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The Development of Steam Power Technology: Cornwall and the compound engine, An Evolutionary Interpretation

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1. Introduction

In this paper, we offer a re-interpretation of the historical development of steam power technology in terms of the technological paradigm/trajectories approach. Traditional accounts of the history of the steam engine focus on innovations resulting in improved efficiency and in power increase, paying instead scant attention to the innovative activities emerging from the need of adapting steam power technology to quite different economic contexts. Consequently, traditional accounts tend to provide a rather ‘linear’ view of the development of this technology, which, in some cases, results in an unwarranted appreciation of some of the key episodes of the economic and technological history of the steam engine.

In the following, expanding on previous research by Nick Von Tunzelmann, we study the influence exerted by the different contexts of application on the pace and the direction of technical advances. We outline the specific sets of engineering heuristics guiding innovative activities in different application domains. Within each one of these application domains, stable sets of search heuristics emerged from the amalgamation of specific economic circumstances with the ‘internal logicö of the steam technology paradigm. This determined an uneven pace of technical advance among the applications sectors. Further, the space of technological opportunities was also explored following sector-specific directions. Thus, we see the long term development of steam power technology as a process of gradual formation of niches (each one pertaining to one or more steam power applications). In most niches, a dominant design was progressively established. However, over time, the exploitation of the dominant design could lead to expansion of existing niches to new domains causing an overall redefinition of the different niche boundaries. We first turn our attention to the situation in Cornwall. The second section describes the problems surrounding the introduction and use of Boulton and Watt engines in Cornwall, setting the stage for the development of what became known as the Cornish engine. In the third we focus mainly on the development of this Cornish engine, but we also pay attention to the Woolf engine. In the fourth section we analyse the development of the compound engine in the Netherlands between 1825 and 1850. In the concluding section, we consider the broader implications that our account has for the study of the role played by technical change in the early phase of the industrialization process.

2 Boulton & Watt in Cornwall

In the seventeenth and eighteenth centuries mining activities were severely limited by flooding problems. Not surprisingly, some of the first attempts of employing steam power were aimed at finding a workable technical solution to mine draining problems. In 1712, after a prolonged period of experimentation, Thomas Newcomen developed a steam pumping engine that could be effectively used for mine drainage. Using steam at only atmospheric pressure, the Newcomen engine was well within the limits of the engineering capabilities of the time. Moreover, the Newcomen engine was robust, reliable and its working principle was quite simple. Hence, once installed, the engine could work for a long period of time with almost negligible maintenance costs. Given these merits, Newcomen engines became soon of quite widespread use for mining activities and waterworks (Cardwell, 1994). Following Von Tunzelmann (1995, p. 106), we can say, that after Newcomen's invention, the steam engine established itself as the relevant technological paradigm in mine draining.

The Newcomen engine had a major shortcoming: its high fuel consumption, which was determined by the necessity of alternatively heating and cooling the cylinder at each operating cycle. In coal mining, where large supplies of 'cheap' coal were available, fuel consumption did not represent a tremendous limitation, but in other mining areas (notably in the copper and tin mines of Cornwall, where coal had to be imported from Wales by sea) fuel inefficiency did not permit a widespread diffusion of the engine (Von Tunzelmann, 1978, chap. 4).

Between Newcomen and Watt there were no dramatic changes in the design of steam engines. Nevertheless, a number of incremental improvements of the steam technology was achieved. Some of them were the result of the progressive perfecting of manufacturing methods of the various components of the engines. Other improvements were the result of a continuous investigation, mainly through a 'trial and error' process, on the design of a Newcomen engine. By means of a small model of an engine of which he systematically varied each component in turn, John Smeaton was finally able to individuate the best configuration of the different elements of the Newcomen engine raising significantly its performance (Cardwell, 1994) . Since the early diffusion of the Newcomen engine, fuel consumption was regarded as the main 'metric' to be used for evaluating the performance of a steam engine. The most common measure of the performance of a steam engine was called the 'duty' and it was calculated as the quantity of water (measured in lbs) raised 1 feet high per 1 bushel (84 lbs) of coal consumed. In 1772 Smeaton built a Newcomen engine with a duty of 9,450,000 (lbs), almost doubling the results previously attained (Hills, 1989, p.131).

From an engineering viewpoint, the duty provides an indication of the thermodynamic efficiency of a steam engine. However this measure has also an important economic meaning because it is a measure of the productivity of an engine with respect to the largest variable input in the 'production process' (Von Tunzelmann, 1970, pp.78-79) According to Dosi, technological trajectories are generated by the interplay between the 'autonomous' drift of technology (within the boundaries defined by the prevailing technological paradigm) and a particular set of inducement factors of economic type (e.g. relative factor prices). Economic inducement factors are likely to play a role in determining the specific direction of the technological trajectory when the paradigm is its emerging stage. Over time the heuristics get progressively established and technical advances become increasingly localized and irreversible. (Dosi, 1982 and 1988, especially pp. 1142-1145)

The adoption of the 'duty' as one of the main parameters for the evaluation of the performance provides a precious indication of the direction taken by innovative efforts. In terms of Dosi's paradigm/trajectory approach, we can say that a set of technological heuristics aimed at focusing the search for innovations in a fuel(coal)-saving direction were progressively established (Von Tunzelmann, 1995, pp. 14-15).

In 1769 James Watt took a patent for an alteration in the basic design of the engine (introduction of the separate condenser) that allowed for a drastic reduction in coal consumption. The Newcomen engine as improved by Smeaton was capable of a duty between 7 and 10 millions. Watt's pumping engine, in a first moment, raised the duty to 18 millions and later, when its design was fully established, to 26 millions (Hills, 1989, p.131). Such an economy of fuel made profitable the use of the steam engine in the mines situated in locations where coal was expensive. Consequently, the first important market for the engine developed by Watt was the Cornish copper and tin mining industry. Cornish mine 'adventurers' (in this way mine entrepreneurs were called) were keenly interested in technological improvements that could curtail their dear fuel bill. Boulton and Watt engines became immediately very popular in Cornwall. Between 1777 and 1801, Boulton and Watt erected 49 pumping engines in the mines of Cornwall. Jennifer Tann has described the crucial role of the 'Cornish business' for the fortunes of the two partners in these terms:

Whether the criterion is the number of engines, their size or the contribution to new capital, Cornish engines comprised a large proportion of Boulton & Watt's business during the late 1770s to mid 1780s. From 1777 to 1782, Cornish engines accounted for more than 40% of Boulton & Watt's total business and in some years the figure was significantly higher. In the early 1780s Cornish business was more fluctuating but with the exception of 1784, Cornish engines accounted for between 28% and 80% of Boulton & Watt's business (Tann, 1996, pp.29-30).

The typical agreement that Boulton & Watt stipulated with the mine adventurers of Cornwall was that they would have provided the drawings and supervised the works of erection of the engine. They would have also provided some particularly important parts of the engine (such as some of the valves). These expenditures would have been charged to the mine adventurer at their cost (i.e. not including any profit for Boulton & Watt). In addition the mine adventurer had to buy the other components of the engines not directly supplied by the two partners and to build the engine house. All this amounted to the total fixed cost associated with the adoption of a steam engine. (Von Tunzelmann, 1978, pp.51-52)

The profits for Boulton & Watt resulted from the royalties they charged for the use of their engine. Watt's invention was protected by the patent for the separate condenser he took in 1769, which an Act of Parliament had 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 to the Newcomen engine. This required a number of quite complicated calculations, amounting at identifying the hypothetical coal consumption of a Newcomen engine supplying the same power of that of the Watt engine installed in the mine.

At the beginning, this type of agreement was accepted in very favourable terms by the mine adventurers. However, after some time, the pricing policy of Boulton & Watt was perceived as extremely oppressive. There were several reasons for this. Firstly, winter months in which most water had to be pumped (and the highest premiums had to paid) were the ones in which mines were least productive. Secondly, mine adventurers knew the amount of the payments they owed to Boulton and Watt only after these had matured. Finally, in the late eighteenth century, several engineers in Cornwall had started to work at new improvements to the steam engine, but their attempts were frustrated by Boulton & Watt's refusal to license their invention. The most famous case in this respect was the one of Jonathan Hornblower who had developed the first compound steam engine in 1781 and who found the further perfecting of his invention heavily obstructed by the actions of Boulton & Watt.

Watt's patent resulted fairly broad in scope (covering all the engines making use of the separate condenser and all the engines using steam as 'working substance'). In other words, the patent was endowed with a very large blocking power. Boulton & Watt used the patent in a strategic way, enforcing an almost absolute control on the evolution of the steam technology (on patent strategies see Granstrand, 1999, pp.218-226). This strategy was motivated by the peculiar position of the company (consulting engineers decentralizing the major part of engine production). All in all, it seems quite clear that Watt's patent had a highly detrimental impact on the rate of innovation in steam technology (Kanefsky, 1978).

As time went by, some adventurers responded to the blocking patent by installing a number of 'pirate' engines erected by local Cornish engineers. In this way, they challenged explicitly the validity of Watt's patent. A lengthy legal dispute followed. The dispute ended in 1799 with the courts confirming the legal validity of Watt's patent and, in this way, attributing a complete victory to Boulton & Watt. The dispute had also other far-reaching consequences. Boulton and Watt, with their legal victory (pursued by them with relentless determination), alienated completely any sympathy towards them in Cornwall. After the expiration of Watt's patent in 1800, steam engines orders to Boulton and Watt in Cornish mines ceased completely and the two partners had to call their agent in the county back to Birmingham. However, it is also important to mention, that at this stage the market for manufacturing power had become the main focus of the company.

3 The Cornish engine versus the Woolf engine

Following the leave of Boulton and Watt, Cornish mining activities underwent a period of ‘slackness’, as the mine adventurers were content with the financial relief coming from the cessation of the premiums and they neglected the maintenance and the improvement of their engines. This situation lasted until 1811, when a group of mine ‘captains’ (the mine managers were termed in this way) decided to begin the publication of a monthly journal reporting the salient technical characteristics, the operating procedures and the performance of each engine. Their explicit intention was twofold. Firstly, the publication of the reports would have permitted the rapid individuation and diffusion of best-practice techniques. Secondly, it would have been introduced a climate of competition among the engineers entrusted with the different pumping engines, with favourable effects on the rate of technical progress.

Joel Lean, a highly respected mine captain, was appointed as the first ‘engine reporter’. The publication was called Lean’s Engine Reporter. After his death, the publication of the reports was continued by his sons and continued until 1904. In 1839 a synthesis of the first period of reporting, was published under request of the British Association for the Improvement of Science with the title of Historical Statement of the Improvements Made in the Duty Performed by the Steam Engines in Cornwall (Lean, 1839).

Concomitant with the beginning of the publication of Lean’s Engine Reporter, Richard Trevithick erected the first high pressure engine of the so-called ‘Cornish’ type. The Cornish engine was simply a Watt single-acting engine employing high-pressure steam. High-pressure and condensing action were combined in a carefully regulated operating cycle (‘Cornish cycle’). The engine had negligible costs of maintenance and it was susceptible of continuous improvements in its efficiency. The layout of the engine designed by Trevithick became soon the basic one for Cornish pumping engines.

In the following years the Cornish engine revealed itself as the highest accomplishment in steam technology (Von Tunzelmann, 1978, p. 263). Interestingly enough, Trevithick did not patent his high-pressure pumping engine:

“Trevithick only regarded this engine as small model designed to demonstrate what high-pressure steam could do. He claimed no patent rights for it: others were free to copy it if they would” (Rowe, 1953, p.124)

After the beginning of the publication of the Lean’s Engine Reporter, Cornish engineers, followed the example of Trevithick and normally preferred not to take patents for their inventions. Table 1 reports the patents granted to Cornish engineers over the period 1750-1852. (see Appendix table 1). If we take into account that over the same period, 873 patents for innovations in steam engines were granted (Sullivan 1990, p.355) - so that the Cornish contribution to the total is less than 2%! - and that Cornwall at that time was, without any doubt, the area with the most vital engineering community in this field, this fact is indeed striking. Motivated by the disappointing experience of the Boulton & Watt patent monopoly, Cornwall and Cornish engineers had adopted a collective invention regime Nuvolari (2001).

As a consequence of the publication of the engine reports and this widely perceived awareness of the benefits of the adoption of a collective invention regime on the rate of innovation, the thermodynamic efficiency of Cornish engines begun to improve steadily. On strictly engineering grounds, this amounted to a very effective exploration of the merits of the use of high-pressure steam. The improvement over time of the efficiency of the Cornish engines (as resulting by collating several sources) is displayed in figure 1. The figure clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical change. (See Appendix figure 1)
In the contemporary engineering literature, it is also possible to find passages that indicate a conscious awareness of the benefits emerging from a context of cooperative rivalry, in which the rate of innovation was not hostage of a supplier monopoly as it was in the Boulton & Watt era. For example, John Taylor (one leading mine entrepreneur), in 1830, wrote:

"Under such a system [the Lean's Reporter] there is every kind of proof that the application of steam has been improved, so as to very greatly economise fuel in Cornwall, and also that the rate of improvement has been fairly expressed by the printed reports.....[A]s since the time of Boulton and Watt, no one who has improved our engines has reaped pecuniary reward, it is at least fair, that they should have credit of their skill and exertion. We [adventurers] are not the partisans of any individual engineer or engine maker; we avail ourselves of the assistance of many; and the great scale upon which we have to experiment makes the result most interesting to us." (quoted in Farey, 1971, pp.251-252)

It is worth remarking another important feature of the process of technical change in Cornish engines. Over time, a typical design (single cylinder, high pressure, single acting engine, with plunger pump: this was design of the engine erected by Trevithick in 1812) emerged. Interestingly enough, however, alternative designs were never completely ruled out. For example, in different periods, some engineers (Arthur Woolf and James Sims) erected two-cylinders compound engines. Thus, the design of the Cornish engine always remained in what we might call a sort of fluid state and this probably facilitated a more thorough exploration of the space of technological opportunities, avoiding the risk of remaining trapped in a local optimum configuration (see Barton, 1969, for a detailed technological history of the Cornish Pumping engine).

In this context, the case of Arthur Woolf and his Woolf engine is very interesting. Woolf left Cornwall at an early and went to London. He spent some time at the small business of Joseph Bramah where he acquired a lot of knowledge of metal working, which proved to be very useful. After leaving Bramah his first job was to erect a second-hand Boulton and Watt engine (Harris, 1966, 23). Gradually establishing himself as an engineer, he was employed by Hornblower and Maberly for the construction of a steam engine at a brewery. By his connection to Hornblower he got involved in the legal process Boulton & Watt started against Hornblower. There were at least two important ideas developed by Woolf in the early years of the 19th century. This first was an improved boiler, that could safely produce high pressure steam. He obtained a patent on this in 1803. The second idea was an improvement in Trevithick simple high pressure steam engine. According to Harris:

Woolf realised that the waste steam from Trevithick's high-pressure non-condensing engine was still capable of doing useful work and he endeavoured to utilise this in a condensing engine after it had been employed in a high-pressure engine (Harris 1966, 35)

In 1804 Woolf obtained a patent on an engine incorporating this principle of compounding. In a Woolf engine, the steam at high pressure first drove the piston in a small cylinder, then at low pressure it was used for a second larger cylinder. The cylinders were placed side to side and connected at the same point of the beam on this double cylinder engine.[1] In the same year he started experimenting at the brewery where he was employed, first with a converted Boulton & Watt, later with an entirely new engine. Woolf encountered many problems and tests and comparisons with Boulton & Watt engines were at least inconclusive. He and his partner Edwards decided to move their business to Cornwall. The business was not successful and after a few years, Edwards left for France. Woolf also did not make much money from his patent on the double cylinder engine, but he became one of the most eminent engineers in Cornwall of that time. In Cornwall Woolf got several opportunities to build double cylinder engines, the first three for winding, later also a number for pumping water. The first pumping engine, at Wheal Abraham was the largest double-cylinder engine built to that time; it would work for almost nine years. The highest duty was 56 million in May 1816, a milestone at that time. Although in a first phase the Woolf engine seemed to outperform its rivals, soon he lost his advantage to his competitors. Woolf was not able to reproduce completely the success of his first engine. Other double cylinder engines did not meet the expectations or after a while they performance gradually

[1] Hills (1989), pp. 105-107. The compound engine was introduced in England only after 1845 when John Mc Naught positioned the high pressure cylinder at the other end of the beam (between the trunnion and the crankshaft). The practice of adding an high pressure cylinder to existing low pressure engines was called 'Mc Naughting'. See Dickinson (1938), p 106.

declined. The Woolf engine was soon overtaken by the single cylinder high-pressure engine.

The ‘controversy’ between the single cylinder engine of Cornish type developed by Trevithick and the Woolf compound engine was ‘resolved’ in 1824. John Taylor ordered Woolf to build two comparable engines to be used in a test. The Cornish engine achieved a duty of 42 millions, whereas the Woolf engine a duty of 40 millions. Although the performances were comparable, it was clear that investments in the more complicated and expensive Woolf engine were not recovered by an increased performance. Woolf himself reverted to the single cylinder engine and the Cornish engine as designed by Trevithick became the dominant type in Cornwall mines.[2] The idea of Woolf however was taken up in other places, as we will see in the next section.

The relative failure of the Woolf engine did not stop experiments with the lay out of steam engines. An example is the (limited) diffusion in Cornwall of the two-cylinder compound engine patented by James Sims in 1841. The first engine of this type erected at the Carn Brea mine performed very well in terms of duty (it was the second best engine in the Reporter in the early 1840s). However, being a patented design made it scarcely popular with other engineers and mine owners, who preferred not to pursue further that direction of exploration (Barton, 1969, pp.110-112).

4. Surprise: a niche for compound engines in the Netherlands

A Dutch company, the NSBM (the Dutch Steam Boat Company) founded in Rotterdam in 1824, built several compound engines between 1830 and 1845. These steam engines were almost exclusively used on riverboats. This proved to be a small but significant niche for compound engines. A few other companies also took up the production of compound engines, but there were direct links to the Rotterdam company. The development and construction of compound engines at the NSBM in turn was directly related to the Cornish community of steam engineers. In this paragraph we describe and analyse the introduction of compounding in the Netherlands with particular emphasis on the transfer of knowledge and technology from Cornwall. We also explain the factors, contributing to the initial success of this niche and the (relative) failure to diffuse to other markets. This section is mainly based on (Verbong, 1995).

In Dutch history the invention of the compound engine generally is attributed to G.M. Roentgen (1795-1852), a naval officer, who more or less by accident on a journey to the Dutch East Indies got stuck in Great Britain. He became interested in the possibilities of steam navigation. He succeeded in convincing the Dutch Admiralty to design a steamboat for passenger transport and

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[2] ‘[After the experiment]...Woolf devoted his talents to perfecting the Cornish engine and became the most prominent engineer in Cornwall; in 1828, of the sixty engines entered in the Monthly Reports, seventeen were under his care’ (Dickinson (1938), p.104).

went to England for a second time to supervise the construction of this boat. After his third visit he wrote a well-known memorandum on the usefulness of steam engines for the Navy (Roentgen, 1824). He soon quit - or was forced to quit - the Navy and became technical manager of a shipping-company in Rotterdam, the NSBM. Within a few years, the new company started to design and build steamboats. The engines were provided by John Cockerill of Seraing in Belgium (at that time part of the United Kingdom of the Netherlands, but soon Roentgen decided to start building steam engine in Rotterdam. He founded a machine factory and hired a young Cornish engineer, O.N. Harvey as technical director (Scholl 1978). He had met Harvey during his third visit in London in 1823 (or 1824). Harvey was a nephew of Henry Harvey, the proprietor of Hayle Foundry in Cornwall. The technical advisor of this foundry was Arthur Woolf. Harvey would stay at Rotterdam for five years. In 1828 his uncle Richard Trevithick, another famous Cornish steam engineer, visited the Dutch factory. Trevithick was impressed by the technical capabilities of the new company. In 1829 Harvey left together with part of the trained workforce for a job at the Gute Hoffnungshütte at Ruhrort, Germany, owned by Haniel. After a few years, he went back to Cornwall and became director of Hayle Foundry.

One of the first projects for the NSBM was to build a towing boat for towing naval ships in shallow water. Due to financial problems, the completion of this boat, the Hercules, took more than four years. According to his biographer, Roentgen had, while he was working on this project, a brilliant idea: he added a low-pressure engine to the high-pressure steam engine already installed. At that moment, the compound engine was invented. From a perspective of the hero-inventor, this romantic reconstruction maybe seems attractive but a careful reconstruction of the events at the NSBM factory in this period shows that there was no invention of the compound engine. The compound engines, built by the NSBM, were the result of a gradual development process, which took at least six or seven years. More-over, it is hardly plausible, as the involvement of the Cornish engineer Harvey suggests, to attribute this development completely to Roentgen. We will first give a short summary of the reconstruction of the steam engines and turn to the contextual factors and the influence of the Cornish connection.

Roentgen, pressed by the government to complete the Hercules, decided to skip the plan to build new engines for this tugboat. He removed a steam engine from another ship and used those on the Hercules. This high pressure engine had two cylinders. Roentgen wanted, as a rough drawing shows, to add two low-pressure engines in order to increase the power of the boat, one to each high-pressure cylinder. There was however no time (and money) to build these engines and Roentgen decided to dismantle another boat and to use only low-pressure engine. Before this project could be completed, the NSBM was forced to deliver the boat. The Hercules was used for towing naval ships at siege of Antwerp in 1830, after the Belgium secession. Only the high-pressure engines were used. When the hostilities ended (the war between Belgium and Holland lasted only a few weeks, but it would take the Dutch king nine years before he finally accepted the new status quo), the boat returned to wharf. Before the project could be completed, a few practical problems had to be solved. The capacity of the low-pressure engine was too small for expansion of the steam of boat high-pressure engines. To solve this, a cogwheel was introduced, that allowed the low-pressure engine to work at a much higher stroke rate. Another problem was that the steam did not leave the two high-pressure cylinders at the same. This was by design, because this increased the manoeuverability of the boat. As a consequence a reservoir was needed to keep the 'store' the steam temporally. A valve allowed the steam to escape in case only the high-pressure engines were used.

In a new project, the rebuilding of the James Watt, renamed as the Stad Keulen, Roentgen used the same concept of two high-pressure and one low-pressure engine, but because these were new engines, Roentgen was able to adjust the dimensions of the cylinders and the cog-wheel could be skipped. Again it took much more time to complete this boat than Roentgen had promised, but in 1835 he proudly announced to the shareholders of the company that the Stad Keulen was ready. He added that another company, the Gute Hoffnungshütte, also had taken up the production of engines according to his design. Despite the exodus of part of his workforce to Haniel, relations with the German company and Harvey had remained friendly. One or two years before, Roentgen realised that he could dispense of one of the high-pressure cylinders without compromising the manoeuverability of the boat. The condition was that the two remaining pistons did not move in phase. This was precisely the idea of using two engines on boats instead of one, as Roentgen pointed out in a French patent explanation in 1834. Roentgen argued that the system of Woolf was not suited for application on boats, because in that system, the pistons moved simultaneously. In order to achieve a regular movement and optimal manoeuverability two complete Woolf engines were needed. In Roentgen's system only one compounded engine was necessary. Compared to the conventional system with two separate engines, Roentgen's system was superior in fuel economy. He added further, that the idea of compounding was not limited to two cylinders, but one could also use expansion in three, four or even more cylinders. Although particularly useful for application on steam boats, the system of Roentgen could be used in factories too. The pistons did not necessarily have to be connected to the same driving shaft. The title of his French patent was 'Machine a vapeur expansive a cilindres independants et combine'. This shows Roentgen's perception of his own idea: he did not claim to have invented a new type of engine. His proposal to combine the different parts of steam engines in a variety of configurations, offered a new flexibility to steam technology. Most of these idea were of course well known, especially in Britain. His British patent application (1834) had the very modest title A certain improvement or certain improvements in steam engines.

The NSBM applied Roentgen's system on at least 25 boats, used on the Rhine, Elbe and Wolga and also a few engines were placed in factories. The Gute Hoffnungshütte and another Dutch company also built compounded engines for boats, but the total number did probably not exceed fifty. For most applications single high-pressure steam engine were preferred. The only application was on river boats, a relatively small niche. The diffusion of this type engine to seagoing vessels was severely limited, because it combined the use of relatively high pressure and a Watt type low pressure engine. In a Watt engine water is injected into the condenser, causing the steam to condense. This water is used again for producing steam in the boiler. Because of the large quantities of water needed (20-30 liters to condemns 1 kg steam), sea going ships could use no fresh water, but had to use sea water. Above a certain temperature (and pressure), kettle stone (fur) was formed in the boiler, deteriorating the performance of the boiler and in the worst case, destroying it completely. The critical temperature was 144 degrees C, corresponding with a pressure of about 4 atm. Around 1830 this was the maximum pressure used in Woolf engines (and probably also in the Roentgen engines).

The solution to this problem was the development of another type of condenser, the surface-condenser. In this condenser there was no direct contact between the steam and the cooling water. Already in the 1830s British engineers like I.K. Brunel obtained patents on surface condenser, but technical problems prevented a rapid introduction. The main problem was to seal the tubes, containing the steam, in order to prevent leakage. From the 1850s onwards, the compound engine made a comeback. Within twenty years compound engines became the standard type of engines on large ships. Increasing pressure led to the development of triple and quadruple compound engines. The supremacy of the compound engine would not last long. Around 1900 more powerful and efficient diesel engines started to replace compound engines.

At that time the compound engines from the earlier period were completely forgotten. An accidental discovery in 1889 of drawings of these engines led to new interest in the æprehistoryÆof the compound engine. The English engineer, David Croll, managing director of the NSBM, sent the drawings to The Engineer. This journal published a series of articles on those NSBM engines, establishing Roentgen as the inventor of the compound engine.[3] This was disputed by a son of Harvey in a letter to the journal. According to Harvey jr. Roentgens engine was only a slightly modified Woolf engine and more-over his father probably had been responsible for the development of the compound engine.

How does this development of the steam engine fit within the overall history of the steam engine and the Cornish engine in particular? Both in Cornwall and at NSBM the main heuristic in the

[3]Roentgen himself had never the idea that he invented a new engine, but from the perspective of late 19th century engineers, the main difference of the compound engine and the Woolf engine was the introduction of a receiver. Roentgen was forced to use a kind of reservoir because the dimension of the cylinders he used, did not match. He named this pipe a ‘refrigerator’, probably because in the early days the steam in this tube was used for preheating boiler-water. Gradually, he became aware of the importance of this part of the system. In his British patent application he used the term ‘intermediate reservoir’ and he described the option of allowing fresh steam in the reservoir or using the heat from exhaust gasses for overheating the steam.

search for an improved performance of the steam engine was increasing the pressure. The standard Boulton & Watt engine used only atmospheric pressure, but already in the 18th century engineers attempted to use higher pressures. Roentgen was well aware of this. In his 1824 memorandum, he presented a design for a tug with two Boulton & Watt engines, but he remarked that for the future the use of higher pressures could offer great advantages, especially for application on boats. His main arguments: high-pressure steam engines were cheaper, less heavy, needed less space and used less fuel. These were all very relevant aspects for the application on boats. According to Roentgen, the fuel economy was directly related to the pressure. This illustrates the importance of using higher pressures. Roentgen added that, unfortunately, only the Americans dared to take this logical step. 'Incompetence' was the cause of a few boiler explosions in England, which prevented the application of high pressure - one can add the dominant presence of Boulton & Watt- but this should not prevent the development of high pressure steam technology, which was inherently more safe than sail boats or carriages. It was clear that Roentgen opposed every legal measures banning the application of high-pressures. Despite being the main government advisor in the field of steam technology, he could not prevent a (temporary) prohibition of high-pressure engines on passenger boats in 1829. Well aware of the eminent prohibition he removed the two high-pressure engines for the completion for the Hercules from a passenger boat. Maybe he thought that he could outwit this prohibition be towing the passenger boat by a tug, powered by high-pressure engines. The position of Roentgen with respect to the use of high-pressure is clear. High-pressure engines had several advantages, some of them particularly relevant for application board.

The next question is why Roentgen started to use compounded engines. Although we have no concrete evidence, it is very likely that the Cornish connection played a major role in this. Roentgen may have visited a Woolf engine in England, but meeting and hiring Harvey provided Roentgen with the best possible access to the innovative work done by Woolf, Trevithick, Sims and others at that time in Cornwall. Besides, Woolf engines were built on the continent by a former business partner of Woolf, Edwards, and others already before 1820. The idea of compounding must have been discussed by Roentgen, Harvey and other, mainly English engineers at the NSBM factory. It is impossible to reconstruct the individual contributions of Roentgen, Harvey and others. But certainly, the specific context of steam navigation played an important role. Compounding in the original design for the Hercules was introduced to increase the power of the tug.

As we have described, this was the start of the development of the new compounded engine. The compounded engine offered several advantages compared to two separate engines: more compact, less weight and less fuel without compromising the manoeuverability of the boat. This last aspect was particularly important for tugs, but less important for regular navigation. Compounding was not the only alternative however. When Harvey left Rotterdam for Ruhrort, he started building Cornish engines, single cylinder high-pressure engines, not compounded engines. Cornish engines were at least equivalent to compound engines and less complicated. A Cornish engine for the Stadt Mainz failed to meet the expected performance, despite a careful preparation and detailed advice from Woolf and Trevithick. The construction of compound engines only started after Harvey had left in 1832. Another Dutch company that produced a few compound engines, was founded by a former chief engineer at the NSBM, Penny who changed his name to Penning.

5. Concluding remarks (preliminary)

The development of the Cornish engines can be seen as an alternative trajectory to the main-stream development of steam technology, symbolised by the Boulton & Watt engine. The main objective of the Cornish path was to increase fuel economy and the main heuristic was increasing the pressure used. The use of high-pressure was certainly not limited to Cornwall, but the very specific context in Cornwall produced an innovative community, that produced a highly effective engine, the Cornish engine. As we have seen the definition of the Cornish engine was more or less fluid, allowing the continuous generation of new varieties of configurations.

One of these variations, which can at least partly been ascribed to the Cornish context, was the compound engine. Although it produced certainly better than the Boulton & Watt, it could not compete with the single cylinder Cornish engine. As thermodynamic studies later showed, the principle of compounding becomes interesting with pressures higher than 4 atm, but this was exactly the maximum pressure used in the 'decisive' experiment in 1822! A few years later, the result of such an experiment could have been reversed. The Roentgen compound engines enjoyed some success, but only in a fairly small and limited market. Within this niche it probably was a competitive engine, although no direct comparisons were available. The breakthrough to other markets did not occur, because of serious technical barrier (passenger boats) or the reluctance to use high-pressure in general (Navy).

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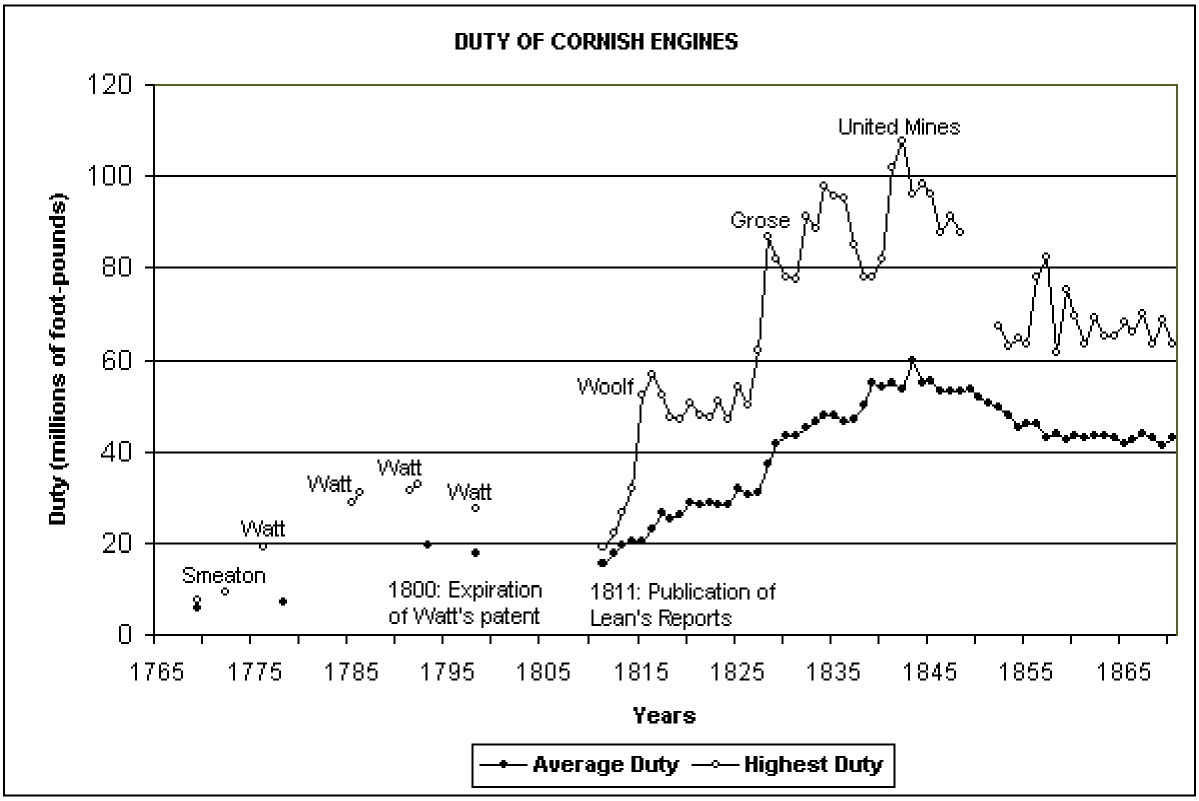
Appendix

Figure 1: Duty of Cornish Engines



Sources: Lean (1839), Pole (1844), Dickinson and Jenkins (1927), Barton(1969)

Table 1: Cornish Steam Engine Patents (source: Woodcroft (1857))

Cornish steam engine patents		
Number	**Date**	**Patentee**
1298	July 13, 1781	J. Hornblower
2243	June 8, 1798	J. Hornblower
2599	March 24, 1802	R. Trevithick & A. Vivian
2726	July 29, 1803	A. Woolf
2772	June 7, 1804	A. Woolf
2832	March 26, 1805	J. Hornblower
2863	July 2, 1805	A. Woolf
3346	June 9, 1810	A. Woolf
3922	June 6, 1815	R. Trevithick
6082	February 21, 1831	R. Trevithick
6308	September 22, 1832	R. Trevithick
8942	April 29, 1841	J. Sims
10201	May 23, 1844	J. Taylor
11859	September 9, 1847	J. Sims