

Lean's Engine Reporter and the Development of the Cornish Engine: A Reappraisal

by

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THE ORIGINS OF *LEAN'S ENGINE REPORTER*

A Boulton and Watt engine was first installed in Cornwall in 1776 and, from that year, Cornwall progressively became one of the British counties making the most intensive use of steam power.¹ In Cornwall, steam engines were mostly employed for draining water from copper and tin mines (smaller engines, called 'whim engines' were also employed to draw ore to the surface). In comparison with other counties, Cornwall was characterized by a relative high price for coal which was imported from Wales by sea.² It is not surprising then that, due to their superior fuel efficiency, Watt engines were immediately regarded as a particularly attractive proposition by Cornish mining entrepreneurs (commonly termed 'adventurers' in the local parlance).³

Under a typical agreement between Boulton and Watt and the Cornish mining entrepreneurs, the two partners would provide the drawings and supervise the works of erection of the engine; they would also supply some particularly important components of the engine (such as some of the valves). These expenditures would have been charged to the mine adventurers at cost (i.e. not including any profit for Boulton and Watt). In addition, the mine adventurer had to buy the other components of the engine not directly supplied by the two partners and to build the engine house. These were all elements of the total fixed cost associated with the erection of a Boulton and Watt engine.

Boulton and Watt derived their profits from the royalties charged for the use of their engine. Watt's invention was protected by the patent for the separate condenser he took out in 1769, which an Act of Parliament prolonged until 1800. The pricing policy of the two partners was to charge an annual premium equal to one third of the savings of the fuel costs attained by the Watt engine in comparison with the Newcomen engine. This required a number of quite complicated calculations, aimed at identifying the *hypothetical* coal consumption of a Newcomen engine supplying the same power as the Watt engine installed in the mine. The calculation system was cumbersome and the figures computed were frequently objected to, so that in a number of cases Boulton and Watt decided to switch to a fixed annual sum based on the general fuel-saving potentialities of the engine they had installed, in the hope of avoiding the problems related with the computation of the actual coal savings.⁴ At the beginning, this type of agreement was rather favourably accepted by Cornish mine adventurers but the fixed annual sums frequently came to be disputed when mines were not profitable. It must be remembered that, from the early 1780s, the

exploitation on a large scale of the Parys Mountain copper mines in Anglesey caused a reduction in copper prices putting the profitability of many Cornish mining ventures under strain.⁵

It is also worth remarking that, in the late eighteenth century, several engineers in Cornwall had begun to work on further improvements to the steam engine, but their attempts were frustrated by Boulton and Watt's interventions. Watt's patent was very broad in scope (covering all engines making use of the separate condenser *and* all engines using steam as a 'working substance'). The enforcement of almost absolute control on the evolution of steam technology, using the large blocking power of the patent, was indeed a crucial component of Boulton and Watt's business strategy.

The most famous case in this respect was that of Jonathan Hornblower⁶ who had taken a patent for the first compound engine in 1781 and who found the further development of his invention obstructed by the actions of Boulton and Watt. In 1782, a first engine of the Hornblower type was erected for the Radstock colliery near Bristol. Initially, the performance of the engine was far from being satisfactory. Working at low pressures, the Hornblower engine could not exploit the advantages of compounding. Interestingly enough, about 1785, Hornblower discussed with Davies Gilbert (who would also later on — in the early 1800s — engage in a long correspondence with Richard Trevithick on the subject of the efficiency of steam engines) the possibility of adopting in his compound engines 'the condensation of steam raised by quick fire' (i.e., high-pressure steam and expansion).⁷ After a period of experimentation, the Hornblower engine became capable of delivering a performance similar to that of Watt engines.

In 1791, Hornblower began to erect engines in several Cornish mines, threatening Boulton and Watt's monopoly position. Concomitantly, he applied to Parliament for an extension of his 1781 patent. The argument on which Hornblower based his petition to Parliament was the same as that underlying Watt's petition of 1775: the engine had required a long and costly period of refinement after the patent was taken, so an extension was necessary to enable him to reap a fair profit from his invention. Boulton and Watt opposed the petition on the grounds that the salient features of the engine were a clear plagiarism of Watt's invention. As in the case of the prolongation of Watt's 1769 patent, Boulton's powerful influence succeeded in gaining the favour of Parliament on his side so that Hornblower and his partners decided to withdraw the petition.

Yet, the conflict was far from being settled. After Parliament's decision, Hornblower went on erecting his engines in Cornish mines. Many Cornish adventurers saw in his engines the possibility of reducing their costs by avoiding the payment of the high royalties claimed by Boulton and Watt. At the same time, another Cornish engineer Edward Bull began to install steam engines for several Cornish mines. Bull's engines were essentially a simplified version of Watt (they dispensed with the beam, the piston rod acting directly the pumps) and thus a much clearer case of piracy than Hornblower's, but at this time the majority of Cornish mine entrepreneurs were ready to challenge explicitly the validity of Watt's patent.

Boulton and Watt had no choice but to sue Bull for infringement. In his defence, Bull explicitly called in question the validity of Watt's patent on the basis of the insufficiency of the specification. The dispute ended in 1799 with the courts confirming the legal validity of Watt's patent thus giving complete victory to Boulton & Watt. During the lawsuit, Watt published a notice in the Bristol newspapers claiming that his 1769 patent covered *all* the following features: 1) cylinder with closed top, 2) piston driven by steam (instead of

atmospheric pressure as in the Newcomen engine, 3) steam jacket to cylinder, 4) separate condenser, 5) air pump, 6) piston sealed by oil or grease.⁸ In practice, it is impossible to move away from the design of the Newcomen engine without making use of some of these features.⁹

Hornblower, however, considered Watt's patent to be limited to the separate condenser. In his engine, steam condensation took place in the lowest part of the second (low-pressure) cylinder and, for this reason, Hornblower was convinced that he was not infringing Watt's patent. He later found out that the separate condenser could greatly improve the performance of his engine but this addition meant that Hornblower could not fully exploit his invention without infringing Watt. Since Hornblower's patent of 1781 would have expired normally in 1795, a successful request for extension would have had the effect of prolonging protection for Hornblower's invention after the expiry of Watt's extended patent. As we have seen, Parliament, by virtue of Boulton's influence, was not ready to meet the request. At that point Hornblower decided to adopt the separate condenser in his engines and to resist claims from Watt on the ground the Watt's patent was invalid due to insufficient specification.

After the clash on the prolongation of patent, Boulton and Watt and Jonathan Hornblower did not meet again in court. Boulton and Watt adopted the cautious strategy of starting their campaign of legal actions by suing makers of engines who were clearly infringing the patent. The first lawsuit was the one directed against Edward Bull; a second lawsuit was directed against Jabez Hornblower (brother of Jonathan) and Maberley who had started erecting pirate rotative engines in the London area. On the basis of the victory obtained in these two cases, Boulton and Watt sent injunctions to all the other users of 'pirate' engines they could identify (including the owners of Jonathan Hornblower's engines). At this point, none of them was able to oppose the injunctions and so they all came to some form of settlement for the payment of the royalties. In Cornwall, the dispute also had other far-reaching consequences. Boulton and Watt, with their legal victory (pursued with relentless determination), completely alienated any residual sympathy towards them. After the expiration of Watt's patent in 1800, steam engine orders to Boulton and Watt from Cornish mines ceased completely and the two partners had to call William Murdock, their engineer working in the county, back to Birmingham. However, it is also important to mention that, at this stage, the market for industrial power had become the main focus of the company.

Following the departure of Boulton and Watt, the maintenance and the improvement of Cornish pumping engines underwent a period of 'slackness', as the mine adventurers were content with the financial relief coming from the cessation of the royalties. This situation lasted until 1811, when a group of mine 'captains' (mine managers) appointed a highly respected colleague Joel Lean to produce a monthly journal (*Lean's Engine Reporter*)¹⁰ containing detailed reports on the performance (measured in millions of lbs of water lifted one foot high per consumption of a bushel of coal, or, as it was termed by contemporary engineers, the 'duty') of many steam engines at work in the Cornish tin and copper mines (for more details on the procedures adopted for calculating the duty of Cornish engines, see Appendix 1).

The explicit intention was twofold. Firstly, the publication would permit the rapid identification and diffusion of best-practice techniques. Secondly, it would create a climate of competition among the engineers entrusted with the different pumping engines, with favourable effects on the rate of technical progress.

For each engine reported, the Leans¹¹ published the following information:

- i) the name of the engine and the mine in which it was located,
- ii) the diameter of the cylinder (in inches),
- iii) the load on the pistons (in lbs. per square inch),
- iv) the length of the stroke in the cylinder (in feet),
- v) the number of pump lifts, the depth of each lift (in fathoms), the diameter of each pump (in inches),
- vi) the period during which the engine was in operation,
- vii) the length of stroke in pumps (in feet),
- viii) the weight of water raised at each stroke (in lbs.),
- ix) the consumption of coal (in bushels),
- x) the number of strokes effectuated in the period considered,
- xi) the duty of the engine (lbs of water lifted one foot per bushel of coal consumed),
- xii) the average number of strokes per minute, and
- xiii) the name of the engineer entrusted with the engine and eventual remarks on potentially interesting features of the engine and of its working behaviour.¹²

The availability of a historical source such as *Lean's Engine Reporter* provides an almost unparalleled perspective on one of the most topical moments of the history of the steam engine.

THE CONTOURS OF TECHNICAL PROGRESS IN CORNISH ENGINES

In one of his patents taken out in 1782, Watt had suggested the idea of expanding steam before condensation. The idea behind the adoption of the principle of expansion was that of fuel economy (allowing the 'expansive force' of steam to perform some of the overall work). This was done by cutting off the steam when the piston was at the beginning of its course and letting the expansion of the steam inside the cylinder complete the stroke. However, in order to achieve some gain in fuel efficiency using steam expansion, higher pressures than atmospheric ones ought to be employed (at low pressures, the gain in efficiency was bound to be very limited). High pressure expansive engines have a higher fuel efficiency than low pressure ones because they operate between a wider range of operating temperatures. In the words of Carnot:

The reasons for the superiority of what we call high pressure engines over engines operating at a lower pressure are now evident. Their superiority lies essentially in their ability to utilize a greater fall of caloric. Since steam that is produced at a higher pressure is also at a higher temperature, and since the temperature of condensation always remains much the same, the fall of caloric is obviously greater. But, in order, to derive really advantageous results from high-pressure engines, the fall of caloric must be used in the best possible way. It is not enough that the steam should be formed at a high temperature; it is also essential that, through expansion, it should reach a sufficiently low temperature. The mark of a good steam engine, therefore, must be not only that it uses steam at high pressure but also that it uses it at pressures that are not constant but which vary substantially from one moment to the next and progressively decrease.¹³

Given their conception of the steam engine as vapour-pressure engine, early nineteenth century engineers found extremely difficult to account for the superior fuel efficiency of the high pressure expansive engine.¹⁴

Watt, however, was strongly adverse to the use of high-pressure steam. He was afraid of the possible negative consequences of publicity about boiler explosions, fearing that this could have discredited the use of steam power irreparably.¹⁵ After the expiration of Watt's key patent in 1800, engineers were, however, free to begin the exploration of the high-pressure/expansion combination. Concomitantly, with the beginning of the publication of *Lean's Engine Reporter*, Richard Trevithick and Arthur Woolf installed high-pressure expansive engines in Cornish mines. These were the first systematic attempts of employing high pressure steam expansively in a condensing engine. Engines embodying these design features would later become known as 'Cornish' engines. In the following years the Cornish engine proved to be the highest peak in steam engineering of the first half of the nineteenth century.¹⁶ The engine had negligible costs of maintenance and it was susceptible to continuous improvements in its efficiency. Most of these improvements were charted in the tables of *Lean's Engine Reporter*.

Figure 1 displays the evolution over time of the efficiency of Cornish steam engines (based on the collation of several sources).¹⁷ The figure clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical advance. The growth in the efficiency of Cornish engines seems to be tightly linked with the rate of capital formation in the Cornish mining industry. Installation of new capacity permitted experimentation with designs facilitating the discovery of new improvements. Hence, the period of high duty growth coincided with the rapid expansion of the Cornish mining industry and, conversely, the phase of recession after the 1850s determined a slow decline of average duty followed by a period of substantial stagnation.¹⁸ Figure 1 seems also to suggest the existence

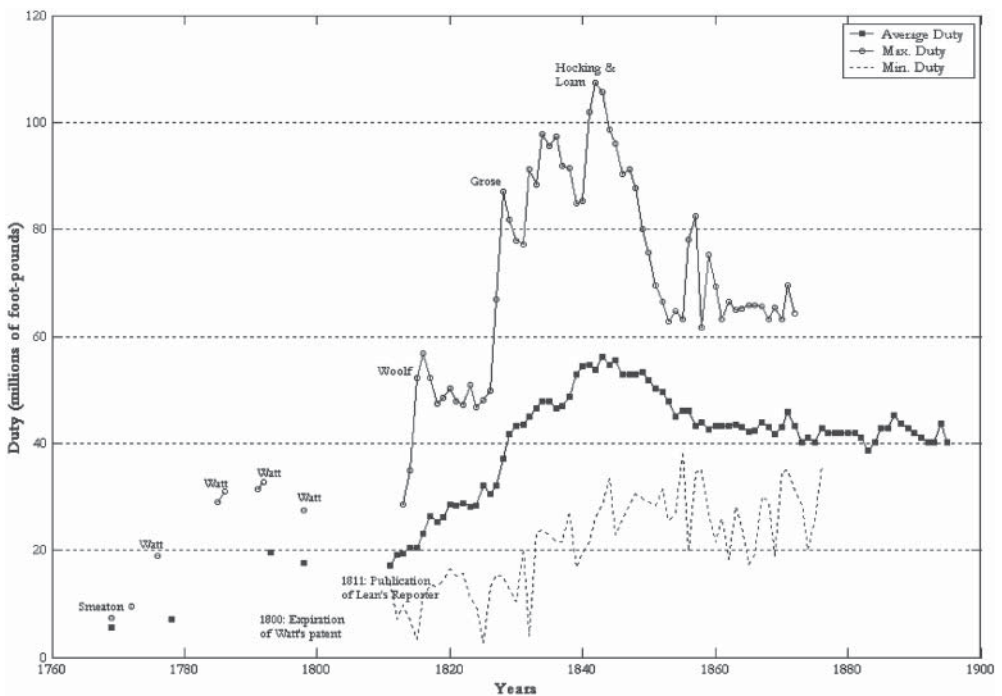


Fig. 1. Duty of Cornish Engines, 1769–1895. Sources: see text (note 17).

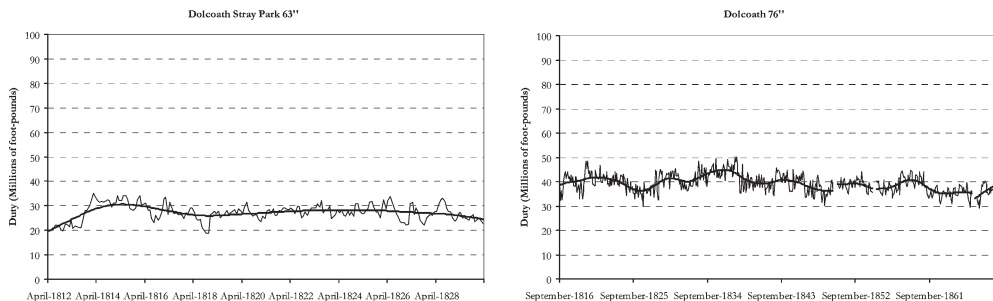


Fig. 2. Duty of Cornish engines (the emergence of the high pressure 'paradigm').
Source: *Lean's Engine Reporter*.

of three 'epochs' of rapid technical change (particularly visible in the three sharp bursts that characterize the behaviour of the series of best duty).

The first epoch of rapid technical change one can discern in Figure 1 covers approximately the period 1811–1818. This period, which also corresponds to the start of *Lean's Engine Reporter*, can be seen as one of experimentation aimed at finding the best design for implementing the use of high-pressure steam in an expansive way. Two distinctive engine designs emerged in this period, one associated with Richard Trevithick and the other one with Arthur Woolf. Trevithick adopted a single-cylinder condensing design, which later on would become the definitive layout of the 'Cornish engine'. Woolf, who had served as an apprentice under Jonathan Hornblower, preferred instead a compound double-cylinder layout. In the same period, another Cornish engineer, William Sims, also introduced a particular type of compound design comprising the addition of a small high pressure cylinder to existing low pressure engines which could then be operated using high pressure steam expansively.

Figure 2 shows the monthly duty values of two engines which are characteristic of this very early use of high pressure steam in Cornwall.¹⁹ As is apparent, the duty of Cornish engines exhibits a short term fluctuating behaviour. This was because operating conditions (amount of water to be pumped, quality of coal, etc.) were subjected to variation from one month to the other. In order to identify the 'trend behaviour' of the duty values, we have filtered the values using the so-called Hodrick–Prescott filter (see Appendix 2, for a description of this technique). The filtered values are represented by thick lines, whilst the original values incorporating short run fluctuations are represented by thin lines.

Dolcoath Stray Park 63" was one of the best low pressure engines erected in Cornwall by Boulton and Watt and it can be used as a useful yardstick to evaluate successive improvements in fuel efficiency attained by Cornish engineers in the early nineteenth century. The best duty delivered by this engine was a little above 30 million in the period 1814–1815. In November 1818, the cylinder of this engine was replaced.²⁰

Dolcoath 76" erected by Jeffery and Gribble in September 1816 was one of the first steam engines embodying what would become that typical design for Cornish engine. It was a single cylinder engine, working expansively with steam generated by Trevithick boilers. This engine was consistently able to deliver duties above 40 million, clearly outperforming the Watt low pressure engine. Hence, Figure 2 might provide an indication of the advantages of using high pressure steam as they were apparent to Cornish engineers during

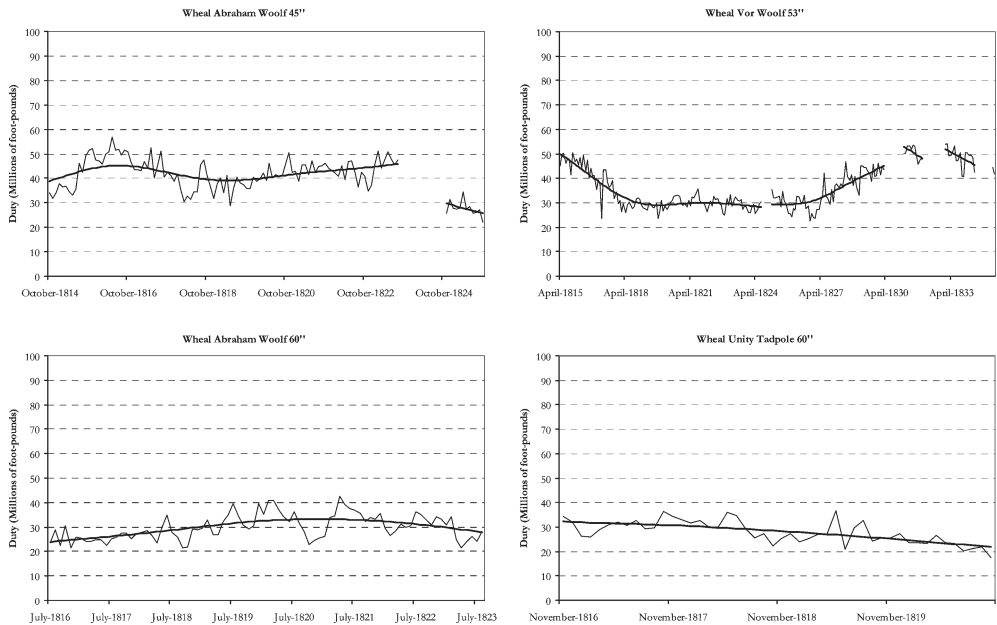


Fig. 3. Duty of Cornish engines (early compound engines designed by Arthur Woolf).
Source: *Lean's Engine Reporter*.

the 1810s. Dolcoath 76" is also of particular interest because it was reported without major interruptions for almost 50 years.

Figure 3 shows the behaviour of some of the early compound engines designed by Arthur Woolf. Wheal Abraham Woolf 45" was the first compound engine (cylinders 24" and 45") erected by Arthur Woolf in Cornwall. After its installation, the engine scored a duty above 40 million and then above 50 million. In August 1818, the cylinders of the engine were refitted.²¹ As is apparent from the figure, these repairs halted the declining trend which was setting in, making possible a new phase of duty growth. In a trial of three days performed in August 1818 to which John Farey personally attended, the engine supplied by 'the best Welsh coals' scored the unprecedented duty of 65.21 million. Farey noted that during the trial steam pressure in the boiler was 65 psi. However, such steam pressure was not deemed to be sustainable for long periods and steam pressure in normal operating conditions was usually set between 40 and 45 psi.²² The engine was re-erected at Wheal Wentworth mine in 1824.²³ After the transfer the performance deteriorated remarkably.

Wheal Vor 53" was the second compound engine (cylinders 28" and 53") erected by Woolf in Cornwall (see Figure 3). The engine scored duties above 40 million in the first two years of its life history; however, in the subsequent periods, the performance deteriorated rapidly. The engine was converted to single cylinder by Sims and Richards in March 1824 and once again the modification seems to determine a new phase of increasing duty.

Wheal Abraham 60" was the third Woolf compound engine (cylinders 33" and 60"). The engine did not deliver a particularly remarkable duty.

In 1816, with the Wheal Unity Tadpole 60" engine, Woolf attempted to improve the performance of an existing Watt engine, converting it to his compound design (cylinders

34" and 60"), by means of the addition of a small cylinder and replacing the boiler with a high-pressure one. As shown by Figure 4, the result was not particularly satisfactory in terms of duty improvement.

Figure 3 clearly shows that the performance of Woolf compound engines after a period of operation tended to deteriorate. In this respect, it is enlightening to compare the behaviour of Dolcoath 76" with that of Woolf compounds. Dolcoath 76" exhibits a rather stable performance around 40 million, Woolf compounds instead (with the partial exception of Wheal Abraham 45"), although capable of scoring duties above 40 million, do not seem capable of sustaining such performances for long periods of time. There were two main reasons for the quick deterioration of performance in Woolf compounds: i) the difficulties in keeping the two cylinders steam tight and ii) the cast iron water-tube boilers were prone to rapid obsolescence. The water used for generating steam in Cornish mines typically contained a good deal of residual minerals. Hence, incrustations developed quickly inside the boiler, in particular in the small tubes that, consequently, tended to burn out. Furthermore, the repeated heating and cooling of cast iron made the boiler susceptible of cracking. In fact, cast iron was not a suitable material for boilers where it could be subjected to unequal heating and in this period there was no way of discovering whether there were any flaws in the castings which might fatally weaken them.²⁴ For these reasons, Woolf water tube boilers after a period of use had to be operated at lower pressures than those needed for fully reaping the advantages of expansive action.²⁵

Besides introducing the compound engine and the water-tube boiler, Arthur Woolf exerted a major impact in raising the general standard of Cornish engineering workmanship. During the years spent in London, Woolf was trained as a millwright in the famous engineering works of Joseph Bramah in Pimlico.²⁶ Farey gives a detailed description of the role played by Woolf's example on Cornish engineering practices:

In the construction of these two engines [Wheal Abraham 45" and Wheal Vor 53"], Mr. Woolf introduced a perfection of execution that was quite unknown in Cornwall at that time, and which had never before extended to such large engines in any other district. Mr. Woolf, in his previous practice in London, had taken an active part in extending and applying all those improvements in means of executing steam engines with superior workmanship and durable materials, that were brought into use after Mr. Watt's retirement, at the expiration of his patent in 1800: these improvements were introduced partly by Mr. Watt's successors in the Soho manufactory, and by their early competitors, who made great exertions to excel them in style of workmanship; Mr. Woolf adopted all these improvements and added others of his own, whereby he gave to his new engines all the stability and certainty of action that could be derived from the most accurate and durable manner of putting their parts together. The improvements in execution that Mr. Woolf thus introduced into Cornwall were found so advantageous, that they have been adopted in all the engines that have since been erected in that district.²⁷

William Sims was more successful than Woolf in upgrading existing engines to high pressure steam.²⁸ In his compound design, the cylinder of the existing Watt engine acted as the low pressure cylinder. To this Sims added a small high-pressure cylinder in which a pole performed the function of the piston. (Sims had bought Trevithick's plunger-pole patent before the latter left for Peru in 1816). High-pressure steam was generated by Trevithick wrought iron boilers. Figure 4 shows the duty behaviour of some of these 'upgraded' engines.

United Mines Poldorey 63" was altered to compound in 1818, Wheal Chance Sims 45" in 1816 (later on, it was converted back to a single cylinder again). In June 1817, United

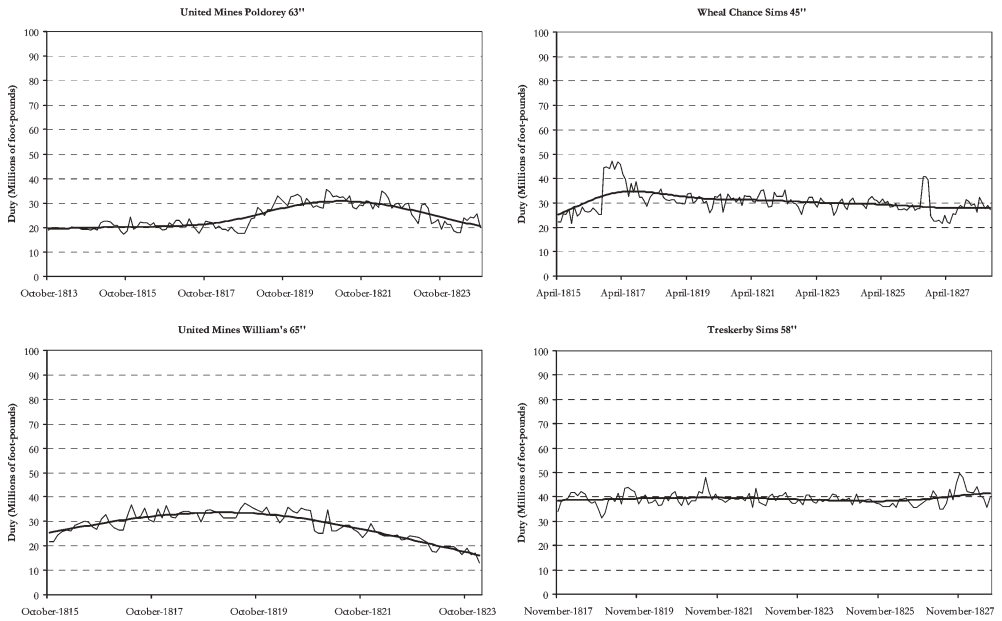


Fig. 4. Duty of Cornish engines (William Sims compound design).
Source: *Lean's Engine Reporter*.

Mines Williams 65" was converted to the plunger pole design although in May 1821 this engine was also converted back to a single cylinder. Finally, in November 1817, Sims converted the Treskerby 58" engine to his compound design. This engine was considered by William Pole as the best engine erected according to the compound design conceived by Sims. As shown by Figure 5, these modifications can be considered rather successful as they enable old Watt engines to deliver duties between 30 and 40 million. It is also interesting to note that most of these engines were converted back to single cylinder design, when, in the early 1820s, the belief grew in the Cornish engineering community that compound engines did not provide sizable advantages in terms of duty and that the experienced improvements in fuel efficiency were likely to be related much more to the use of higher steam pressure rather than to the double cylinder design.

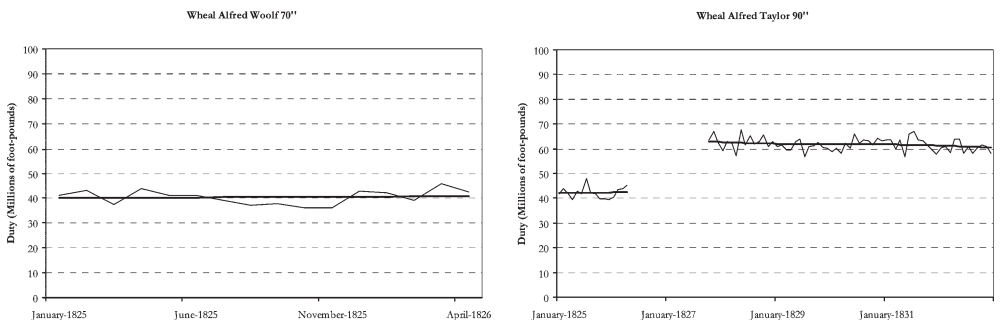


Fig. 5. Duty of Cornish engines (the test at Wheal Alfred mine). Source: *Lean's Engine Reporter*.

In his *Treatise*, Pole gave a detailed description of the introduction of William Sims' compound engines:

In 1816, when Trevithick left England for South America, Mr. William Sims, an engineer of considerable reputation in Cornwall agreed with him for the patent right of the pole for the purpose of attaching it to Boulton and Watt's, and so forming an expanding engine. This was done by allowing steam to enter first at high pressure under the pole or plunger, and partially to expand in that cylinder, by being cut off at a certain fraction of the stroke. It was then permitted to pass into the cylinder of a Boulton and Watt engine, where expansion was further extended, and afterwards the condensation took place as usual. The plunger was attached to the same beam as the piston of the great cylinder, and the engine was similar in action to those erected by Woolf. Mr. Sims and his son. . . ., being in partnership at the time, immediately altered five engines to this plan. . . ., and in all these cases Trevithick's cylindrical boilers were substituted for the original waggon-shaped ones, the steam being worked at 40 lbs per square inch above the atmosphere. The best engine of this construction was the one at Treskerby, and the application generally effected considerable improvement on the Boulton and Watt engines. The duty of the Wheal Chance engine for one month, in 1817, reached very nearly 50 million, but afterwards fell off, from the engine and boilers being allowed to get in bad order. Some of the engines were in use for many years, and were formidable rivals to Woolf's engines, but were, with them, equally put aside by the introduction of high pressure steam into the single cylinder.²⁹

A sort of ultimate test between the Trevithick single cylinder and the Woolf compound design was carried out in 1825 at Wheal Alfred mine where two new and fully comparable engines were installed by Arthur Woolf. The duty of the two engines (Wheal Alfred Woolf 70" (compound 40" and 70") and Wheal Alfred Taylor 90") is given in Figure 5. As is apparent, during the year 1825, the two engines scored a similar duty (slightly above 40 million). On the grounds of its reduced cost and 'ease' of maintenance, the single cylinder was favoured, becoming the predominant design in Cornwall.

The single cylinder design was further improved in the mid 1820s by Samuel Grose who insulated pipes, cylinders and boilers in order to avoid all possible heat losses. Figure 6 shows the duty of two engines designed by Grose and incorporating the new insulation system; the second sharp burst in the values of best duty in Figure 1 is the result of this innovation.

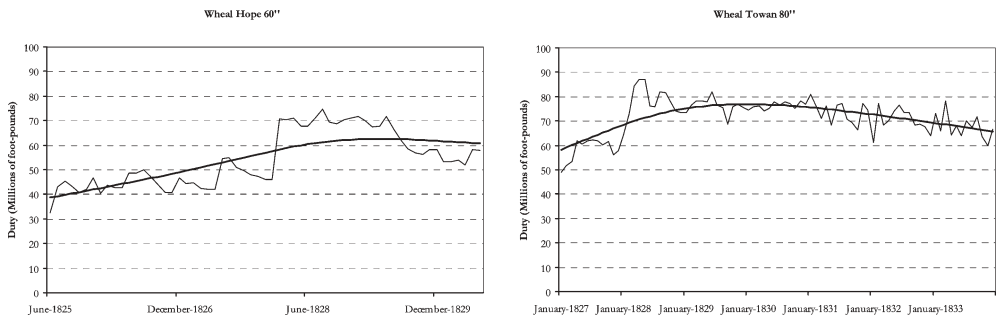


Fig. 6. Duty of Cornish engines (engines designed by Samuel Grose).
Source: *Lean's Engine Reporter*.

Wheal Hope 60" was the first engine embodying these relatively minor modifications, which nevertheless, determined a drastic improvement in the duty (above 60 million). Encouraged by the performance delivered by Wheal Hope 60", Grose adopted similar practices of heat conservation in Wheal Towan 80" engine, achieving further gains in duty (above 80 million).

In this respect, it is interesting to note the behaviour of Wheal Alfred Taylor 90" displayed in Figure 5. This engine was originally installed at the Wheal Alfred (it was the single cylinder engine used in the test between the single and compound design). In October, it was transferred at Consolidated Mines where it was renamed as 'Woolf'.

Woolf took the opportunity of the reinstallation of the engine to incorporate the insulation system of Samuel Grose.³⁰ This accounts for the sharp performance jump exhibited by the duty values after the reinstallation. This example also well illustrates the role played by *Lean's Engine Reporter* in permitting the prompt identification of the most fruitful pathways of technical advance. This example also shows that, at least to some extent, a number of innovations could be 'retrofitted' into existing engines. Thus, maintenance operations or the transfer of a steam engine from one mine to another were occurrences that the engineers could exploit for 'upgrading' existing machines.

Grose's practices were quickly and widely adopted. Additionally, from the early 1830s, Cornish engineers also increased the ratio of expansion further. This led to an additional 'spurt' in duty growth, so that, in this phase, it was not uncommon for engines newly erected to score duties above 80 million. Figure 7 reports the duty of two engines of this phase. Fowey Consols Austen 80" erected by William West in a trial in 1835 reached the record duty of 125 million.³¹ Wheal Vor Borlase 80", another engine designed by Thomas Richards, can also be considered as an engine typical of this period.³²

In the late 1830s James Sims the son of William Sims attempted to revive the compound principle, putting the small high-pressure cylinders above the low pressure one (in the Woolf design, the two cylinders were put side by side).

The Carn Brea 90" (cylinders 50" and 90") displayed in Figure 8 was the most successful engine of Sims' compound design. In this phase, the main competitors of James Sims were Hocking and Loam (the successors of Woolf in the mines managed by John Taylor). Figure 8 gives also the duty values of United Mines Taylor 85" the most successful engine designed by Hocking and Loam and the only one to score duties above 100 million in *Lean's Engine Reporter*. By the early 1840s, the Cornish engine had probably reached its practical

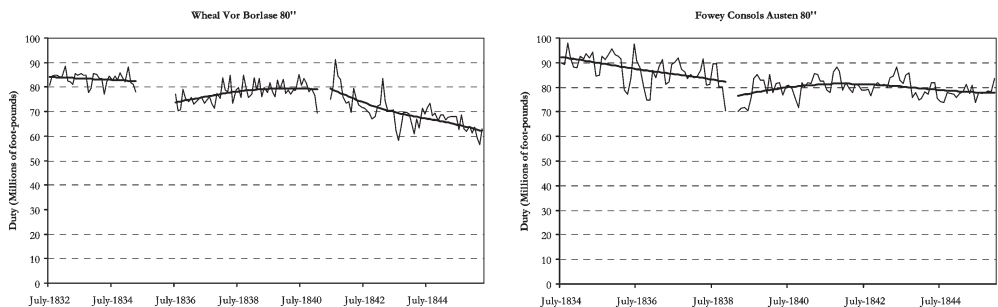


Fig. 7. Duty of Cornish engines (the 1830s). Source: *Lean's Engine Reporter*.

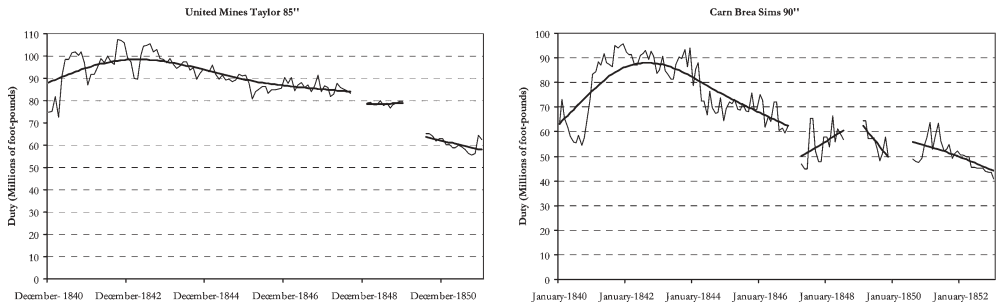


Fig. 8. Duty of Cornish engines (the maturity phase). Source: *Lean's Engine Reporter*.

limits, so one can consider this period as the maturity phase of the technological trajectory of the Cornish engine design. Carried to the extreme, the principle of expansion produced an extremely powerful shock to the piston and to pitwork at each opening of the steam valve. Such an operating cycle was likely to increase the probability of breakages in the pumps and their supports and to accelerate the wear and tear of the engine.³³ In fact, the main motivation behind James Sims' elaboration of a new compound design was not the search for further fuel economies, but the need to find a remedy for the strain that large engines were putting on the pitwork. Both Sims' design and the competing solution proposed by Hocking & Loam (a circular protuberance in the piston with a corresponding cavity in the cylinder top) did not encounter much success.³⁴ The values reported in Figure 8 seem indeed to suggest the occurrence of a number of breakdowns both for the Carn Brea and for the United Mines Taylor engine.

Figures 2–8 allow us to shed some light on some features on the process of 'learning by using' arising from the actual operation of each engine. According to John Farey, the typical life cycle of the duty of a Cornish engine in general could be seen as characterized by an inverted U shape pattern.³⁵ In the first period of operation the duty of the engine tended to rise steadily. This was because this period was a phase of particularly intensive learning by using. A good deal of this accumulated experience was idiosyncratic (i.e., engine-specific), essentially amounting to find the optimal way of dealing with the specific 'quirks' of each engine. In particular, Farey individuated two factors accounting for initial duty rise:

- 1) some time of actual operation was necessary in order to identify and remedy leaks in the engine and in the boilers and/or to correct other stemming deficiencies from the construction and erection of the engine.³⁶
- 2) improved operation of the engine stemming from learning by using process: in particular, it was necessary to accumulate experience concerning:
 - i) the managing of the fires and dampers;
 - ii) the size of the fire grates and the number of boilers to be worked at once;
 - iii) the regulation of the feeding of the boilers;
 - iv) the best management of the cleaning of the boilers;
 - v) the best level of steam pressure in the boiler;
 - vi) the best ratio of expansion (determined by the cut-off point) at which the engine (given a particular load in the pumps) was to be operated.³⁷

The increase of duty by means of this process of learning by using at the engine level progressively ran into diminishing returns and it was finally offset by physical wear and

tear, producing an inverted U shape pattern of duty evolution. The main sources of physical deterioration identified by Farey were:

- 1) the wearing out of pumps, engine and pitwork causing 'derangements' which negatively affected the performance delivered by the engine.³⁸
- 2) leaks in boilers.
- 3) wearing out of boilers plates which meant that steam pressure had to be reduced for safe operation.³⁹

Additionally, as the mine deepened, an increasing load was charged on the engine and this was likely to force the engine to operate at a sub-optimal rate of expansion.

In general terms, inspecting Figures 2–8, one does not find generally a clear corroboration for the inverted U shape pattern hypothesized by Farey (although some of the engines may be said to fit that pattern). In our interpretation, the inverted U shape pattern is to be understood as a 'notional' pattern of duty evolution. In particular, one has to take into account that during its lifetime an engine was subjected to a series of repairs and others modifications, which could affect its performance. Hence, most engines exhibit a wave-like behaviour. Repairs and modifications determined alternating phases of duty increases and declines.

Figure 9 provides a unified view of innovation in Cornish engines by showing the duty behaviour of some of the engines mentioned above. The picture again suggests that the technological history of the Cornish engine can be usefully considered as divided in three major phase: i) an early phase of exploration of the merits of high pressure steam; ii) a phase of consolidation with a number of innovations focused on reducing the dispersion of heat

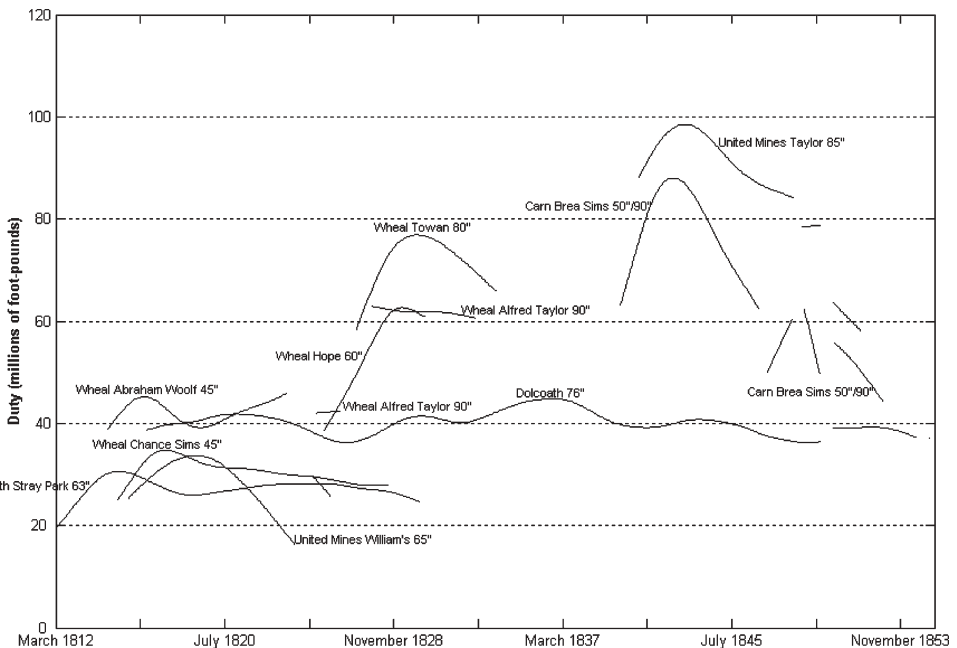


Fig. 9. Duty of some famous Cornish engines. Source: *Lean's Engine Reporter*.

(Grose); and iii) a maturity phase in which the principle of expansion is probably stretched to its very limits.

LEAN'S ENGINE REPORTER: ISSUES OF INTERPRETATION

Traditionally, historians of technology have regarded the reporter as a vehicle for the effective sharing of technical information. As Cardwell noticed:

The publication of the monthly *Engine Reporter* seems to have been quite unprecedented and in striking contrast to the furtive secrecy that had surrounded so many of the notable improvements to the steam engine. It was a cooperative endeavor to raise the standards of all engines everywhere by publishing the details of the performance of each one, so that everybody could see which models were performing best and by how much.⁴⁰

Bridget Howard has recently suggested a different interpretation of the foundation of *Lean's Engine Reporter*.⁴¹ In her view, the idea of setting up the engine reporter was actually due to Arthur Woolf and the real aim was to promote the Woolf compound engine among Cornish adventurers and managers. In support of her argument, she notices that in the 1810s, *Philosophical Magazine* (a London-based journal, whose editor at the time was Alexander Tilloch, one of the 'patrons' of Woolf during his sojourn in London, who had paid the expenses for his experiments and his patents) published extracts of the *Lean's Reporter* with the not-so-veiled purpose of advertising the Woolf engine.⁴² Furthermore, Howard observes that, from September 1827, Thomas and John Lean published two separate editions of the engine reporter (each of them reporting engines of different mines). In the second issue of 'his own' engine reporter (October 1827), John Lean published the following statement (his italics):

As few, probably, even of those into whose hands the engine reports have regularly fallen, have adequate conceptions of the striking improvements which have been made in steam engines within the last sixteen or seventeen years, it may not be unadvisable to state that my father began to make his observations in the year 1811. Among the first of the engines which fell under his inspection were those of Dolcoath mine. One of these accomplished in the first month 13 millions, and the other two, 8 millions each — (I am now speaking of the engines used in drawing water from the mine) — The last of these three has since risen to 30 nearly, the other to 35 and the third to 45! In the year 1811 the amount of bills for coal consumed in that mine was £11179 15s. 10d. — in the year 1823 it was only £4592 10s. 11d.; difference £6587 4s. 11d.! The price of coal in 1811 was rather greater than that of 1823; but to overbalance this very considerably, I have to mention that in the year 1811, the adventurers had only six steam-whims at work, whereas in 1823 they had eight, besides a steam stamping mill, which of itself consumed from five to six hundred or, perhaps, I may even say seven hundred bushels of coal monthly. But the loss which was sustained, independently of this, was incalculable; for such a wretched state were things reduced to by the *inattention* and *carelessness* of engineers, and engine-men, that not a winter passed by without leaving a very considerable portion of the mine deluged. Now these are a few of the many happy facts which might be clearly demonstrated to have resulted from the *publicity* which has been given to the duty of steam engines. Numerous others might be stated, if there yet remained an individual so prejudiced as to question the utility of such monthly exposures. Engine-reports have been rendered a blessing to the community. They have excited a spirit of inquiry among all those concerned in mining speculations; and among engineers and engine men, *especially*, they have been the means of raising and maintaining a commendable emulation; and of

stimulating to increased exertions, diligence and attention. Nor they will cease to be of vital importance as long as they continue to be made with *scrupulous regard to truth and equity* — as long as he to whom the office of engine-reporter has been intrusted, is not to be intimidated by the menaces of self-interested men, or shaken from that inflexible integrity which he should steadfastly hold as the *dearest*, the *brightest* gem of his life!

It is worth remarking that the entire tone of the statement is very much in line with traditional accounts which consider the origins of the practice of engine reporting as a rather successful way of raising the general level of engineering standards in Cornwall, by — using John Lean's words — exciting a 'spirit of inquiry' and by 'maintaining a commendable emulation'. In fact, Howard pinpoints the last part of the statement linking it with Thomas and John Lean's decision of issuing two separate reporters. In her view, it can be argued that the statement and the separation of the reporters reveal a profound disagreement between the two brothers concerning the practices of reporting. In particular, she suggests that the conflict was related to the standard of correctness adopted in reporting the duty of the various engines. Thomas Lean (I), who emerges as rather a deceitful figure in her historical reconstruction, was liable to be heavily conditioned by Arthur Woolf.

As we have seen, in 1827 Samuel Grose successfully developed a system of thermal lagging of the engine which determined a quantum jump in engine performance (first above 60 million and then above 80 million, see again Figure 6). At the time, Woolf was the main competitor of Grose in the race for the highest duty. In October 1827, Woolf installed a new engine at Consolidated Mines adopting Grose's system of thermal lagging⁴³ which also scored duties above 60 million. Howard suggests that John Lean's decision to publish a separate report was precisely motivated by the undue favours that his brother Thomas was inclined to concede to Woolf when reporting the performance of his engines in the 'duty race' against Grose. This would explain the last part of the statement published by John Lean in October 1827. However, John Lean's decision to 'divorce' may not be just a consequence of the supposed irregular duties reported during the fierce competition between Grose and Woolf in the period 1826–1828, but 'may well have been the culmination of a long period of unhappiness'.⁴⁴ After the separation, Grose's best engine was reported in the John Lean's reporter whereas Arthur Woolf's best engine continued to be reported in the one issued by Thomas. The compilation of two separate reporters by Thomas and John Lean did not result in a 'perfect' segregation of engineers among the two reporters (the decision whether to have an engine reported or not was a prerogative of the mine captains). After the 'divorce', most engineers continued to have engines (at different mines) reported with *both* Thomas and John. Grose, Sims, and Jeffree had engines in both reporters. In particular, William and James Sims, one of the main competitors of Arthur Woolf, continued to have a considerable number of their engines reported in Thomas' reports. As will see, in the period 1847–1858, William West would instead submit all his engines to the newly created Browne's Engine Reporter.

Be this as it may, another episode seems to indicate that Woolf's influence in 'fixing' the duties reported — if it was ever exerted — was probably much more limited than what is supposed in Howard's account. As we have seen, in 1825 two engines — one on Woolf compound design and the other on the more popular single cylinder design — were ordered by John Taylor for the Wheal Alfred mine. The explicit aim of the order was to solve the 'controversy' concerning the fuel efficiency of the single cylinder versus the compound design developed by Woolf. If Woolf could exert some effective influence in the registration of the duties reported, the trial would have probably been the most convenient opportunity

for him to strengthen his position on the Cornish market. The two engines engaged in the trial, according to the duties registered by the Leans, delivered the same performance, so that the lower costs of erection of the single cylinder design caused it to be generally adopted. This, in practice, amounted to a definitive defeat for Woolf's compound design. It is also worth noting that John Taylor,⁴⁵ one of the most important mining entrepreneurs, adopted the system of also reporting the duties of the engines in other mining ventures in which he was involved outside Cornwall, in particular in Wales and Mexico.⁴⁶ In our interpretation, this provides some support for the argument that he was *genuinely* convinced of the usefulness of this undertaking.

In our judgment, other shreds of available evidence indicate that engine performances were, by and large, considered as reported with a sufficient degree of accuracy by informed contemporaries not directly connected with Woolf and his supporters. Davies Gilbert (an intimate friend of Richard Trevithick, one of Woolf's main rivals in the early 1810s) in a paper published in *Philosophical Transactions of the Royal Society*⁴⁷ had no particular reservations in using the duty figures reported in the issue of July 1826 of *Lean's Reporter* to illustrate improvements attained in steam technology due to the adoption of the expansive principle. W. J. Henwood, a contemporary observer who in the late 1820s and early 1830s performed a number of tests on the performance of Cornish steam engines without seeming to be connected with any particular Cornish engineer, in his *Presidential Address to the Royal Institution of Cornwall* made extensive use of the duty figures published in *Lean's Engine Reporter* to document the historical evolution of the performance of the engines at work in Cornish mines in the period 1811–1870.⁴⁸ Finally, James Sims, an engineer, who in partnership with his father William was one of most prominent rivals of Arthur Woolf, in a short essay published in 1849 in *Mining Almanack*⁴⁹ discussed the performances of various Cornish engines employing the duty figures contained in *Lean's Reporter*.

The upshot of these considerations, in our view, is that the traditional account of the foundation of the *Lean's Reporter*, such as the one given by Pole⁵⁰ and which is repeated in most of the contemporary engineering literature (i.e., the reporter was set up in order to improve engineering standards and ensuring the rapid diffusion of best-practice techniques), ought still to be considered as broadly accurate. All this, of course, leaves unexplained what determined the decision of Thomas and John Lean to issue separate reports. Concerning the issue of the accuracy of the duty figures reported, Figure 10 shows the average duty of the engines reported by John Lean in the four months before and after the separation occurred in September 1827. As it is possible to see, there are no major changes in the duties reported. If the division between Thomas and John was actually motivated by disagreements concerning the 'fairness' in the procedures adopted for calculating the duties, one could have expected that, after the separation of the two reports, the duty of at least some of the engines now reported by John would have undergone some major change.

This is not to say that the duty figures reported in *Lean's Engine Reporter* were always peacefully accepted. Howard is undoubtedly correct in pointing out that the fierce competition among engineers time and again generated heated debates on the relative performances of various engines and on the accuracy of the duty reported. In fact, the duty of particular engines was frequently checked in public trials undertaken by purposely created commissions of independent experts.⁵¹ In our view, the separation between Thomas and his brother John and the ensuing compilation of two separate reporters in the period 1827–1831 cannot be with certainty linked to a conflict concerning the accuracy of the duties reported; it should be also noted that the statement published by John Lean suggests that if there were

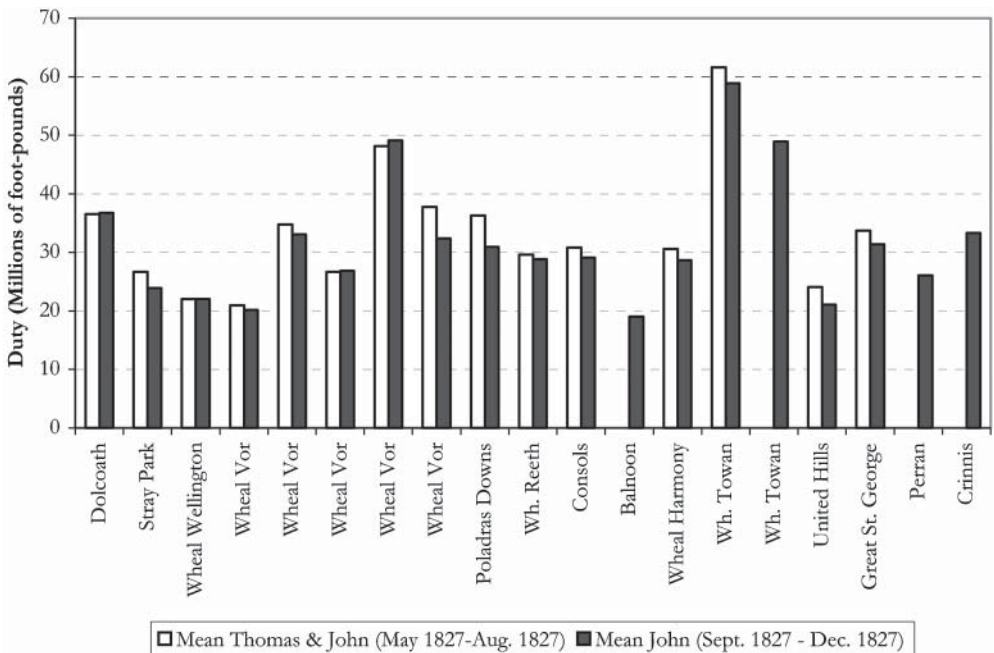


Fig. 10. Duty for the engines in John Lean's Engine reporter (May 1827–December 1827.

Source: *Lean's Engine Reporter*.

ever a conflict concerning the performances reported, this probably arose in the period immediately preceding the separation. In fact, the statement acknowledges the beneficial role that the reports had in the general growth of the duty of the engines employed in the Cornish mines. The tone of the statement seems also to suggest that, at least for an (unspecified) period following the creation of the reports, John Lean considered the duties of the engines as faithfully registered. However, the existing evidence does suggest that the (not very successful) attempt of setting up a new reporter by William Browne in the period 1847–1858 was clearly the outcome of the dissatisfaction of William West, one of the most active Cornish engineers of the period, towards the duty figures reported by Thomas Lean II.⁵² West ceased to have all his engines reported in *Lean's Engine Reporter*, submitting them to the new reporter. Finally, it must be recalled that there was another, still rather obscure, attempt to set up a new independent reporter, covering the period 1834–1841, by William Tonkin.⁵³

CONCLUSION

Vincenti suggests that engineers tend to make use of systematic data collection to *bypass* the absence of an adequate theoretical understanding of the operative principles of a technology.⁵⁴ This was exactly the situation in early nineteenth century steam power technology, when no fully fledged understanding of the working of the steam engine was available. In this broader perspective, *Lean's Engine Reporter* seems to be another of these attempts

at systematic collection of performance data. Overall, the undertaking seems to have been rather successful, leading to a remarkable acceleration of innovation in Cornish steam engineering and to the precocious adoption of high-pressure steam.

APPENDIX 1: THE PERFORMANCE OF CORNISH STEAM ENGINES AS MEASURED IN *LEAN'S ENGINE REPORTER*

The main aim of the reporters was to ascertain the monthly duty performed by each engine. The duty was computed using the following formula:

$$D = \frac{L \times l \times s}{C} \quad (\text{A1.1})$$

where D indicates the duty performed by the engine (expressed in millions of lb lifted one foot high by consuming a bushel of coal), L the load of the water contained in the pumps (expressed in lb), l the length of the stroke in the pump (expressed in feet), s the number of strokes performed by the engine during the month, C the monthly consumption of coal (in bushels). Clearly, the reliability of the duty estimated depended on the reliability of the four observations used in the computation. Let us consider each of them separately:

- 1) L (the weight of water in the pumps): this was not measured *directly* but estimated on the basis of the volume of the pumps. Thus, when the pumps were not completely filled with water, (the Cornish term for such a behaviour was 'working in fork', this could happen when the mine was well drained or in periods of low rainfall), duty tended to be overestimated. Additionally, one has to notice that leakages in the pumps led also to an overestimate of the weight of water actually lifted and, as a consequence, the duty performed. On the other hand, the weight of water lifted was computed by multiplying the volume of pumps for a constant that represented the weight of a unit volume of spring water. Of course, the water pumped from Cornish mines, containing a non-negligible amount of minerals in suspension, was in general heavier than pure spring water. This introduced an upward bias (going in the opposite directions of the foregoing downward biases) in the overall estimation of L . During the 1830s, various experiments were carried out in order to measure *directly* the weight of water lifted. William Henwood and John Rennie measured the actual weight of the water pumped by the Wheal Towan engine and found that it was about 7.6 per cent lower than the one calculated using the volume of the pumps.⁵⁵ Thomas Wicksteed, during his experiment on the Holmbush engine, instead found a gap of about 13.5 per cent; finally, other experiments on the Eldon's engine at United Mines found a gap of about 4 per cent.⁵⁶ The conclusion that contemporaries such as William Pole and Thomas Wicksteed drawn from the results of these experiments was that the *Reporter* contained an inner tendency to *slightly* overestimate the water actually pumped by the engine. Overestimation could safely be considered to be between 4 and 10 per cent. Furthermore, no allowance was made for friction. The amount of friction to be overtaken depended on the specific circumstances of operation of each single engine (length of the pumps, their state, their inclination, etc.). This was an important factor to be taken into account when the performance of two engines was compared.⁵⁷

- 2) l (the length of the stroke in the pumps): the length was calculated on the basis of the length of the piston stroke (multiplied by the proportion of the beam comprised between the pivot point and the attachment to the pump stroke).⁵⁸ Accordingly, when the engine performed a shorter stroke, this method led to an overestimation of duty. The length of the stroke performed by the engine could be regulated quite easily by the engineer by properly adjusting the tappets which controlled that descent of the piston. In fact, making the engine perform a shorter stroke was considered as the easiest possible way of 'cheating' (in the sense of having an engine credited for a higher duty than the one actually performed). According to Farey, the length of the stroke used in the reporter was the *full* length of the stroke in the cylinder.⁵⁹ The actual stroke performed was about three of four inches shorter and this produced a difference between reported and actual length of about 1/25, as resulted from an experiment carried out in 1816. However, according to Pole (1844), the length of the stroke used in the reports was the *mean* length. This contrasting evidence probably indicates that some change occurred between 1816 and 1844 in the measurement of the stroke length. Pole also mentioned an experiment conducted on an engine at Consolidated Mines which showed that the difference between actual and reported stroke length did not exceed 1 per cent).⁶⁰
- 3) s (the number of strokes performed): the number of strokes was registered by a special counter that was installed by the 'reporter'. The counter was protected by a Bramah's lock and the key was entrusted exclusively to the engine reporter. An experiment of four months conducted in 1839 showed that the counter overestimated the number of strokes performed by about 2.5 per cent.⁶¹
- 4) C (the bushels of coal consumed): this was measured on the basis of the coal purchased as resulting from the mining accounts. It is worth noting that bushel was a measure of volume, corresponding to a cylindrical vessel of 18.8 inches of diameter and 8 inches deep. This vessel was to be heaped up above the border to form a cone with the same base of the cylinder and at least 6 inches high.⁶² Typically the weight of the coal bushel was reckoned to be 84 lb. This was a fairly good estimate for Newcastle coal.⁶³ But in Cornwall where Welsh coal was used the weight of the bushel was normally higher. Rather surprisingly, early commentators of the Cornish engine reports such as Gilbert, Henwood and Taylor did not take into account the greater weight of the Welsh coal compared with the Newcastle one and considered the bushel equal to 84 lb, underestimating its actual weight.⁶⁴ In 1831, Thomas Lean measured the weight of a bushel in 31 Cornish mines and found out that the average weight was equal to 92.43 lb (the maximum observation being 98 lb and the minimum 88 lb).⁶⁵ From 1835 in the engine reports, the bushel was formally reckoned to be 94 lb. Various criticisms were voiced against the use of a unit of volume rather than weight as a measure of the coal input. According to William Pole, these criticisms were wide of the mark. He noted that 1 bushel = 94 lb could be used rather safely as a general conversion figure, discrepancies from that value were likely to have only minor effects on the estimated duty.⁶⁶ Additionally, one has to note that in Cornwall, until the end of 1836, coal was sold by the bushel (more precisely by the wey, corresponding to 64 bushels). Hence, the duty calculated in terms of bushels provided a measure of engine efficiency, endowed with a direct *economic* significance.⁶⁷

The upshot of all this is that the duty figures reported are to be considered as an *approximate* estimation of the fuel efficiency of the engines reported. However, since most

of the engines were reported for a number of consecutive months, it is likely that the possible influence of special circumstances on the estimated duty could have been easily individuated. In fact, it was common practice to perform special trials lasting one or two days on the best-duty engines or on dubious cases. In these trials, a number of independent observers took care to ascertain properly the four observations necessary for calculating the duty of the engine in question.⁶⁸ Furthermore, in some of the largest mining ventures, such as Consolidated Mines, the duty of the engines was calculated *daily* using another strokes counter under the control of the mine captains. The average daily duty was compared with the one published in the monthly reporter when this was issued. The two measures were in most cases found to correspond very closely.⁶⁹

John Taylor, one of the leading mining entrepreneurs in the Cornish district, published several papers with the aim of dispelling the scepticism with which the duty figures published in *Lean's Engine Reporter* had been received outside Cornwall. In one of these papers published in *Quarterly Mining Review*, Taylor provided a detailed account of the reporting procedures noticing that there was very little room for fraud by the engineers and the workers entrusted with the engines. Furthermore, his position of mine entrepreneur gave him also the possibility of crosschecking the validity of the duty figures with the reduction of coal expenditure. He observed:

The evidence of progressive improvement. . . . which the periodical reports of duty have gone on to exhibit, is corroborated by the unerring testimony of the account books of mines; and those savings which in the one [the monthly duty papers] appear in somewhat theoretic form are in the other apparent in the solid condition of money saved, and so in fact gained.⁷⁰

The overall conclusion of Taylor's paper was that 'the application of steam has been improved so as to economize fuel in Cornwall, and that the rate of improvement has been fairly expressed by the printed reports'. Taylor was without doubt one of the most convinced advocates of the accuracy of *Lean's Reporter*. Other competent contemporary observers, such as Davies Gilbert, Thomas Wicksteed, John Farey, William Pole and William Henwood, who had first hand experience with the methods used to report the duty of the engines, generally regarded the publication as providing reliable estimates.

APPENDIX 2: THE HODRICK–PRESCOTT FILTER

The Hodrick–Prescott (or Whittaker) filter is a smoothing method which provides an estimation of the long term component of a series. Assume that x_t (with $t=1,2,\dots,T$) is the original time series. The estimation of the long-term trend (\bar{x}_t) is obtained by minimizing the following function

$$\sum_{t=1}^T (x_t - \bar{x}_t)^2 + \lambda \sum_{t=2}^T [(\bar{x}_{t+1} - \bar{x}_t) - (\bar{x}_t - \bar{x}_{t-1})]^2 \quad (\text{A2.1})$$

The function minimizes the variance of x_t around \bar{x}_t (first term) subjected to the constraint that the estimated value should not be too 'distant' from the rest of the trend (second term). The parameter λ controls the 'curvature' of the trend (as $\lambda \rightarrow \infty$, \bar{x}_t approaches a linear trend). In our estimation we have used $\lambda = 14400$ as is conventional for monthly economic series. The estimates shown in Figures 2–9 were robust to variations of the parameter over the range 14000–16000.

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22. Ibid. p. 123.
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25. Harris op. cit. pp. 59–60.
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55. Henwood, W. J. 'On the Expansive Action of Steam in Some of the Pumping Engines on the Cornish Mines', *Transactions of the Institution of Civil Engineers* 2 1838 p. 58.
56. Pole op. cit. p. 154.
57. Wicksteed, T. 'On the Effective Power of the High-Pressure Expansive Condensing Engines in Use at Some of the Cornish Mines', *Transactions of the Institution of Civil Engineers* 2, 1838 p. 121.
58. Von Tunzelmann op. cit. p. 81.
59. Farey op. cit. vol II.
60. Pole op. cit. p. 153.
61. Von Tunzelmann op. cit. p. 81.
62. Farey op. cit. p.181.
63. Ibid. p. 337.
64. Howard, B. 'Was the Bushel 84 lbs. or 94 lbs.?' *Journal of the Trevithick Society* 29 2002 pp.123–128.
65. Farey op. cit. p.232. In the same year William Henwood measured the weight of bushel at three mines and found an average of 93.6 lbs. The degree of wetness of the coal also influenced the weight of the bushel. When coals were dried the average weight of the bushel in the three mines was 87.1 lbs.
66. Pole op. cit. p. 155.
67. von Tunzelmann op. cit. p. 82.
68. See, for example, Lean op. cit. (10), pp. 57–62.
69. Taylor, J. 'On the Duty of Steam Engines', *Quarterly Mining Review* 5 1831 pp. 54–55. Charles Babbage also mentioned the system of daily assessment of the duty in his *On the Economy of Machinery and Manufacturing* (Kelley New York 1971 reprint of 1835 original pp. 284–285): 'The advantage arising from registering the duty done by steam-engines in Cornwall has been so great that the proprietors of one of the largest mines, on which there are several engines, find it good economy to employ a man to measure the duty they perform every day. This daily report is fixed up at a particular hour, and the engine-men are always in waiting, anxious to know the state of their engines. As the general reports are made monthly, if accident should cause a partial stoppage in the flue of any of the boilers, it might without this daily check continue two or three weeks before it could be discovered by a falling off of the duty of the engine. In several of the mines a certain amount of duty is assigned to each engine; and if it does more, the proprietors give a premium to the engineers according to its amount. This is called million-money and is a great stimulus to the economy in working of the engine.'
70. Taylor, J. op. cit., pp. 51–52.