Chapter 5: The Emergence of High-pressure Cornish engines: The Role of the Patent System and the Theory of Collective Invention

The 18th century was a period marked by the birth of the steam era and ingenious design modifications, particularly by Watt, including the invention of rotary motion which spread the engine's field of applications to industry. But it was during the 19th century that steam power exercised a revolutionary effect on the economy by approaching the maximum of its productive efficiency and accelerating multifold its diffusion process. The epicenter of this transformative process was the metal mines of Cornwall which attracted a number of talented engineers.

This chapter will explore two major themes. First, it will trace the period of experimentation which was particularly intense during the first quarter of the century when engineers explored different design trajectories before preferences settled by favoring the single-cylinder high-pressure engine. The application of high-pressure steam induced, in turn, a number of secondary inventions which complemented a number of improvements which appeared independently. The second part of the chapter will discuss the source(s) of this inventive activity which will be evaluated by discussing the role of the patent system contrasted to elements emphasized by the theory of collective invention.

Technological innovations in the Cornish mining industry

The dawn of the 19th century ushered an era of intense technological innovation centered in the mining district of Cornwall, beginning with the distinct designs of two engineers, Trevithick and Woolf. Trevithick's background played a critical role in shaping his pioneering contributions. His father, an engineer in charge of pumping engines in Cornish tin mines, had him educated at the village school but by the age of 20 Trevithick acquired sufficient expertise to be placed in charge of the engines in a local mine. It is likely that his drive to work on high-pressure steam drew a fair amount of inspiration while he lived in Redruth in 1797-8 next to William Murdoch, Watt's close associate, who built a model steam carriage with high-pressure steam. But the initial stimulus which prompted interest on the subject must have been the low profitability of many Cornish mines, the need to have access to an adequate quantity of water, and the fairly high prices of B&W engines which drew the ire of Cornish adventurers, especially in conjunction with the high premiums prior to the patent's expiration.[1] These factors led him, and some other engineers, to focus their efforts towards technological alternatives. As mines became deeper and the weight of the associated machinery increased, it became imperative to augment pressures in order to avoid lessening the power of engines due to the application of the expansion principle.[2]

Richard Trevithick was the first one to use high-pressure steam in 1802 when he got a patent, along with Vivian, and started installing his first engines the following year. Its main working principle was using steam to press against the atmosphere the same way a Watt engine would use the atmosphere to push against a vacuum. The piston was resisted by the force of the atmosphere and hence the useful part of the steam's force was the one which exceeded atmospheric pressure. His engine used pressures 10 times

[1] In the B&W vs Bull case which was lost for the defendant, Trevithick testified as an expert witness of behalf of Bull. See Robinson, "James Watt," p. 127.

[2] Jewkes, et. al., *The sources of invention*, p. 39; Hodge, *The steam engine*, p. 73; Pole, *A treatise*, p. 69.

as high as that of the atmosphere (above 100 lbs per square inch). No condensation was necessary and hence the cumbersome apparatus to produce a vacuum became redundant since steam was exhausted into the atmosphere at the end of the stroke. The elimination of the cold-water cistern and pump, condenser, air-pump, the beam, the supporting rods and framework added to the economy of parts. The engine was composed of just a boiler, cylinder, piston, and valves. Its main advantage was its simplicity and the ability of its smaller piston to deliver a greater amount of work, hence its first advantage over low-pressure engines was that it was cheaper to make.[3] However, such engines did not manage to be very successful because they were considered to be dangerous and inferior to B & W engines; "they were found decidedly inferior to Mr. Watt's engines, for draining water from deep mines; and no other than Mr. Watt's engines were used for that purpose in Cornwall, for some years after Messrs. Trevithick and Vivian obtained their patent."[4] Vivian's commitment to the engine faded and it fell upon Trevithick to pursue its marketing.

However, Trevithick did not put all of his eggs in a single basket. A major event in the history of high-pressure steam took place in the summer of 1812 when he erected an engine at Wheal Prosper mine. This was a single acting Watt engine on the inverted plan using condensation but working at a boiler pressure of 40 p.s.i., a figure which required strengthening the steam case and boilers as well as modifying the valves.[5] It was the first true Cornish engine. An important feature of it was utilizing the expansion principle which was used by Watt as early as 1785 but since the pressure was a little above the one of the atmosphere, expansion could not produce impressive results.[6] Trevithick's use of expansion meant that it drew power from the boiler for c. 1/10-1/5 of the stroke and ended up the latter at the same pressure as the one a Watt engine began with. *Ceteris paribus*, the duty of the engine could increase by two- to three-

[3] On Trevithick's initial efforts using high-pressure, see Pole, *A treatise*, pp. 49-52. A description with the main working mechanism of Trevithick's engine can be found in Stuart, *Historical and descriptive anecdotes*, pp. 455-8. See also Landes, *The unbound Prometheus*, p. 102; Mokyr, *Twenty five centuries of technological change*, p. 88; Temin, "Steam and waterpower," p. 188; Von Tunzelmann, *Steam power*, p. 22; Lardner, *Popular lectures*, pp. 144-5.

[4] Farey, *A treatise on the steam engine*, vol. 2, p. 39. In 1804 one of Trevithick's engines working in Wales with a 65 p.s.i on the piston did a duty of 17.5mil, a figure which was inferior to the standards of B&W engines. See Hills, *Power from steam*, p. 103.

[5] Such pressure was applied to a whim engine at Dolcoath in 1806 but never to one in pumping. Barton, *The Cornish beam engine*, p. 33. For a description of how a single-cylinder high-pressure engine worked and its similarities with the Watt model, see Ewing, *The steam engine*, p. 25.

[6] The principle of expansion was particularly important in regions with high coal prices in light of the potential it offered for fuel economy. An ordinary non-condensing engine receives the steam into the cylinder at a pressure which is below the one in the boiler, carries this pressure throughout the stroke and exhausts the steam into the atmosphere. This is wasteful since steam still has the potential of producing much work. The expansion principle involves the use of a small amount of steam from the boiler which is regulated by the cut-off valve. The steam continues to expand at a diminishing, but still considerable, rate to the end of the stroke. Maximum economic expansion is obtained when the steam pressure falls below the one required to overcome frictional resistances. Fell argued in favor of the expansion principle by publishing the following table on the fuel rates of engines working with and without expansion.

Steam pressure above atmosphere	10	20	30	40	50	60	70	80	90	100	110	120
Fuel rate without expansion	11.9	8.1	6.8	6.1	5.7	5.1	5.2	5	4.8	4.75	4.7	4.63
Fuel rate with expansion	10.3	6	4.5	3.8	3.4	3.1	2.8	2.7	2.5	2.4	2.3	2.2

Source: Fell, *Some notes on the advantages of using steam expansively*, pp. 5-12.

fold while maintaining the same consumption of fuel as a Watt engine. However, in practice, neither its performance was impressive nor its life was long.[7]

The use of expansion could save on fuel but produced irregular movement. Trevithick attempted to address this problem by the plunger pump or pole engine, a new design for which he got a patent in 1815 with the first installation taking place at Herland mine in 1816.[8] It worked with pressures ranging from 60-120 lbs p.s.i. and at 5/6 of the stroke expansively. It used compounding by working with high-pressure steam which was expanded in a plunger-pole cylinder added to the engines. However, this type had multiple design flaws the most important of which was the quick cooling of the plunger when it was exposed to the air as it was pushed out of the cylinder leading it to lose valuable heat; the greater the heat of the steam used, the greater the loss suffered. This defect, along with the absence of the vacuum and the danger of explosion from the great elasticity Trevithick worked the steam, gave an end to the use of these engines shortly after Trevithick left for South America in 1816. Overall, Trevithick's presence in Cornwall was marked by the installation of several engines but, as one local authority observed, "as he paid but little attention to the proportion of the parts, their performance was not very good."[9]

Prior to his departure for South America Trevithick agreed to pass the patent right for the pole engine to William Sims, a local engineer with considerable reputation. The latter, as well as his son James, worked on hybrid forms of engines incorporating elements of the pole and B & W engines coming up with two-cylinder compound engines. This sort of design involved two cylinders being placed one on top of the other sharing the same piston rod. The cylinders were of unequal capacity, the larger one being 4 times larger than the smaller one above it. Steam passed in the form of high-pressure under the pole, partially expanded in the smaller cylinder after being cut off at a fraction of the stroke. It then passed into the larger cylinder of a B & W engine where it expanded further. The plunger was attached to the same beam as the piston of the great cylinder. The engines based on these modifications were worked with pressures of 40 lbs and marked an improvement of old B&W engines because they allowed them to deliver 30-40mil duties. Johnson provided detailed descriptions of the working mechanism of one of Sims' engines and one made by John Gilbert & Co. of London, both of which can be classified under this category of engines. He noted that the regularity of motion produced by such engines in sectors where this was highly valued (e.g., textiles) rendered them very popular. Johnson also notes that in a comparison between Sims' and Watt engines with a double-acting crank working non-expansively, the former produced a 40% economy of fuel. However, the performance of such engines subsequently fell due to poor maintenance of parts and were thrown into oblivion in favor of high-pressure, single-cylinder engines.[10]

Trevithick's efforts were paralleled by those of Arthur Woolf, an engineer whose reputation was formed while working in London as a millwright at Joseph Bramah's engineering works at Pimlico and at Meux brewery. Woolf got four patents during the period 1804-10 though the last one referred to an engine whose vision never moved beyond the experimental stage and hence he derived no benefit out of it. The first and second ones (1804 and 1805) referred to a double-acting compound engine working with rotary

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[7] According to an account, in the case of engines with exceptional performance the ratio of work compared to Newcomen and Watt engines was 14 and 6 times more respectively. Trevithick, *Life of Richard Trevithick, vol. 2*, pp. 186-7. See also Nuvolari and Verspagen, "Technical choice, innovation, and British steam engineering," p. 704.

[8] Pole, *A treatise*, pp. 57-9.

[9] Henwood, "Account of the steam engines in Cornwall," p. 35.

[10] Barton, *The Cornish beam engine*, pp. 107-10; Johnson, *The imperial cyclopaedia of machinery*, pp. xii-xiii, xxxvi-xxxvii, 36.

motion synthesizing Trevithick's high-pressure steam with the double cylinder engine invented by Hornblower in 1781.[11] Steam was expanded from the small, high-pressure cylinder to the larger, low-pressure one.[12] Woolf claimed that his design was based on a scientific principle, i.e., that there was a linear relationship between excess pressure and the increase in the volume of steam: steam at an excess pressure of two pounds per square inch would double its volume in expansion; an excess of three pounds would triple its volume, and so on. Woolf made a reference to his erroneous "law" in a patent specification though he did not explain its variance with other established principles such as Boyle's law.

Woolf was employed at the time at Meux's Brewery. He asked his employers to conduct experiments which led him to figure out that steam ought to be allowed to expand double its bulk for every 10-12 lbs above the pressure of the atmosphere. However, after two years, his employers got impatient with him and let him go. He had come to London as a young carpenter to gain experience. When he left Meux brewery he was in his mid-40s and an engineer of distinction.[13] Woolf, feeling disgruntled, formed a partnership with Humphrey Edwards, a millwright from Lambeth, collaborating on the construction of his engine. Design flaws initially gave place to the correct proportions of the two cylinders (in a 1:5 ratio) and, despite relying on a false theoretical premise, his engine eventually provided satisfactory performance. Woolf came up with a model of his engine which was exhibited, among others, to Charles Partington who, in turn, referred to it in a series of lectures he gave to the London Mechanics' Institution and provided a description of its working mechanism.[14] The engine was also inspected by William Sims. He was asked by his employer, the Williams family who were large shareholders of the Gwennap mines, to visit London in order to inspect one of Woolf engines. Sims was thoroughly impressed and urged his employer to install the Woolf engine albeit his advice was not followed due to disagreements on the particulars of the contract. The positive reviews continued. Early in 1811 a party comprised of Richard Trevithick and Henry Harvey, his brother-in-law (of Hayle Foundry), along with two engineers conducted a trial of a Watt engine at Battersea Distillery and of the Woolf engine exhibited at Lambeth. The Watt engine was of 8hp and ground 5.9 bushels of wheat with one bushel of coals. With the same quantity of fuel, the Woolf engine,

[11] Hornblower patented a two-cylinder engine passing the steam from one cylinder to a second one doing further work before passing to the condenser. He erected several engines during the period 1782-91 but, challenged legally by B & W, the mine owners paid royalties to the latter in order to escape litigation. The Hornblower engines proved no more efficient compared to Watt engines because the pressure was too low. Pole, *A treatise*, pp. 52-3; Van Riemsdijk and Brown, *The pictorial history of steam power*, p. 29; Hills, *Power from steam*, p. 132; Harris, *Arthur Woolf*, pp. 43, 52-3; Von Tunzelmann, "Technological diffusion," p. 77; Mokyr, *Twenty five centuries of technological change*, p. 90.

[12] The use of high pressure was a prerequisite for compounding. The concept aimed at utilizing the energy of the steam left over after the piston did its work in the first cylinder by conveying it into a second one. The difference in temperatures between the two cylinders was minimized and this offered the potential of a major reduction in fuel consumption.

[13] Harris, *Arthur Woolf*, p. 48; Stuart, *Historical and descriptive anecdotes*, p. 471. Rennie was brought in to replace him. He was of the view that the performance of Woolf vs. Watt engines stood at 3:4 and that a Watt engine was easier and less complicated in its construction. He also felt that a larger boiler would get a greater amount of work out of the Woolf engine. It should be noted, however, that Rennie had a bias in favor of Watt engines and hence his opinion could not be considered impartial.

[14] Partington stated that the same quantity of coals would generate a duty of 30mil. for a "perfect" Watt engine while the figure for Woolf's engine would reach 50mil. However, he also noted that the construction cost of the latter would be nearly double the cost of the former. Partington, *A course of lectures*, pp. 44-5; Harris, *Arthur Woolf*, p. 49.

of 9 hp, ground 17.3 bushels. It should be noted, however, that the Watt engine was an old one while the one by Woolf was new.[15]

However, the partnership fell apart in May 1811 due to the lack of sufficient demand and the loss of the engineering shop in London. Edwards migrated to France and eventually the Woolf engine became more popular in the continent, rather than in England, due to the higher price of fuel. In September 1811 Woolf moved to Cornwall armed with his patent for the compound engine and another one for his cast-iron tubular boiler. In advertisements he placed in local publications he claimed that his engines used one-third of the fuel of B & W engines. Shortly after he accepted the position of engineer at the United Crowan Mines and was asked to improve the performance of engines at Crenver, Oatfield, and Wheal Abraham.[16]

The initial performance of Woolf engines, such as those installed at Wheal Abraham and Wheal Vor, was quite impressive, being double the figures of the best low-pressure Watt engines. The news quickly disseminated through the *Philosophical Magazine* published by Alexander Tilloch, Woolf's friend and collaborator and drew the support of knowledgeable engineers such as Loam and Donkin. The latter stated in 1817 that in several experiments he witnessed between the Woolf and Watt engines in mills grinding corn, the results on fuel rates were decidedly in favor of the former. While a Woolf engine would grind 18 bushels of corn, on average, with one bushel of coal, the low-pressure engine would grind 10-12.[17] The comparison was equally favorable when taking into account Trevithick's high-pressure engines. Farey captured this sentiment by noting that "the merits of Mr. Woolf's system now [1816] became generally known amongst the miners in Cornwall, who had before been prejudiced against it; for the inferiority they had found in Mr. Trevithick's engines led them to believe that no high pressure engines could excel those of Messrs. Boulton and Watt, until the improvements of the same engines by using high pressure steam, with an increased extent of expansive action, became a fact too palpable to be any longer overlooked. Mr. Woolf's system afterwards became understood, and by degrees it was generally put in practice at the mines, to a greater or lesser extent."[18]

However, the performance of Woolf's engines was not consistent and tended to decline fairly quickly due to leakages by the piston and valves.[19] His engines were fitted with metallic pistons, instead of using the old hemp packing, with the expectation they will perform better. But metallic pistons needed to be removed and cleaned from time to time because the grease or fish oil left a residuum due to its long exposure to heat which worn the piston irregularly and thus rendered the fit with the cylinder imperfect. Another deficiency stemmed from the working of boilers which were fed by water rich in minerals. The latter deposited over time stony incrustations, particularly in the tubes. Attending engineers would diminish the pressure of steam in order to avoid replacing them right away; however, this inaction impacted negatively the expansive function which was necessary to achieve peak performance. In their minds it was preferable to continue working them despite the consumption of extra fuel as long as they performed with the same regularity as opposed to stopping the working of the mine in order to repair them, an action that would come at a great cost due to the disruption. Finally, cast iron tended to crack with the repeated heating and cooling routine and hence Woolf' boilers had to operate at lower pressure

[15] Harris, *Arthur Woolf*, pp. 51-2.
[16] Barton, *The Cornish beam engine*, p. 33.
[17] Harris, *Arthur Woolf*, pp. 41, 48; Cardwell, *From Watt to Clausius*, pp. 155-6; Dickinson, *A short history of the steam engine*, pp. 99-100.
[18] Farey, *A treatise on the steam engine, vol. 2*, p. 95.
[19] Ibid., pp. 96-7; Nuvolari and Verspagen, "Lean's Engine Reporter," p. 174.

after a period of use and this added yet another reason for not being able to reap the full benefits of expansive action.

Doubts were generated among potential adopters as to the accuracy of the performance of these engines when they were first reported. Negative comments became common. Rastrick, a prominent Cornish engineer, did not hold Woolf engines in high esteem "for the complications were, in my mind, sufficient to condemn them." Davies Gilbert referred to them as "the worst of its sort in Cornwall."[20] In 1820 Woolf proposed to erect some engines of his own construction at Consolidated Mines where he was the engineer. But William Francis, the managing agent, was opposed to it preferring, instead, B&W engines working on Trevithick's modifications. Woolf was persuaded to conform to his wish but he continued to make his own engines, in fact, one erected at Wheal Alfred in 1824 was one of his best. But not for long.

An event took place that same year (1824) which marked the end of the Woolf engines' era. At that point, complaints about their declining performance were coupled with others about the complexity in the design of his engines and their high maintenance cost. A consensus formed that expansion could be practiced as well in single-cylinder engines and hence preferences tilted towards Trevithick's simpler design having a shorter cut-off, greater expansion, and using pressures similar to the ones used at that time in compounds. To settle the debate on which type was the best, a trial of two comparable engines was arranged in 1824 at Wheal Alfred. It was between a single cylinder engine made by Neath Abbey, being essentially an improved version of the B & W model, and a double cylinder compound made by Harvey & Co. In the latter Woolf's cast-iron boiler was used. Both engines did similar duties, around 42mil. The main factor that rendered the single cylinder competitive was the fact it worked with a high degree of expansion. It was cheaper to buy, easier to maintain and, given that the compound failed to show better fuel economy, it marked the end of Woolf engines. Woolf dominated the Cornish mining scene from 1816, the time Trevithick departed for his 11-year stint in South America, to the time of the Wheal Alfred trial with only the two Sims presenting a competitive alternative.[21] However, during the 1820s many of his engines were converted back to single-cylinder engines, in fact, Woolf himself contributed some important alterations; and at that time Sims' pole compound engine also largely disappeared. Woolf decided to retire in 1832 after developing an antagonistic relationship with several local miners in the years preceding this decision.

The outlined competition regarding Trevithick, Woolf and Sims engines does not exhaust the different technological trajectories explored by Cornish engineers. Other models such as the Bull and inverted type of engines offered additional options albeit failed to gain a dominant position.[22] Most importantly, the

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[20] Cited in Harris, *Arthur Woolf*, pp. 53-4. See also Cardwell, *From Watt to Clausius*, p. 159; Van Riemsdijk and Brown, *The pictorial history of steam power*, p. 29; Farey, *A treatise on the steam engine, vol. 2*, p. 214; Pole, *A treatise*, pp. 52-3, 56-7; Dickinson, "The steam engine," pp. 193-4; Ewing, *The steam engine*, p. 25.

[21] By 1823 the two Sims, father and son, installed a total of 22 engines while Woolf followed with 14. Hills, *Power from steam*, pp. 107-8; Barton, *The Cornish beam engine*, pp. 32-4, 37-9, 42-4, 46-50, 58, 88-90.

[22] The Bull engine, invented in the closing years of the 18th century, suffered from considerable wear and tear due to shaking since there was no beam intervening between the piston and pump rods. A more serious design flaw was the position of the cylinder directly over the shaft, hence making difficult the changing of pitwork and impossible using the same pitwork for drawing ore. The Bull engine was unpopular with engineers because it was difficult to get to the stuffing box through which the piston rod worked. The inverted type of engine was a response to the defects of Bull engines. It was a cross between a Bull and a Watt engine with its main fans being Hornblower, Woolf and, especially, Sims. The inverted engine had its beam not much above ground level and hence the engine house was lighter and less expensive compared to conventional constructions. But its main virtue was that it was better suited

intense experimentation which took place up to the mid-1820s in search of the most efficient designs generated spin-offs on some related technical issues.[23] The use of high-pressure steam rendered imperative the search for boilers that could withstand such pressure loads. The boilers used in the first batch of Trevithick engines were deficient and often failed to deliver the power they were intended for. Trevithick appreciated the need to address this issue and came up with a new type, later called the "Cornish" boiler, which he used c. 1812 at Dolcoath mine for the first time. It was cylindrical in shape having a central flue running through the middle and had the fire inside at one end. Trevithick claimed that his new boiler was responsible for raising duty to 40mil, a figure which was certainly an exaggeration; nevertheless, his boiler did supersede eventually all others. As noted earlier, Woolf's approach on the subject was detrimental to the success of his engine. His own cast-iron boilers performed well when new. However, with time passed, they exhibited the same defects as other tubular boilers: they suffered from unequal expansion and contraction and eventually became useless due to incrustation caused by the earthy matter of the mines' water. Woolf's failure with cast-iron boilers led him to construct in 1818 a wrought-iron boiler on Trevithick's design which he succeeded in making it steam-tight without having to place rope between the plates. He achieved that by using a special cylindrical punch to form the rivet holes and making all the rivets of a uniform gauge. Another area of progress aimed at achieving better insulation. The methods developed involved covering the boilers with thick blankets of felt, brick and plaster to avoid exposing them to the cold air and the same methods were used for pipes and cylinders. Woolf, in particular, also made some important contributions by improving furnaces and advising the firemen to spread the coals thinner on the grates. Finally, the supply of steam was cut off at a shorter distance than hitherto was practiced. The cumulative benefits of these improvements were quite substantial.

In the years from the mid-1820s to the late-1830s there was a lull when it comes exploring different design venues and, if anything, trials seemed to solidify the notion that Trevithick's version of the Cornish engine was the way to go forward.[24] Engineers focused on better design of parts, small improvements in cleaning, oiling, and firing but, especially, on achieving even better insulation.[25] The insulation of boilers improved by using brickwork while cylinders and steam pipes were jacketed with wooden casings or clothing. The care taken to avoiding loss of steam can be illustrated by one of the engines at Huel Towan, one of the best in Cornwall. The cylinder was surrounded by a case filled with dense steam from the boiler. The steam pipes and nozzles were covered with saw-dust 16-20 inches deep while the boilers had a layer of ashes. Several engineers played a leading role in pushing for such micro-improvements but the leading figure seems to have been Samuel Groce based on experiments he conducted in 1825 with an engine he erected at Wheal Hope. Ten years later a relatively unknown engineer, William West, who acted as deputy engineer under Groce came up with an engine which shattered the hitherto performance of duties by

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to accommodate double action although it was a virtue that became irrelevant with the disappearance of double-acting engines in the 1830s. The last of this type of engines was built in Cornwall in 1862 but it continued in the mining districts of the northeast and Scotland. Barton, *The Cornish beam engine*, pp. 106-10.

[23] Farey, *A treatise on the steam engine, vol. 2*, pp. 38, 182; Hills, *Power from steam*, pp. 103, 131; Pole, *A treatise*, pp. 59-61, 175-6; Tooke and Newmarch, *History of prices, vol. VI*, pp. 534-7.

[24] According to experiments made by Perkins whose findings were published in 1836, the use of expansion had better results in single- as opposed to double-stroke engines. Perkins, "Observations," p. 362.

[25] Kanefsky, *The diffusion of power technology,* p. 116; Von Tunzelmann, "Technological diffusion," pp. 85-6; Ibid., *Steam power*, p. 263; Pole, *A treatise*, pp. 63-5; Nuvolari and Verspagen, "Lean's Engine Reporter," p. 174; Henwood, "On the expansive action of steam," p. 53; Enys, "Performance of steam engines in Cornwall," p. 60.

achieving during a public trial an incredible 125mil, a reading that was not sustained in the years following this event. Engines such as this incorporated the aforementioned technological improvements with each being a minor step forward but amounting to major progress cumulatively. None of them required any alteration of the main body of the engines and hence did not demand major investments in capital.

By mid-century the Cornish engine reached the apogee of its development. It was basically a Watt engine working expansively with high-pressure steam.[26] Writing in 1839, the Lean brothers noted that “the engine was reduced to its simplest form – a single engine on Boulton and Watt’s construction. And although our engines exceed in duty three or fourfold what Boulton and Watt had ever attained, or, perhaps, thought possible of attainment, yet they are, after all, in name and in reality, Boulton and Watt’s engines.”[27] It incorporated various modifications brought by a number of engineers who deserve credit particularly in light of the fact they received no monetary rewards for their efforts except witnessing expansion of their businesses along with fame and enhanced reputations. These improvements related to proportions and some technical details, the boilers used, and their ability to withstand strong steam. The hp generated by an engine varied with the area of the cylinder, each 22.5 square inches giving one hp. But another factor determining power was the strokes per minute which varied within a range, low figures reflecting economical working. It follows that the effective hp of single-acting Cornish engines could vary widely;[28] and, as always, more powerful engines had an advantage over smaller ones both because of higher fuel economy and due to savings by having to employ less attending engineers.

Despite the continuous improvements in what came to be called the Cornish engine, an unexpected event took place in 1839. Compounds made their appearance again, fifteen years after the critical Wheal Alfred trials which seemed to have rendered them irrelevant. James Sims rebuilt an old engine at Carn Brea mines based on some modified principles of his compound engines which gave impressive performance. Two years later, in June 1841, he took out a patent for this engine.[29] But of even greater importance was a version of compound engines invented by William McNaught, patented in 1845. It resembled the Woolf engine to the extent it used a small high-pressure cylinder which passed the steam to a low-pressure one where it was further expanded. But it was different in that it aimed to improve beam engines of the Boulton & Watt type by placing the high-pressure cylinder between the main column supporting the beam and the crank, where the cold-water pump was normally fitted. This simple alteration proved to be ingenious. There were many engines at that time which were overloaded due to the excessive number of machines they were called to drive. “McNaughting” them was found to be the solution because not only they exerted more power but did so with higher fuel economy.[30] McNaught stressed this virtue in his

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[26] Beginning in 1850, the Lean reports, to be discussed below, published the pressures on the boiler. The highest was 50 lbs per square inch and the mean was 34.5 lbs. Higher pressures were not attempted because of the potential for accidents since the stresses on metals for engines working virtually around the clock would be difficult to bear. Von Tunzelmann, “Technological diffusion,” pp. 85-6.

[27] Lean, *Historical statement*, p. 152.

[28] This was testified by a relevant table compiled in 1855 by J. Darlington and published in the *Mining Journal*. See Barton, *The Cornish beam engine*, pp. 32-4, 37-9, 42-4, 46-50, 58, 88, 100; for a detailed description of the working mechanism of the engine, see pp. 88-90.

[29] Barton, *The Cornish beam engine*, p. 52.

[30] Baynes cited an engine c. 1846, presumably (but not explicitly stated) as McNaughted, whose nominal hp was 60 but its effective one 67. He suggested the following methods of finding the hp of an engine which has been McNaughted: 1) Take the square inches area of the cylinder, multiply by the velocity of the piston in feet per minute and multiply by the average pressure indicated, then divide by 33,000; 7/10 of the product will be the effective hp.

patent: "the effect of increasing the power of the engine, of lessening the consumption of fuel in proportion to the power produced, and by working the steam expansively in the low-pressure cylinder a further saving of steam may be effected, and consequently a proportional saving of fuel."[31] "McNaughting" was also an attractive proposition since more power could be gotten out of existing engines without having to scrap them. McNaughted and other compound engines caught up with the diffusion wave of high-pressure engines in manufacturing districts. In 1859 they accounted for 42.5% of hp in the cotton industry of the Manchester district (32,282 hp).[32]

The period 1846-70 marks the third and last phase in the history of steam power in the context of this study's time frame. It was a period of technological stagnation devoid of any major developments either in terms of new designs or micro-inventions with only few exceptions when it comes to the latter.[33] It was a period which stands at complete contrast with the two previous phases, i.e., 1802-24 which was characterized by a multitude of different design patterns dominated by the ideas of Trevithick, Woolf and Sims as well as the appearance of several spin-offs classified as micro-inventions; and the period 1825-45 which was mostly about perfecting Trevithick's version of the Cornish engine and the resurgence, towards the end of this phase, of improved versions of the compound alternative.

Cornish innovation: the role of patents vs collective invention

The extraordinary wave of inventions which appeared in Cornwall during the first half of the 19th century begs the question regarding the source(s) of this phenomenon. According to the theory of collective invention, first formulated by Allen and applied to the Cornish case by Nuvolari, the cumulative improvements along the evolutionary path of high-pressure steam have to be understood as the outcome of an institutional environment based on shared information and knowledge, as opposed to a setting in which property rights in the form of patents, acted as the triggering mechanism of this activity. This section will engage in a critical assessment of Nuvolari's interpretation by arguing that the empirical evidence does not support the sort of binary choice he advocates with would-be inventors opting for knowledge sharing. The latter phenomenon did take place and it did act as a driver of innovation. However, it will be argued that the patent system played the most critical role in fostering inventive activity.

Allen's concept of collective invention was based on the observation that productivity improvements among blast furnaces in England's Cleveland district during the mid-19th century could not be attributed to any single individual but was the outcome of a series of micro improvements based on a collective effort which unfolded in an evolutionary fashion.[34] The concept relies on the premise that the merits following the introduction of a new technique are freely disseminated among other prospective adopters,

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2) Multiply the square inches area of the cylinder by the velocity of the piston in feet per minute, and again by the indicated pressure in lbs as above, then divide by 44,000; the product will be the effective hp. Baynes' preference was for the second method. Baynes, "Experiments in steam power," p. 369.

[31] Cited in Hills, *Power from steam*, p. 157. See also Ewing, *The steam engine*, pp. 26-7; Musson, "Industrial motive power," p. 421.

[32] The vast majority were operating in the range of 15-60 lbs p.s.i. Condensing engines accounted for 56.8% (43,126 hp) and non-condensing ones for 0.6% (448 hp). See Kanefsky, *The diffusion of power technology,* pp. 124, 126.

[33] Efforts to achieve economy of fuel continued after mid-century coming up with engines with an increased length of stroke. See Barton, *The Cornish beam engine*, p. 61.

[34] Allen, "Collective invention."

as opposed to practicing secrecy and seeking benefits through patents; in fact, such improvements (e.g., a taller furnace or a hotter blast) were not patentable. The theory implies that, at any given moment, there is a likely division of firms among two groups: first, those which are willing to bear the risk of experimenting and potential costs since the deviation from an existing design bore the risk of increasing cost of production; if successful, such firms would leapfrog by realizing the ensuing benefits. Second, there is another group of laggards which would eventually catch up. Collective invention spreads such risks among firms and hence competitive industries are able to realize high rates of invention. Innovative activity was a by-product of normal business operations, as opposed to an outcome of R&D projects, and the benefit was exploited not only by the firm which first witnessed it but also by its competitors. Output and profits increased for all firms participating in this information-sharing scheme. The degree to which productivity at the sectoral level increased was a function of investment and capital formation rates and it fluctuated based on the ebbs and flows of such rates; the higher they were, the more experimentation could take place and the more technological ingenuity was to be expected.

Still, the theory of collective invention needed to address the motivation behind the release of information by successful inventors. Allen suggested several factors to explain this behavior. First, in certain historical instances competitive behavior is driven by the personal ambitions of owners or managers and hence the only way to settle scores was by releasing information regarding the achievements of their own firms. Second, the release of the information takes place because it would be too costly to keep it a secret. In the case of the iron industry, construction based on new designs took place by employing contractors and consulting engineers who shifted from firm to firm. These professionals not only knew how a new furnace was designed but also how it operated. Other people would also have information about the new design, from managers to fillers. The lower the wages of these individuals, the more likely it would be to reveal information to competitors. The third reason that may lead to collective invention is the prospect of raising profitability by sharing information. The release of information by one firm may prompt other firms to behave in a similar fashion and hence the said firm may become the recipient of multiple bits of useful information.[35]

One of the core elements in Nuvolari's thesis in applying this theory to the Cornish case is that the design of new engines during the period in question was not based on the formulation of relevant scientific principles, a statement that reflects a general consensus.[36] The state of scientific knowledge at the beginning of the 19th century was in no position to explain the superiority of high-pressure engines in

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[35] Following Allen's thesis, manifestations of collective invention have been claimed for a couple of other industries, including Dundee's flax industry. According to Miskell and Whatley, "local industrialists shared a detailed knowledge of one another's businesses which grew from frequent fact-finding visits to neighbouring premises. The purchase of an additional steam engine by one manufacturer or the successful outcome of a repair job by another would quickly become common knowledge and generate further demand. Charles Mackie noted in the early 1820s that: 'The managers are visiting each other's mills daily to learn that no mill should get before them in spinning quantity and to see what power any of their brother managers had derived from a second or third boiler.' This close contact and information-sharing had a motivating effect on the manufacturers" in terms of adopting the latest technological improvements backed by the fear that, if one was left behind, it would mean the end of the business. It should be noted that the pattern of industrial development in Dundee was very different from the one in Leeds, its main competitor. In the former, there was a sudden increase of small mills in the 1820s and by 1832 Dundee had 40 flax mills operated by 693 hp. Leeds, in contrast, had only 25 mills with a total of 915 hp. See Miskell and Whatley, "Juteopolis," p. 185.

[36] The review of Nuvolari's thesis relies on the following publications: Nuvolari, "Collective invention" and on his joint work with Bessen (Bessen and Nuvolari, "Diffusing New Technologies,") and Verspagen (Nuvolari and Verspagen, ("Technical Choice, Innovation and British Steam Engineering").

relation to low-pressure ones. In fact, it has been suggested that much of it (e.g., the caloric theory of heat) was detrimental to the development of a theory pertinent to steam engines.[37] In light of it, a would-be inventor had one of two choices. First, to rely exclusively on his own knowledge on the subject and engage in experiments under secrecy until he felt that a new engine design or a component of it was good enough to seek a patent in order to gain pecuniary benefits for his efforts. This is the route Watt undertook. However, a major factor that steered Cornish inventors away from the patent system, according to Nuvolari, stemmed from the well-known acrimony between the local adventurers over Watt's patent and the protracted legal battles it entailed which led the Soho firm abandoning the county. During this phase of acrimony technological innovation and fuel efficiency standards stagnated.[38] Simply put, local engineers and adventurers had developed a culture or an ethos that was negatively predisposed to secrecy stemming from holding a patent.

Instead, the Cornish engineering community sought to advance its fortunes by relying on extrapolation from the relative performance of new design patterns and the trial-and-error experiments undertaken by competitors. By practicing information disclosure and sharing accumulated experience, it became more feasible to explore technological opportunities without compromising pecuniary gains. In Nuvolari words: "In local production systems where technical advances were the product of collective endeavours as in Cornwall, the organization of innovative activities was governed by specific institutional arrangements, alternative to the patent system, which made sure that new technical knowledge remained in the public domain … In the case of 'cumulative systems technologies' (that is, technologies consisting of a number of interconnected components and in which current improvements are highly related to previous innovations), strong enforcement of intellectual property rights might, in the end, hinder technological progress." In contrast, "the creation of an 'open' collective invention setting … produced a marked acceleration in the rate of technological advance."[39]

A key role in promoting this new ethos of knowledge sharing was played by the initiation of Lean's *Engine Reporter* in 1811.[40] The reports started with Joel Lean in August 1811, were published in a local newspaper (the *West Briton*), and ran for 14 months. Joel Lean died in September 1812 but the reports continued as an independent publication taken over by his two sons, Thomas (I) and John, and eventually by two other relatives. Per Nuvolari's narrative, observation and analysis of the data reported in this publication allowed local engineers to identify the most efficient designs and, despite the lack of contribution from scientific principles, to advance the technological sophistication of local steam engines.

A critical assessment of the attempt to apply the theory of collective invention to the Cornish case, however, reveals facts that render such an attempt questionable. Let us start with one of the two key players in the unique Cornish institutional environment, the mine adventurers. There was a peculiar

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[37] On the state of science, including contemporary views relevant to this subject, see Cardwell, *From Watt to Clausius*, pp. 159-64; Mendelssohn, *Science and western domination*, pp. 132-5, 140; von Tunzelmann, "Technical progress during the Industrial Revolution," p. 149; Jewkes et. al., *The sources of invention*, p. 70.

[38] Nuvolari and Verspagen, "Lean's Engine Reporter."

[39] Nuvolari, "Collective invention," quotes from pp. 360-1.

[40] The two brothers ran the reports together for the years 1812-27. In the period 1827-31 the two brothers compiled two separate reports with most of the engines included in the one by Thomas and about one-third in the one by John. The period 1831-7 was covered by Thomas I alone and the period 1837-47 by Thomas I in collaboration with his brother Joel (II). After that, Thomas II (Thomas I's son) took charge of the reports for the period 1847-97. The final years, 1897-1904 were covered by J. C. Keast. In October 1834 a separate report was put in place by William Tonkin but it referred to a few engines, the majority of them being included in the Lean reports. See Nuvolari and Verspagen, "Lean's Engine Reporter," p. 187, note 11.

element to mine ownership. Local investors obtained a grant of working the mine from the owner of the land, a renting contract, usually for 21 years. The rent or "dues" were paid as shares of the ore extracted, ranging from 1/18 to 1/15 but even up to 1/12 or 1/10 in the most profitable mines. At the initiation of the enterprise mine shares were subscribed, normally 64 of them. Such shares were easily transferred, the only obligation being notifying the "purser," one of the adventurers who was responsible for the administration of the venture. When the mine was profitable, profits were distributed based on the number of shares held while every 2-3 months a meeting was held to have the shareholders contribute to mining costs, again based on the number of shares they held. The crucial element of this ownership paradigm was that adventurers were not tied to a single mine but were free to buy shares in different ones.

It follows that, in principle, mine adventurers had every interest in maximizing the engines' performance in the mines they invested in, that is, the performance of multiple types of engines although not necessarily the performance of every engine, as the theory of collective invention would dictate, since they were still in a competitive position *vis a vis* mines they had no financial interests in. The degree to which they practiced an ethos of an open dissemination of knowledge, however, comes into question in light of the difficulties encountered by J. Y. Watson in trying to solicit information prior to the writing of his book. His experience carries major weight in light of the fact he was one of the two most eminent experts on the local mining industry, along with Pole, and part of a small group of engineers who published on the subject (also including figures such as Enys, Galloway, Gilbert, Henwood, Perkins). Writing in 1843, he complained that "Cornishmen seem to think they thrive best in secrecy … In collecting materials for this book, considerable difficulties in getting accurate accounts of the mines have been met with … And if any of them should be inaccurate, it is the fault of those, who cast a veil over their proceedings, and view with jealousy and distrust any attempt to obtain an insight into their doings."[41]

Watson's experience casts doubt to the claim of the presence of an ethos of openness on the part of investors. On the other hand, there is also no denying of the adventurers' open hostility in paying premiums, an ill-feeling that presumably still lingered since the acrimonies with Watt and Trevithick's first patent were not far apart. However, their attitudes, important as might have been, have to be weighed against the fact that the Soho firm was able to collect from Cornwall nearly £140,000 translating to a mean annual revenue of a little over £6,000 (see chapter 2). These extraordinary figures surely must have been a tremendous temptation in the minds of inventors, the ultimate arbiters on the question on whether a patent should be pursued vs. a policy of knowledge sharing.[42] A useful starting point for disentangling the impact of these two contradictory factors would be to review the provisions of the patent system at the time, the extent to which it offered protection of property rights as well as the extent innovative activity in Cornwall was tied to it.

Patent legislation during the steam era was very imperfect, to say the least, in several respects. One of the main flaws was the lack of legal clarity on what a specification should do and hence the impossibility of specifying an invention to the satisfaction of the courts. Back in the 17th century, when this legislation was originated with the *Act against Monopolies* (1624), a patent's specification was deemed unnecessary because it was thought that the mere practice of the invention was proof of its originality. But 10 years later such specification became customarily expected. By the time of Watt, it was clear to him that the

[41] Watson, *A compendium*, p. 4.

[42] If the former, it would justify the expectations of conventional economic theory which views technology creation and transfer as a game of hide-and-seek, with the patent system being the instrument that provides advantages to early innovators. See Sahal, *Patterns of technological innovation*, p. 60.

specification of his invention carried a lot of weight. Watt did not submit drawings because he sought the patenting of a principle of action aimed at diminishing fuel consumption as opposed to seeking a patent for a specific engine; he felt that it would be easy for potential infringers to slightly modify its working mechanism and claim it as theirs. Others felt the same way, that seeking a patent for a particular form of technology and delving into mechanical minutiae would "lock" them into a level of specificity that would allow others to come up with the same technology in a different form. In the context of this logic, submission of drawings was equivalent to inviting piracy. In the 1794 legal battle that brought Watt in collision with Bull, the latter's attorney argued that a patent should never be awarded for a "principle" since it could be applicable to any mechanical device that applied the said principle. But the prevailing opinion of the judges that gave Watt a victory pointed out that what Watt was trying to do was not to patent the expansive force of steam since it was incorporated not only in his engines but also in those of the atmospheric type; instead, the patent was warranted because he came up with a mechanical arrangement which took greater advantage of the expansive force of steam. A principle could not be patented. But a principle embodied in a mechanical arrangement could.[43]

These issues were still a matter of debate by the late 1820s. By that time there seems to have been a consensus that principles alone could not be patented. Farey, for instance, pointed out that if patents were issued exclusively on the basis of principles alone, different inventors would not be allowed to apply different methods of execution of the said principle with some producing better results. But there were a few who thought it would be a waste of ingenuity if patents could not be given on the basis of principles alone just because someone may not have come up right away with a mechanical device to apply it. At that time, patentees were in the habit of specifying not only the principle but all the different methods they could think it could be applied to. In the midst of this legal debate, one could say confusion, Charles Babbage, in a written opinion published in the *Quarterly Review*, expressed in 1830 his views as follows: "The patent laws of Great Britain—a system of vicious and fraudulent legislation which, while it creates a factitious privilege of little value, deprives its possessor of his natural rights to the fruit of his genius, and which places the most exalted officers of the state in the position of a legalized banditti, who stab the inventor through the folds of an act of parliament."[44]

The ambiguity of legal provisions was compounded by interpretations of the law by the courts which were not always favorable to patentees. According to Sullivan, there was a gradual shift towards more positive attitudes which coincided, more or less, with an acceleration or structural break in the rate of inventive activity in 1757. But the record remained mixed. Boulton and Watt won their legal battles because of the great services they offered to the country but others were not given the same latitude by the legal system. Eminent inventors such as Argand and Wedgwood lost their cases in courts issuing decisions not sympathetic to patent petitioners.[45]

Even if the outcome of the legal process was successful, the inventor would have to cope with potential instances of piracy, an endemic problem at that time. Steam engineering refers to a technology which could not have been kept secret based on a formula, as is the case in chemical industries; nor the

[43] Robinson, "James Watt," pp. 115-24. For Watt's views on the principles patent law should be based on, much of which survives in written form reflecting an astute commentator with farsighted views, see ibid, pp. 125-37.
[44] Cited in ibid, p. 117.
[45] Sullivan, "England's 'Age of Invention'," p. 436; see also Robinson, "James Watt," p. 138.

accumulation of knowledge through learning-by-doing acted as an entry barrier since such learning could be acquired by others within a short period of engagement in the production process.[46]

The aforementioned caveats were frustration-causing elements to all those inventors who found themselves in front of the courts. Getting to the courts involved a process which was equally frustrating and, most importantly, costly since monetary "barriers to entry to the technology market via patents were high."[47] According to the *Times Law Report* (January 1799), reflecting on the opinion of Lord Chancellor Kenyon in one of B & W cases that came to the King's Bench in 1799, "… from the balance on the whole, it struck him that there was a great deal of oppression of the lower orders of men from Patents, by those who were more opulent."[48] Down to the 1852 Reform Act separate patents had to be taken for England, Scotland, and Ireland. The cost for an English patent varied based on the invention but it was in the range of £100-120; similar figures had to be paid for patents covering Scotland and Ireland raising the total amount to c. £350. Given the serious cost involved, only 16% of the patents issued in the period 1838-47 covered all three kingdoms.

However, the fee was only part of the expense. There was a very considerable cost in making sure that the invention was not covered by another patent. Publications such as the *Repertory of the Arts*, *Tilloch's Philosophical Journal*, the *London Journal of Science*, and *Gill's Technical Repository* did publish relevant information. But these were summaries and accounted for only a fraction of the record since many holders of patents did not wish to expose details of their technology to the public. To begin with, a potential patentee had to cover the expense of travel to and accommodation in London. Then he would have to visit the Chancery Office and pay a considerable fee for inspecting the record consisting of the specifications and drawings, even more so if he wished to make copies. To record his own invention entailed paying an attorney. Gratuities paid to several people involved in the process, from doormen to high-ranking officials, would add to the cost. Stuart cited figures which would amount to many hundreds, if not thousands, of pounds but he certainly exaggerated, most likely reflecting the views of a reform movement which advocated major changes, including addressing the magnitude of the cost. According to McLeod, travel and lodging expenses, solicitors' fees, and providing entertainment could add £100 to the patent fee, not to mention that the interested party had to spend several weeks in London to get the job done and then wait for 1-2 months, in some cases much longer, to find out the outcome of his petition. These expenses were on top of others relating to the development, testing, and construction of an invention. It goes without saying that the total expenses were beyond the means of most contemporary inventors in light of the fact mean annual income in 1830 was just £19. In some cases, the cost could be shared with employers, partners and other inventors. But in other cases, inventors who entered this arduous process found themselves brought to their knees by the financial burden and ended up dying impoverished. "A patent was a heavy investment, not to be undertaken capriciously."[49]

[46] Dutton, *The patent system*, pp. 110-2; Stoneman, *The economic analysis of technological change*, p. 240.
[47] Epstein, "Property rights to technical knowledge in premodern Europe," p. 384.
[48] Cited in Robinson, "James Watt," p. 137. See also, Dutton, *The patent system*, p. 35; Sullivan, "England's 'Age of Invention'," p. 434.
[49] MacLeod, *Inventing the Industrial Revolution*, pp. 75-8 (quote from p. 77). See also Stuart, *A descriptive history of the steam engine*, pp. 202-3; Dutton, *The patent system*, pp. 110-2. One reason metropolitan London figured so prominently in patent statistics was that inventors, especially in the provinces, were ignorant of the patent system or perceived it as a form of royal patronage not being relevant to them. Bessemer, even after living in London for 3 years, declared ignorant of the patent system and ended up selling his early unprotected inventions for trivial amounts.

The final major caveat was the duration of a patent which was limited to 14 years. Reputable observers at the time felt that it was imperative to extend the period of the grant. Farey pointed out that an inventor had to incur considerable time to develop the idea and great expense engaging with experiments while it would take considerable time for potential adopters to decide, in light of the great cost involved, as well as to train engineers for managing it. In his words, "the adoption is often deferred to the end of the term, and the invention is not brought into use until after the expiration of the fourteen years' term of the patent." It follows that "the uncertainty of recompense to investors whose services have proved advantageous to the community is very discouraging to men of real talent."[50]

In conclusion, the dawn of the 19th century was an era during which patent piracy still thrived while attorneys and patent agents profited the spoils of this confusing legal framework. It was only during the late 1820s when conditions became ripe for change. A select committee of the House of Commons decided to address the numerous complaints that accumulated over the years. In 1835 Parliament passed an act which attempted to remedy the worst grievances addressed against the patent system and, among its provisions, offered to patentees the possibility of obtaining an extension of a patent's term on meritorious grounds if the said inventor failed to gain sufficient compensation for his invention. Such decision followed a review of the case by the judicial committee of the Privy Council and it was based on its recommendation. At the same time, during the 1830s, courts became increasingly more favorable to the rights of patentees with the number of cases being decided in their favor rising drastically.[51]

Notwithstanding the considerable caveats of the patent system, we need to address the question as to whether it was in the interest of an inventor to use it as opposed to trying to capitalize on it by seeking another method of being compensated. Nuvolari in his joint work with Bessen argued that innovators, presumably referring to the first firm(s) adopting a new technology, can capture rents as long as the new technology coexists with an older, inferior one. In such situation the market price is determined by those using the older technology and, since the marginal cost of production of those using the new one is lower, it follows that the firm that innovates can generate supra-normal profits equal to the cost advantage of the new technology. This statement does have a sound theoretical basis. However, the decision to seek a patent vs practicing knowledge sharing is not taken by the innovator, i.e., a potential adopter which refers to a firm, but by the inventor. Bessen and Nuvolari do not clarify under what type of arrangements the inventor would capture at least part of the generated supra-normal profits. Would that come about through the imposition of an annual fee or some other sort of contractual agreement? In the case of Cornwall, there is absolutely not a single reference on the part of the authors to a case study of an inventor who chose not to patent his invention illustrating how this route generated higher profits compared to the ones that could be gotten by opting for the patent route.

In the end, competing theoretical hypotheses are worthless unless supported by the evidence. According to Nuvolari's interpretation, the first major testament to the different ethos evolved during this era was the decision by Trevithick not to seek a patent for his Wheal Prosper engine, erected in 1812, because he probably learned from Woolf's experience who took a patent for his compound engine in 1804. When Woolf moved from London to Cornwall (1812) he tried to capitalize on his patent by proposing an

[50] Farey, *A treatise on the steam engine, vol. 2,* pp. 189-90.
[51] Robinson, "James Watt," p. 137; Sullivan, "England's 'Age of Invention'," p. 436; Farey, *A treatise on the steam engine, vol. 2*, pp. 189-90.

arrangement similar to the one of B & W, i.e., a premium based on fuel savings. The adventurers were not responsive and abstained from adopting his engine until after 1818 when his patent expired.[52]

It is not clear, however, whether Woolf's case reflects a failure of the patent system in light of the fact he made the mistake to wait for 8 years (1804-12) between the time he got his first patent and the time he tried to capitalize on his designs. Woolf did inquire about the prospect of getting an extension of his patent. However, that would have been a costly affair, not to mention the feedback he received was not encouraging. According to Farey who offered extensive insights and comments on Woolf's experience, "if the same favour had been shown to Mr. Woolf--as in the case of Watt with Parliament extending his patent in 1775--he would have been fully recompensed by payments for the use which was actually made of his invention during a few years following after the expiration of his patent."[53] Instead, in the 6 years left some mines decided to adopt his engines with the collective sum of the premiums paid barely covering the expense of obtaining his patent and the cost of experimentation; it simply amounted to salaries he could have obtained in Cornwall for superintendence of engines. In the end, his experience certainly does not prove he was averse to the prospects offered by the system in light of his 4 patents which covered both novel designs for entire engines as well as one of their major components (his tubular boiler).

But was Trevithick's experience reflective of an inadequate patent system? Trevithick got his first patent for his non-condensing engine, along with Vivian, in 1802 and attempted to sell engines charging premiums based on their power.[54] His efforts to introduce the model in the mines of Cornwall materialized only to a limited extent, a major factor being the failure of the patentees to establish workshops to manufacture the engines. Instead, they pledged to give full instructions to makers of engines on the condition of paying license fees which amounted to 12 guineas per hp for small engines up to 6 hp, 9 guineas for engines between 6-9 hp, and 7 guineas for engines above 9 hp. This system spread the manufacturing of engines among a large number of makers some of which did not have a sufficient amount of business and hence failed to impose regimes of standardized production using a large number of highly trained engineers as per Soho's manufacturing paradigm. The Pennydarren Ironworks in South Wales manufactured engines based on Trevithick's patent but the latter commented in 1804 that he did not trust them producing quality engines unless he was present to supervise the task: "The engine that is first sent to Cornwall must be from Coalbrookdale and then the(y) will be well executed but from Wales it wo[u]ld not be so."[55]

The business of making engines fell on millwrights and iron founders who were drawn into it by the prospect of making high-pressure engines at a low price by providing a coarse level of work which, in turn, explains the poor performance of Trevithick's engines. Reputable makers were discouraged from entering this business by several factors: the fear of explosions by using high pressure as was the case with a relevant incident in Woolwich involving one of Trevithick's engines, a misfortune thoroughly exploited by B & W; because of the shops' aversion to manufacture the engine under license from the patentees; and from the presence of so many producers with inferior standards which rendered very difficult obtaining

[52] Another example Nuvolari provides referred to Sims who took a patent in 1841 for the two-cylinder compound engine erected in Carn Brea which did exceptionally well in the early 1840s. But, according to Nuvolari, it failed to be adopted elsewhere because of the patent. See Nuvolari, "Collective invention," pp. 357-61.
[53] Farey, *A treatise on the steam engine, vol. 2*, pp. 188-90, quote from p. 189.
[54] The premiums he charged in 1803 were: For a 3hp £47 5s; for a 4hp £50 8s; for a 5hp £63; for a 6hp £75 12s; for an 8hp £75 12s. See Trevithick, *Life of Richard Trevithick, vol. 1*, pp. 227-8. See also Farey, *A treatise on the steam engine, vol. 2*, pp. 12-3, 39.
[55] For a list of firms manufacturing Trevithick's engines over the years, see Ince, "Richard Trevithick's patent steam engine," pp. 69-73; quote from p. 69.

orders for engines of high quality at a high price. Trevithick did visit several workshops making his engines and provided consultation on manufacturing standards that ought to have been followed. But these visits were not systematic enough to create a uniform high level of performance and soon the notions, erroneous in many cases, of local makers took over. Some of them wished to manufacture powerful engines through larger cylinders albeit kept boilers the same size; the passages allowing the steam to escape the cylinders were often too small; the boilers did not possess sufficient surface to receive heat from the fire, or they were made by cast iron which did not fare very well against the prospect of explosions. In the case of manufacturers who did not require to work the engines at their utmost pressure, accidents were avoided and the level of comfort working with such engines improved but not to the extent of replacing the high reputation enjoyed by Watt engines. Eventually he managed to set a good number of engines but the revenues he derived, £1,250 by 1804, were fairly limited due to the small size of the engines he installed, mainly by businesses of modest size and of limited financial resources. A good number of engines were also installed without Trevithick obtaining any benefit because of the refusal of adopters to pay the premiums. In the case of at least one maker of his engines, Bateman and Sherratt of Manchester which violated Watt's patent, it attempted to do the same with Trevithick until it was stopped under the threat of legal action. In light of these developments, Vivian disengaged from the efforts to sell the engine.

Aside of the engine's poor performance record, another element which explains Trevithick's failure to penetrate the Cornish market was spreading his attention across multiple and diverse projects. In addition to the high-pressure engine and his attempts to come up with a steam carriage, he collaborated with Robert Dickinson, a patent speculator, in several projects relating to navigation all of which led to failure.[56] As these efforts were ongoing, Trevithick found himself in dire financial straits as he tried to raise money by selling or mortgaging his mine shares and property.[57] The two partners ended up in bankruptcy in 1811, having accumulated a debt of £4,000. Trevithick was discharged from his share of the debt in 1814 once he paid a fair, although not the full, amount. It was in the middle of his effort to shed his financial constraints that he came up with the Wheal Prosper engine in 1812. It seems highly unlikely his decision not to seek a patent for it was related to Woolf's atypical experience rather than to the sizeable cost involved in getting a patent in the midst of dealing with his bankruptcy. That is not to say, however, that the common criticisms of the patent system at the time were not deeply ingrained in his mind. In a letter written in 1812, Trevithick stated: "a patent is but for fourteen years, and open to constant infringement; for the inventor of general and useful machinery is a target for every mechanic to shoot at, and unless protected or encouraged by some better plan than a common patent, will have the whole kingdom to contend in law, and most likely receive ruin for his reward, which has too often been the case."[58] The fact Trevithick was not entirely dismissive of the patent system was his successful petition in 1815 to get one for his plunger pump or pole engine. In fact, he seems to have believed that his family would be able to survive out of the royalties from half the patent, the other half having been sold to William Sims for £200

[56] The two of them obtained patent no. 3148 for towing ships and discharge cargo with a steam windlass (1808); patent no. 3172 for stowing ships' cargoes (1808); no 3231, a single patent referring to 9 different inventions relating to "naval architecture and navigation" (1809); another patent obtained in 1810 relating to the propulsion of sea vessels; and his efforts continued through 1815 by obtaining patent no. 3922 for a steam boat.

[57] Referring to his wife, "during the difficulties in London in 1808 and 1810, when Trevithick was overwhelming himself with new experiments and the cost of patents, and laws expenses, lawyers and bailiffs took everything worth having from her place." Quoted in Trevithick, *Life of Richard Trevithick, vol. 2*, p. 36.

[58] In the same letter Trevithick was advocating for an Act of Parliament to grant him 1/10 of the savings to be realized over a 21-year period. In effect, he was seeking an arrangement in which the government would pay for his expenses in developing the steam engine plus a reasonable reward for his efforts. Trevithick, *Life of Richard Trevithick, vol. 2*, pp. 47-9, quote in p. 48.

prior to his departure to Latin America in 1816 at the age of 44. His hopes, however, went unfulfilled due to the engine's poor performance.

Nuvolari's argument regarding the formation of a new ethos in Cornwall, being averse to patenting activity, becomes highly questionable in light of the fact every major design from Trevithick's 1802 engine to McNaught's 1845 compound, with one exception, as well as multiple micro-inventions were tied to the patent system notwithstanding its multiple flaws. Cornish inventors in the early 19th century certainly knew of the spectacular revenues B & W generated in the county and hence their *ex ante* profit expectations, which conditioned their desire to seek a patent, were not necessarily pessimistic despite the friction and disappointments the Soho firm encountered in Cornwall. Woolf's failure to garner monetary rewards for his patent was due primarily to his delay in exploiting it; and Trevithick's equally spectacular failure was not necessarily based on his colleague's experience since "by definition, each patent is inherently different from every other one, and so the failure of an inventor to secure a return on his efforts may not have necessarily indicated to others that their fate would be the same."[59] Instead, it had a lot to do with his focus being dispersed among multiple and diverse projects most of which could not have been realized given the technology at the time. Most importantly, his failure to obtain a patent for his 1812 Wheal Prosper engine, the only major instance a macro-invention was not tied to the patent system, was simply due to lack of funds having to cope at that time with the woes of his personal bankruptcy *due to his insistence being involved with the patent system*. In addition, another factor was that both his and Woolf's engines failed to come up with consistently high-performance results; they did not manage to combine their supreme mechanical skills with the entrepreneurial genius of someone like Boulton and hence to imitate Watt's success in constructing his engine with the highest production standards at the time.

Nuvolari and his collaborators, however, summon one more argument in seeking to buttress the validity of their thesis. According to their analysis, patents issued to inventors based on their stated address during the period 1698-1812 were heavily lopsided towards London's metropolitan area, including Middlesex and Surrey, accounting for 40% of the total while in 1813-52 the share went up to 43%. Would-be patentees in London had the advantage of following closely the administrative procedures involved in granting a patent not to mention that the metropolis had developed a formidable capital goods sector. In contrast, during the same two periods, Cornwall's share declined from 9.38% (12 patents) to a negligible 0.89% (9 patents) despite the fact it was a hotbed of innovation.[60] These statistics point to an acceleration of patenting activity in Cornwall since the 12 Cornish patents during the first of the specified periods translate to 0.10/annum while in the second period the 9 patents translate to 0.22/annum. The argument, however, is that the *relative* importance of Cornwall declined precipitously at the very period the county was going through a phase of intense experimentation on high-pressure steam, the implication being that patent statistics fail to capture it because of the phenomenon of collective invention.

Before addressing this argument, it would be wise to bring up a common criticism of assessing the degree of innovative activity based on patent statistics. The latter is not synonymous with the level of innovative activity, i.e., the translation of a patent into a concrete technology with an economic impact; and, even if

[59] Mokyr, "Editor's introduction," p. 44.

[60] Patenting activity during the Industrial Revolution was dispersed among many industries. Patents relating to steam engines, the largest component of a broader category including also the transmission of power, were at the top of the list numbering 984 during the period 1750-1851, albeit accounting for only 5.75% of the total. See Dutton, *The patent system*, pp. 206-8; Sullivan, "England's 'Age of Invention'," p. 442, Table 3.

it is, it fails to capture the magnitude of the economic impact.[61] Regarding the period in question, the problem was compounded by the fact the patenting system in the UK did not demand testing before an invention was registered. As long as someone was prepared to pay the fee, the invention could earn a patent. Such system opened the prospect of the registration of inventions with little or no economic value, those which were imitative, and those driven by the ego of an inventor in search of prestige bestowed by the granting of a royal grant.[62] During the period which defined the peak of experimentation in high-pressure engines (1800-28), there were 218 names (7.5 per annum, on average) appearing on a list provided by Stuart; some of them were familiar to students of the subject (e.g., Trevithick, Vivian, Woolf, Jonathan Hornblower), though the vast majority failing to leave a mark on the technical evolution of the engine.[63] At the very least, however, patent statistics, do reveal the magnitude of research efforts in a particular field.

But, aside of this note of caution, the main objection to the statistics presented by Nuvolari and his collaborators is twofold. First, the dividing line in their categorization is 1812, the year after the Lean reports appeared. However, the acrimony of Cornishmen with Watt, which according to their thesis triggered the phenomenon of collective invention, dates back to the closing years of the 18th century and coincides with the first experiments and speculation on the use of high-pressure steam. The dividing line should certainly be placed no later than 1802, the year of Trevithick's first patent. Realigning the dividing line by placing it 10 years earlier would have resulted in classifying almost all the patents obtained by Trevithick and Woolf in the second period hence weakening Nuvolari's argument. The second objection stems from the simplistic treatment of patent statistics by failing to point out that the regional distribution of such statistics reflects sectoral shifts overtime. Cornwall was throughout the entire period Nuvolari analyzes an economy lacking diversification hence, *ceteris paribus*, it would be expected to lag behind in this respect compared to other counties which succeeded overtime in hosting a multitude of industries. To use his own data and methodology, an example of the latter would be Lancashire with 5 patents in the first of his specified periods (0.04/annum) but 140 (3.5/annum) in the second.

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[61] According to McCloskey, the textile, iron, canal, railroad, agriculture, and shipping industries accounted for 54% of the increase in total factor productivity in the period 1780-1860 while Craft's relevant figure is 73%. Nevertheless, these industries accounted for only 37% of the patents issued in the period 1781-1850. The discrepancy is due to several factors such as the different contributions innovations make to productivity and the presence of sources of productivity growth other than patented activity. See Sullivan, "The revolution of ideas," pp. 360-1. Small, incremental innovations often are not the subject of patents and sometimes the same applies to inventions of more substantial economic significance such as the mule. Utterback, "The dynamics of product and process innovation in industry," p. 54; Griffiths, et al, "Inventive activity in the British textile industry," p. 884.

[62] An anonymous observer commented in the 1790s: "at present … it seems a fashion to take a patent for almost everything"; cited in Dutton, *The patent system*, p. 111.

[63] Of the patents awarded, Stuart provides insufficient or vague information for 57 of them and hence it is unclear what the invention actually aimed to achieve (e.g., "application of steam," "improvements in construction," "certain improvements"). Of the remainder, 42 of them related to the boiler, 40 to the furnace, fireplace, and the consumption of smoke, 26 referred to attempts towards fuel-economy (including claims of improved fuels and mixing coal with other substances or different kinds of coals), 25 referred to steam-wheels, 14 to valves and the regulation of steam/heat and heating fluids, 12 to new types of engines (e.g., two-cylinder compound, alcoholic-vapor engine, liquid-gas engine, air-engine, double atmospheric engine, engine without air-pump, rotary engine, revolving steam engine), 8 to pistons, 8 to the cylinder (including machinery for casting and boring them), 5 to a different arrangement of parts, 3 to the condenser, 3 to crank motion or alternative mechanisms, 2 to air-pumps, and one patent each to dispensing with the working beam, turning alternating to circular motion, and the cock. Stuart, *Historical and descriptive anecdotes*, pp. 633-50.

The final objection to the theory of collective invention pertains to the role it assigns to Lean's *Engine Reporter*. Did this publication function as a forum of information-sharing aiming at maximizing the aggregate performance of engines or was it simply a recording devise addressing the question whose engineer's design was the best? Nuvolari and his collaborators side with the former interpretation, a view also shared by Cardwell: "The publication of the *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 co-operative endeavor to raise the standards of all engines everywhere."[64] On the other hand, 19th century observers, like Ewing, assigned a narrower role to the reports as simply a way to focus attention on efficiency standards and prove what worked, and what did not, in an era the theory of the steam engine was not developed.[65] The latter view seems to conform better to common sense. There was a significant difference between Cornwall and other parts of the country when it comes to engineers' professional roles. Business people in the latter who wished to buy a steam engine would order directly from the manufacturer who acted both as the designer and the maker of the engine having to answer directly to the business owner. The actual management of the engine was entrusted to an engineer who had little interest in the economical functioning of the engine. In Cornwall, in contrast, the engineers had the responsibility of both designing the engines and managing them across multiple mines without the adventurers' involvement.[66] The greater authority given to Cornish engineers went along with more responsibility in terms of how well their engines worked thereby placing their reputations at stake. It follows there was an even sharper spirit of competition among them which could be mediated through the recording of their engines' performance but without necessarily divulging the secrets of their success.

To resolve the disagreement, all we need to do is to look at the precise information actually recorded by the Lean reports.[67] First, there was information that simply identified the engine such as the name of the mine it worked for as well as the time frame of the trial. There was also information that would have allowed an expert to approximately figure out the power of the engine such as cylinder diameter, length of the stroke, the load per square inch on the piston, and the number of strokes per minute, in addition to basic references to lifts and pumps. None of this information could be kept a secret due to the prospect of technical personnel moving to different jobs; nor was there any vital reason to keep it secret. Finally, the reports recorded information which was either directly relevant to an engine's performance (total consumption of coal, duty, and average quantity of water drawn per minute) or was useful to know in assessing performance such as the depth water was drawn from and whether it was drawn perpendicularly or diagonally.

What is notably absent from the Lean reports are references to all those practices pertinent to the daily management of the engines and the "micro-inventions" the literature has identified as having, cumulatively, a substantial effect on the improvement of duties and the reduction of fuel rates. Even Nuvolari and Verspagen admitted that the reports failed to include information on "important technical characteristics and operating procedures intimately linked with … performance improvements (for

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[64] Cardwell, *From Watt to Clausius*, p. 156; see also Nuvolari, "Collective invention," pp. 355-7.
[65] Ewing, *The steam engine*, p. 26.
[66] Between 1813 and 1830 Woolf was employed in no less than 31 mines, some of the stints overlapping. See Harris, *Arthur Woolf*, p. 109; also Pole, *Treatise*, pp. 160-1.
[67] For a sample of this information referring to all engines reported during 1814, 1821, 1828, 1835, and 1841 see Lean, *Historical statement*, pp. 13-30, 34-55, 63-92, 103-32, and Pole, *Treatise*, pp. 139-48.

example, steam pressure in boilers, rate of expansion, or cut-off point)" raising the question of why such information was excluded since the reports was one of the key vehicles of sharing information.[68]

In light of the objections raised, it is untenable to argue that inventive activity in Cornwall in the first half of the 19th century was not tied to the patent system. The latter was an imperfect instrument for the protection of property rights and one may even argue that certain engine models protected by patents may have slowed down the diffusion of high-pressure steam though certainly not to the extent the B & W patent did so.[69] Having said that, the author is also very keen to warn against a binary choice when it comes to the two competing viewpoints. A thorough review of the literature as well as Nuvolari and his collaborators' work referred to a number of micro-inventions which were not submitted for a patent. To provide just a partial list, they included Woolf's double-beat valve and cataract regulator, Hosking's water gauge, Groce's thermal lagging, and Hocking and Loam's "cylinder cushion." However, simply noting such list without a detailed discussion of the particular circumstances of the respective inventors that led them not to seek a patent, the sort of arrangements that would have allowed them to profit through a patent, or what was the technological impact of these inventions does not rise to the level of robust evidence to support the theory of collective invention. Historical details matter, the best illustration being Trevithick and the reason that led him not to seek a patent for the 1812 Wheal Prosper engine.

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[68] Nuvolari and Verspagen, "Technical choice, innovation, and British steam engineering," p. 691.
[69] This was the case because no patent held for Cornish engines was as strictly enforced as the patent of the Soho firm whose supply of engines consistently lagged behind their demand throughout the duration of its patent.

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