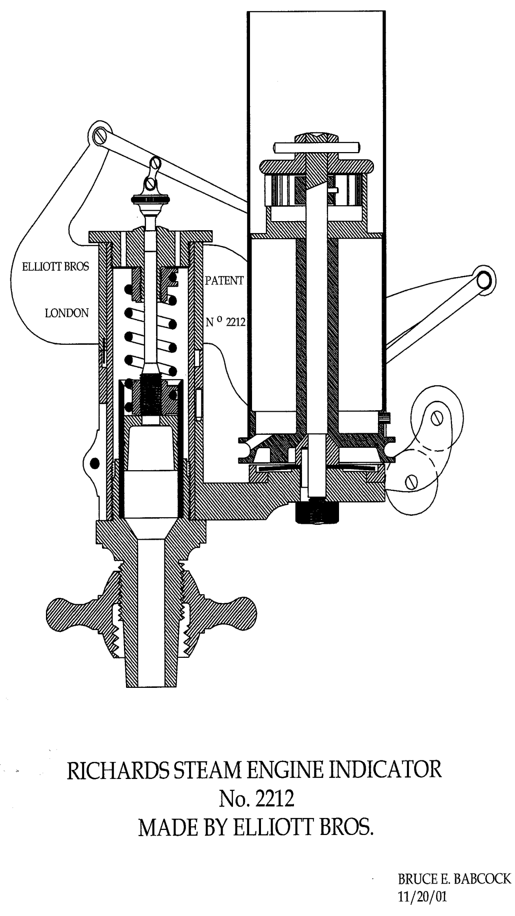


Figure 7. Richards indicator drawing.

Figure 8. Thompson indicator.

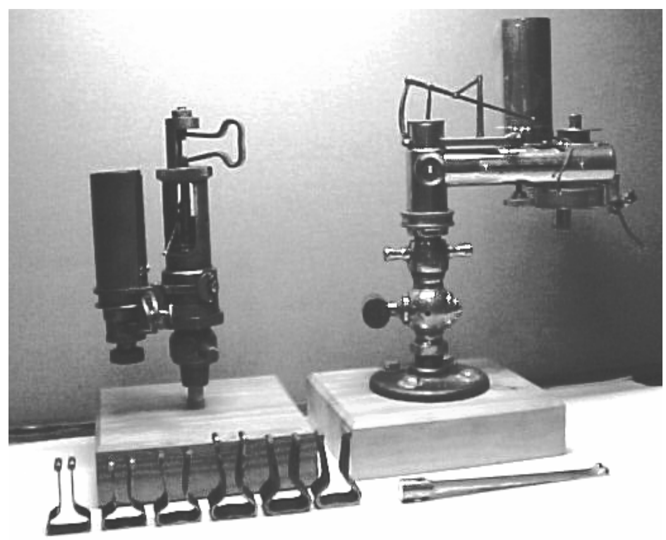


Figure 10. Simplex and Bushnell.

The internal details of this indicator can be seen in Figure 7. The Richards indicator with its amplified pencil movement and the rotating drum introduced by Macnaught contains the basic features found in all mechanical steam engine indicators until their production ceased. The Richards indicator was reported to be satisfactory for speeds up to two hundred and twenty revolutions per minute.

Figure 9. Three indicators that did not use Thompson's pencil movement. Left to right Tabor by Ashcroft, Lyne, and Darke.

The Thompson Indicator

In 1875, J. W. Thompson of Salem, Ohio, introduced the next significant improvement in the design of the indicator. The pencil movement in the Richards indicator was a significant improvement over Mcnaught's, but its inertia eventually limited the speed at which it could be used. Thompson's design reduced the weight of the components enough to allow the use of his indicators at speeds as high as four hundred revolutions per minute. Many manufacturers made Thompson's indicators. A Robertson-Thompson indicator is shown in Figure 8.

Variations in Pencil Movements

Attempts were made by several manufacturers to create a straight movement of the pencil without utilizing Thompson's design. Examples include the Tabor indicator sold by Ashcroft, the Lyne indicator, and the Darke indicator. None of these achieved the popularity of Thompson's patent. Of the three, the Tabor was the most popular. These indicators can be seen in Figures 9. The Tabor is on the left; the Lyne, in the middle; and the Darke, on the right.

Variations in the Design and Location of the Springs

Nearly all indicators relied on coiled springs to resist the pressure of the steam. There are two notable exceptions. The Bushnell indicator used a long horizontal leaf spring that was adjusted for various pressures by sliding a pivot along the spring. The other example is the Simplex indicator that used a spring that has been described as approximating the shape of sugar tongs. The Bushnell and the Simplex indicators are shown in Figure 10 (see previous page). Extra springs are shown below each indicator.

There was also variation in the placement of the springs. Most manufacturers offered indicators with the spring inside of the cylinder as in the Richards indicator in Figures 6 & 7. The Tabor indicator by Ashcroft in Figure 9, the Simplex indicator in Figure 10, and the Crosby in Figure 15 are examples that have the spring located outside of the cylinder to prevent the temperature of the steam from affecting the properties of the spring.

Indicator Accessories

Variations in steam pressures and in the loads on the engines required that a variety of springs be available if an indicator was to be used on various engines. Note that there are seven springs with the Simplex indicator in Figure 10. Each spring was stamped with a number indicating the amount of pressure required to move the pencil lead one inch. For each spring there was a corresponding small wooden scale stamped with the same number as the spring (See Figure 12.). When placed on a diagram made using, for example, a spring rated at one hundred pounds to the inch, the scale stamped "100" would directly measure the pressure in pounds per square inch anywhere along the stroke of the cylinder. The spring shown in Figure 12 is rated at one hundred pounds and is from the Crosby indicator in Figure 15. The K&E scale in Figure 12 is marked "100 TO THE INCH".

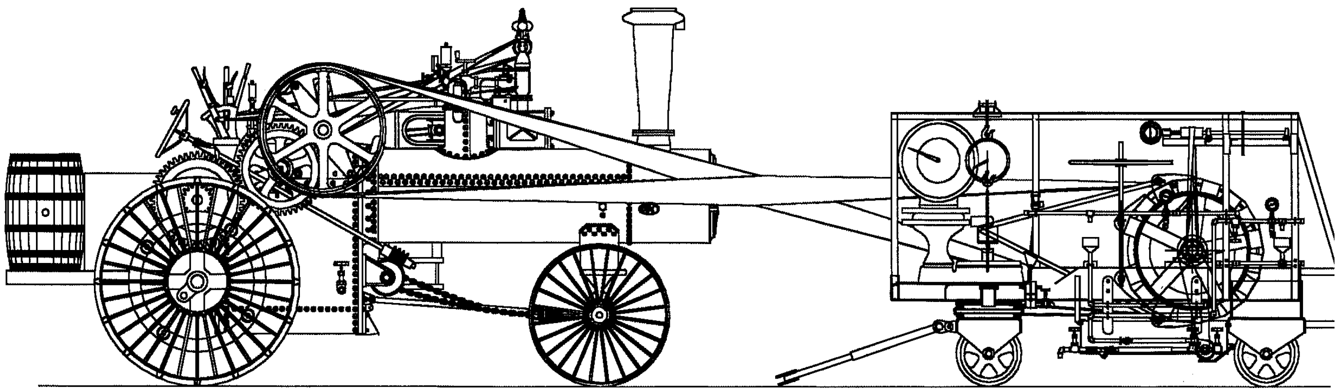


Figure 11. Sketch of a J.I. Case steam traction engine belted up to a Prony brake as would be done to take indicator cards.

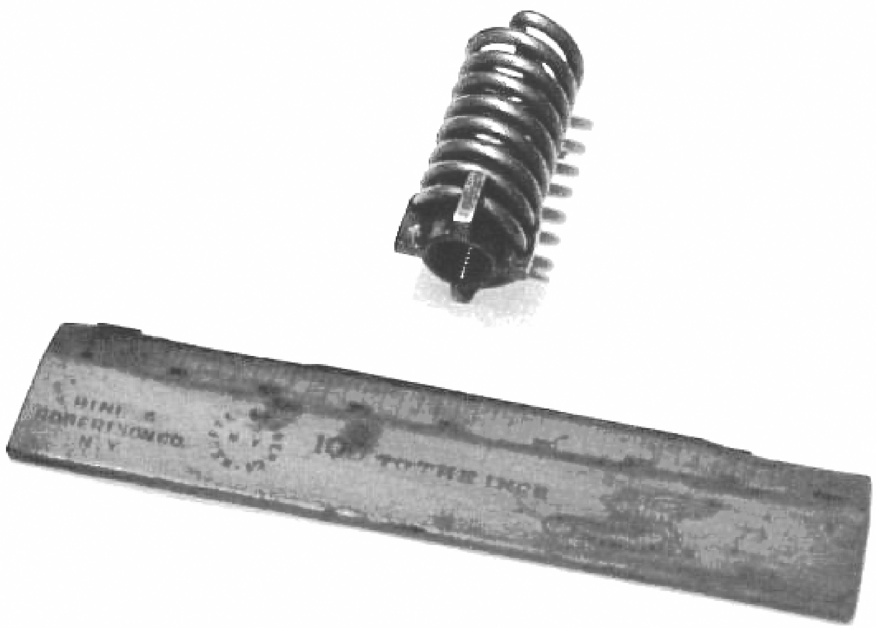


Figure 12. K&E scale and Crosby indicator spring both rated at 100 pounds to the inch.

It was necessary for every indicator to be equipped with a device to reduce the travel of the piston of the engine to three to five inches, the maximum allowable travel of most indicators. It was vital that the reduced travel be in exact proportion to the movement of the piston at all points in the stroke. This reduction was initially accomplished with wooden levers, or pantographs, one variation of which can be seen in Figure 13. As engine speeds increased, these devices became unreliable, and, around 1900, indicator manufacturers began to provide compact devices known as reducing motions that attached directly to their indicators. The changing of small wood or metal pulleys made these devices adaptable to a wide range of strokes. The Robertson-Thompson indicator in Figure 8 and the Bushnell indicator in Figure 10 are equipped with reducing motions of this type.

Most indicators came equipped with steam cocks. Two-way cocks were employed if an indicator was to be used to take cards from one end of a cylinder at a time. Examples can be seen in the Lyne and Darke indicators in Figure 9. A more desirable approach was to connect both ends of the cylinder to a three-way cock and install the indicator on the third port. With this arrangement it was possible to take cards from both ends of a cylinder almost instantly by simply moving the handle of the three-way steam cock. The Robertson-Thompson indicator in Figure 8 is mounted on a three-way cock.

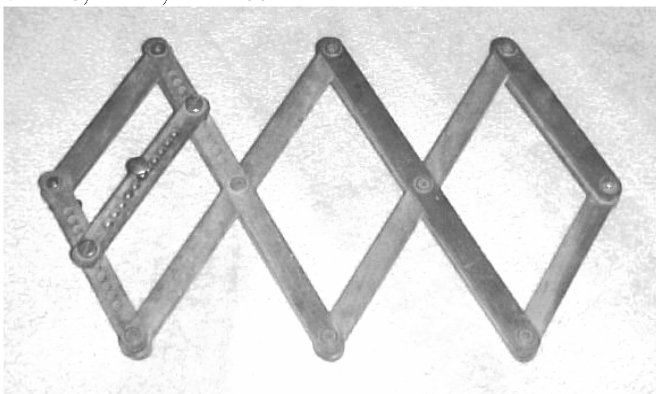


Figure 13. Pantograph.

Working-up the Cards

By measuring the area of the diagram drawn on the card and knowing the bore of the cylinder, the stroke, and the revolutions per minute, it was possible to calculate what is called the indicated horsepower of the engine. The area of the diagram is an indication of the amount of force the steam exerts on the piston. To determine this force it is necessary to know the average pressure, known as the mean effective pressure, or MEP. By using the scale that matched the spring installed in the indicator when the card was created, it was possible to measure the pressure at any point on the diagram. By averaging the readings taken at uniform intervals along the diagram, the MEP could be determined. Parallel rulers, like the one in Figure 14, were available to simplify this process. An easier and faster method was to use a planimeter to measure the area, divide the area by the length of the diagram, and arrive at the MEP.

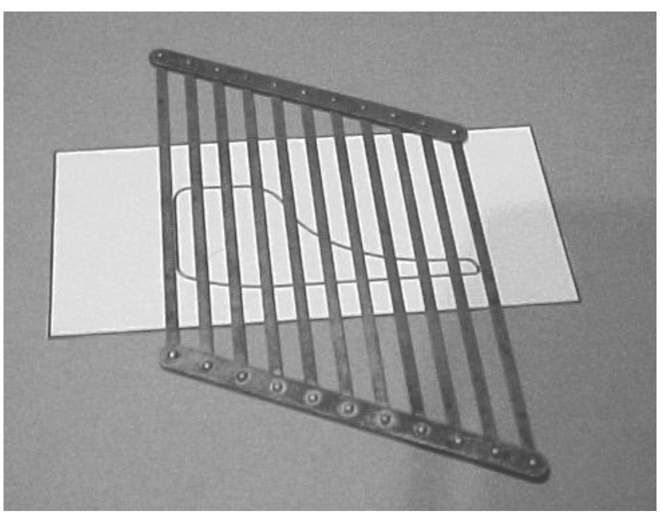


Figure 14. Parallel rule.

Page 320 of the Keuffel & Esser Company's 1909 catalog (Figure 18) lists both the small scales and the planimeters needed to work up indicator cards. Figure 12 shows a well-worn K&E scale made for the Hine & Robertson Company, a supplier of steam engine indicators. The planimeter that K&E offered did more than just measure the area of the diagram; it also determined its mean height, eliminating one step in the process of determining the mean effective pressure. The same catalog page also offers indicator cards printed on metallic paper. When metallic paper was used, the pencil lead on the indicator was replaced with a metal stylus. Replacing the common paper with metallic paper improved the accuracy of the indicator because the friction of the stylus on the metallic paper was less than the friction of lead on the common paper.

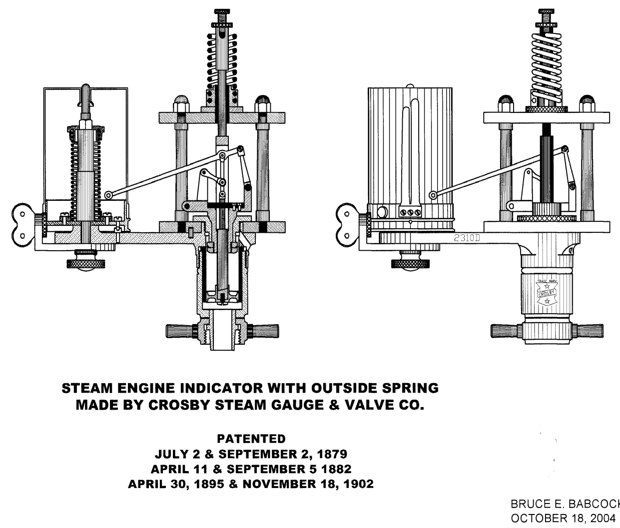


Figure 15. Crosby outside spring indicator.

The formula for calculating indicated horsepower is:

$$\begin{aligned} IHP &= \frac{P \times L \times A \times N}{33,000} \\ P &= MEP \\ L &= \text{length of the stroke, in feet} \\ A &= \text{area of the piston} \\ N &= \text{number of strokes per minute} \\ 33,000 &= \text{foot-pounds per minute per horsepower} \end{aligned}$$

This yields the horsepower for one end of the cylinder. The most accurate method is to take readings from both ends of the cylinder and add them together to get the total horsepower.

In addition to providing quantifiable results, the indicator was also valuable in providing a visual indication of the condition of the engine. A variety of problems could be diagnosed by simply observing variations in the shape of the diagram.

Figure 16. 23-90 Baker steam traction engine and the Prony brake being readied for the indicator demonstraton. Photograph by Dr. Robert T. Rhodes of Northern Kentucky University.

The Steam Engine Indicator Today

About the only place to find a steam engine indicator today is in a museum. The Smithsonian has a nice display, as do a few other institutions. The chances of seeing an indicator in use are rare. In the summer of 2004 I was successful in using a Robertson-Thompson indicator to take cards from one end of the cylinder on a 23-90 (23 nominal horsepower and 90 brake horsepower) A.D. Baker steam traction engine at the Miami Valley Steam Thresher's Show in Plain City, Ohio. To get meaningful readings with an indicator, the engine must be operating under a load. If the size of the load is known, the information that can be acquired is more meaningful. Toward this end I built a large Prony brake that is capable of absorbing one hundred horsepower. Using this brake we were able to vary the load on the engine between fifteen horsepower and fifty horsepower and take readings at the various loads. Figure 16 shows how the power of a steam traction engine is transmitted to the Prony brake via a heavy drive belt. Figure 17 shows an indicator installed on the head end of the cylinder of the traction engine shown in the previous figure.

The Prony brake is another example of a device, like the indicator, that provided early engineers with the data essential to perfecting the design of water wheels, windmills, steam engines, internal combustion engines, and even early electric motors. As with the indicator, much of this data was manipulated with the use of slide rules. Gaspard de Prony, a Frenchman, invented the Prony brake in the 1820s. Cajori notes that slide rules made by Isaac Sargent "commanded the lively attention of the mathematician Prony".

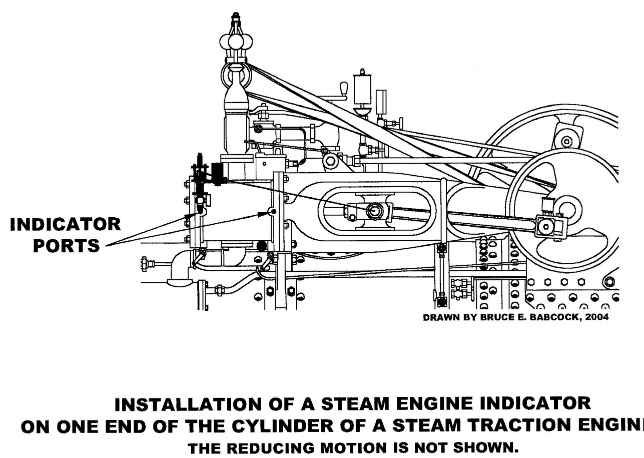


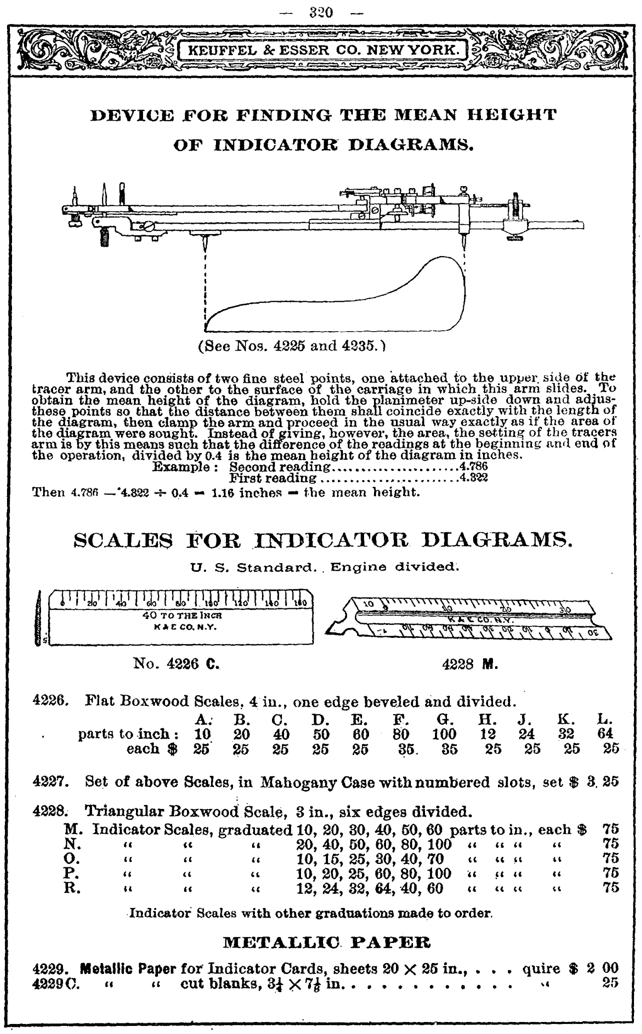
Figure 17.

It is possible to observe vintage Prony brakes in operation every summer at, at least, three antique engine shows. The National Thresher's Show at Wauseon, Ohio, operates the brake from the A.D. Baker steam engine factory every day of their four-day show. Oklahoma Steam Threshers at Pawnee, Oklahoma, demonstrates the use of their brake on steam traction engines as large as one hundred and ten horsepower. And in July, the Miami Valley Steam Threshers at Plain City, Ohio, operate the Prony brake that originally belonged to the Agricultural Engineering Department at the Ohio State University. There are a few privately owned Prony brakes, such as mine, that tour from show to show.

Power Computing Slide Rules

The need for a convenient means of manipulating the data generated by the steam engine indicator and the Prony brake was sufficient to justify K&E's decision to offer slide rules designed for these specific applications. In 1900, K&E offered Hudson's Horsepower Computing Scale (Figure 119a), a cardboard slide rule with two slides that, according to Cajori, was manufactured by W.F. Stanley of London. K&E described the rule:

"With it can be found at once: the indicated horsepower of an engine, the size of cylinder required for any desired power, the piston speed due to any stroke, or revolutions per minute, the ratio of compound cylinders and the proportion of initial pressure realized as mean pressure with the steam cut off at different percentages of stroke".



— 320 —

KEUFFEL & ESSER CO. NEW YORK.

DEVICE FOR FINDING THE MEAN HEIGHT OF INDICATOR DIAGRAMS.

(See Nos. 4225 and 4235.)

This device consists of two fine steel points, one attached to the upper side of the tracer arm, and the other to the surface of the carriage in which this arm slides. To obtain the mean height of the diagram, hold the planimeter up-side down and adjus-these points so that the distance between them shall coincide exactly with the length of the diagram, then clamp the arm and proceed in the usual way exactly as if the area of the diagram were sought. Instead of giving, however, the area, the setting of the tracers arm is by this means such that the difference of the readings at the beginning and end of the operation, divided by 0.4 is the mean height of the diagram in inches.

Example: Second reading 4.786
First reading 4.322

Then 4.786 — 4.322 ÷ 0.4 = 1.16 inches = the mean height.

SCALES FOR INDICATOR DIAGRAMS.

U. S. Standard. Engine divided.

No. 4226 C. 4228 M.

4226. Flat Boxwood Scales, 4 in., one edge beveled and divided.

	A.	B.	C.	D.	E.	F.	G.	H.	J.	K.	L.
parts to inch:	10	20	40	50	60	80	100	12	24	32	64
each $	25	25	25	25	25	35	35	25	25	25	25

4227. Set of above Scales, in Mahogany Case with numbered slots, set $ 3.25

4228. Triangular Boxwood Scale, 3 in., six edges divided.

M.	Indicator Scales, graduated	10, 20, 30, 40, 50, 60 parts to in., each $	75
N.	" " "	20, 40, 50, 60, 80, 100 " " " "	75
O.	" " "	10, 15, 25, 30, 40, 70 " " " "	75
P.	" " "	10, 20, 25, 60, 80, 100 " " " "	75
R.	" " "	12, 24, 32, 64, 40, 60 " " " "	75

Indicator Scales with other graduations made to order.

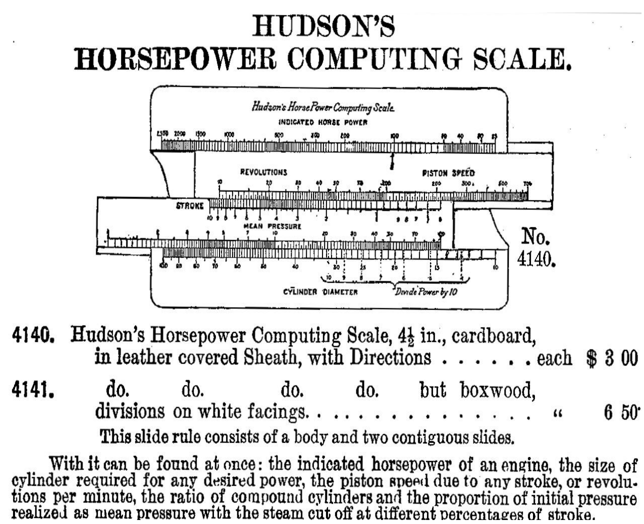
METALLIC PAPER

4229. Metallic Paper for Indicator Cards, sheets 20 × 25 in., . . . quire $ 2 00
4229C. " " cut blanks, $3\frac{1}{4} \times 7\frac{1}{8}$ in. . . . . " 25

Figure 18. K&E catalog page 320.

In 1915, this rule was available in both cardboard and Xylonite and K&E also offered for the first time, a 7-1/4-inch No. 4135 power computing slide rule (Figure 19b). This was a duplex rule, engine divided, with the divisions on white facing. They described it as being especially designed for use in computing power and dimensions of steam, gas, and oil engines. According to the catalog, the rule gave all the data required for finding speed, length of stroke, and size of the cylinders.

The face of the No. 4135 rule carries five series of special graduations, "to be used in determining B.H.P., I.H.P., or principal Dimensions of Steam Gas and Oil Engines of any size. On the reverse face of the Rule are engraved the A, B, C, and D scales usually found on the Manheim Slide Rule".



HUDSON'S HORSEPOWER COMPUTING SCALE.

No. 4140.

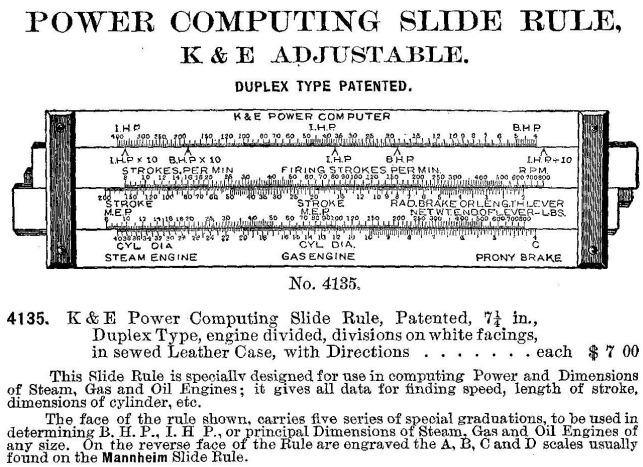
4140. Hudson's Horsepower Computing Scale, $4\frac{1}{2}$ in., cardboard, in leather covered Sheath, with Directions . . . . . . each $ 3 00

4141. do. do. do. do. but boxwood, divisions on white facings. . . . . " 6 50

This slide rule consists of a body and two contiguous slides.

With it can be found at once: the indicated horsepower of an engine, the size of cylinder required for any desired power, the piston speed due to any stroke, or revolutions per minute, the ratio of compound cylinders and the proportion of initial pressure realized as mean pressure with the steam cut off at different percentages of stroke.

Figure 19a. K&E 4135.



POWER COMPUTING SLIDE RULE, K & E ADJUSTABLE.

DUPLEX TYPE PATENTED.

No. 4135.

4135. K & E Power Computing Slide Rule, Patented, $7\frac{1}{4}$ in., Duplex Type, engine divided, divisions on white facings, in sewed Leather Case, with Directions . . . . each $ 7 00

This Slide Rule is specially designed for use in computing Power and Dimensions of Steam, Gas and Oil Engines; it gives all data for finding speed, length of stroke, dimensions of cylinder, etc.

The face of the rule shown, carries five series of special graduations, to be used in determining B. H. P., I. H P., or principal Dimensions of Steam, Gas and Oil Engines of any size. On the reverse face of the Rule are engraved the A, B, C and D scales usually found on the **Mannheim** Slide Rule.

Figure 19b. K&E 4135.

In 1927, K&E revised the power computing slide rule, eliminating one of the slides, and designated it as their No. N-4135 rule (Figure 20). Their description of the revised rule was essentially the same as for their earlier No. 4135 rule.

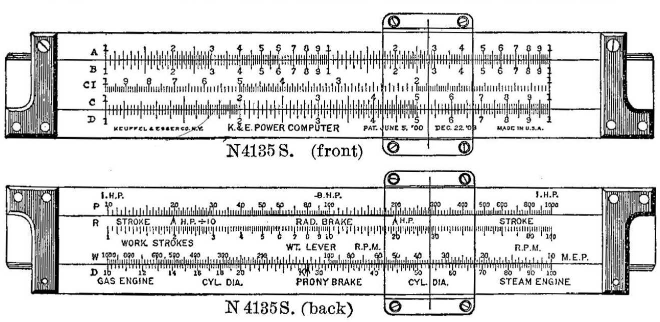
In their descriptions, B.H.P. stands for brake horsepower, which is measured with the Prony brake and I.H.P. stands for indicated horsepower, which is measured with the steam engine indicator.

Power computing slide rules were not offered by K&E after 1937.

Other Power Computing Slide Rules

The following are just two examples of other slide rules designed to be used in conjunction with the steam engine indicator.

- According to Cajori's *A History of the Logarithmic Slide Rule and Allied Instruments,* W.F. Stanley made a rule known as Hale's Slide Rule for Indicator Diagrams.
- In his book *The Slide Rule: A Practical Manual* Pickworth includes an illustration of his Power Computer for Steam and Gas Engines, which he claims "gives directly the brake horse-power of any steam, gas, or oil engine; the indicated horse-power; the dimensions of an engine to develop a given power; and the mechanical efficiency of an engine." This rule is described above in Figure 1.


POWER COMPUTING SLIDE RULE.

N4135 S. (front)

N 4135 S. (back)

N 4135S. **K & E POWER COMPUTING** Slide Rule, **DUPLEX*, K & E Adjustable,** 5 inch, engine divided, divisions on white facings, "Frameless" Glass Indicator; in sewed Leather Case without flap, with Directions . . . . each

This Slide Rule is specially designed for use in computing Power and Dimensions of Steam, Gas and Oil Engines; since it gives all data for finding speed, length of stroke, dimensions of cylinder, etc.

The front face of the rule carries the usual A, B, C, D and CI scales the same as on the front face of the K & E **POLYPHASE*** Slide Rule.

The reverse face carries a series of special graduations for use in computing power and dimensions of Steam, Gas and Oil Engines; and it gives all data for finding speed, length of stroke, dimensions of cylinder, B. H. P., I. H. P. etc.

*REG. U. S. PAT. OFF.

Figure 20. K&E N-4135.

The connection between the slide rule and the indicator was further reinforced by an advertisement in Pickworth's book on the slide rule that prominently featured a steam engine indicator offered by Joseph Casartelli & Son.

Calculations for the steam engine were not confined to the special-purpose slide rules like those described above. Pickworth, for example, in his book on the slide rule included ten problems that involved calculating the power and forces in the cylinders of steam engines. He described how to solve each of them by using a conventional slide rule.

It is clear that, without accurate, quantified information, the slide rule would have been of little or no value to the engineers whose creativity made possible the technological advances of the industrial revolution. There is no doubt that the steam engine indicator and the Prony brake are only two examples of the myriad of instruments that supplied the data needed to make possible the way of life we know today.

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Ben Russell, who was Assistant Curator of Mechanical Engineering at the Science Museum in London, was kind enough to remove the original James Watt indicator from its display case to photograph it, and to make sketches, complete with dimensions. This information was used to construct the replica shown in Figure 2.