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# Empiricism Afloat -Testing Steamboat Efficacy; Boulton Watt & Co 1804-1830[1]

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In October 1817 a motley crew assembled in the Thames Estuary to conduct a series of steamboat trails on a voyage across the English Channel to Rotterdam and thence up the River Rhine. The crew comprised a pilot whose knowledge of the Dutch coastline was acquired through a previous career in smuggling; an engineman who succumbed to the delights of Dutch gin; an engineer/mate whose continuous stoking of the boilers for 30 hours on the return journey resulted in his ankles swelling to the extent that he could not stand; and nine others, led by a former Navy captain and James Watt Jr (son of James Watt, the Birmingham engineer). Watt Jr's optimism for the venture was bolstered by anticipation of a superior performance by Boulton Watt & Co's (BW&Co) marine engines under extended trial, coupled with an unrivalled opportunity for marketing in mainland Europe. This, however, was tempered by anxiety about how his (occasionally peppery) father would react, with the result that Watt JJr took the easy way out and did not inform the elderly James Watt until they reached Rotterdam.[2]

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[2] The voyage took place two years before James Watt senior's death, Matthew Boulton having died eight years previously in 1809. The engine manufacturing firm of Boulton & Watt had formally been transferred to the ownership and management of the founders' sons, James Watt Jr and Matthew Robinson Boulton, on the opening of Soho Foundry in 1796, and by 1817 Matthew Robinson Boulton was playing a relatively small part in the business and none at all in the marine engineering side (Roll, 1930).

Technological innovation in marine engineering in the early nineteenth century involved the transfer of steam engines designed for land use to marine use, which led to the designing of engines specifically for ships. Sailing ship technology had developed over hundreds of years and a large body of tacit knowledge concerning the installation and operation of sails had accumulated.[3] Not only was the steam engine untried aboard a boat, but a new means of propulsion – initially the paddle wheel - was required. There was no obvious body of experiential learning to assist engineers in what amounted to a leap of faith. Moreover, shipbuilding and steam engine manufacture were distinct and unrelated activities, the latter not necessarily located at major ports, whereas sail making, rope making and the import of timber for masts were activities often located at ports near to shipyards. This exacerbated difficulties of specification for engineer and customer alike. Compared with steam engines on land, engines in boats raised new questions of effectiveness, fitness for purpose, safety, problems concerning the use of salt water in boilers, and the need to carry fuel. Moreover, performance measurement was greatly hindered by the number of external variables and the difficulty of isolating them. Nonetheless, testing was necessary for, without it, improvements to the technology were likely to be hit and miss and engineers would have had little evidence on which to compete in the market.

The steam engine had been subject to testing from at least the mid eighteenth century. James Brindley is known to have conducted tests on the Newcomen engine, while John Smeaton took engine testing to a new level of precision (Robinson & Musson, 1969; Smeaton, 1812). James Watt was first interested in the Savery engine, he then conducted experiments on a model Newcomen engine (and later on a model

[3] Sailing ship technology, as is well known, continued to be developed until the end of the nineteenth century (Harley, 1971; Hunter, 1993, 100). American engineers continued to develop wooden sailing ships for ocean travel, the most notable being the clippers (Hindle & Lubar, 1986,116-117).

of his own engine- (Robinson & Musson,1969); he experimented on the properties of steam (Robinson & McKie,1970) as well as undertaking much practical testing on full-size engines in the field, first on Newcomen engines in Scotland and, later, on his own engine, after the commencement of his partnership with Matthew Boulton. Watt acknowledged that 'experimental Knowledge is slow Growth' and that, as an instrument maker, he had no experience of 'engineering in the vulgar manner.' Watt considered himself a natural philosopher first and an engineer second. Nonetheless, while perhaps more at home in the laboratory, he 'went down the shaft and like any of the workmen changed the buckets of the pumps', and in Cornwall he worked alongside the engine erectors to remedy the defects in his early engines (Robinson & Musson, 1969).

Moreover, it was by experiment that Boulton & Watt (B & W) and their customers calculated the machine: horsepower ratios for different industrial sectors.[4] Prior to building the great steam corn mill (Albion Mill) in London, B & W constructed an experimental corn mill at their Birmingham works in order to ascertain the horsepower required to turn a pair of millstones. They gathered a group of faithful and skilled engineers who participated in works- and customer-based experiments and tests (Roll,1930; Tann, 1972). There was, thus, a body of both practical and theoretical knowledge of the stationary steam engine by the early nineteenth century. A key question concerns how much of it was transferable to the marine engine.

In this paper we explore the testing of BW & Co's marine engines *in situ*,

[4] For example, Richard Arkwright demonstrated the hp to spindle ratio for the water frame; G.A.Lee experimented on power for spinning mules; Whitbread demonstrated the power to machine ratio in several brewery functions eg malt milling (Tann, 1972).

afloat, at a pivotal stage in their development in Europe. We address the issue of externalities in steamboat trials, including the identity of the testing agency (individual versus institutional and, if the former, whether of demonstrated/proven competence) and the extent to which modalities - namely features of the context within which the test or trial was performed - were dropped; we discuss internalities, in particular the numerous performance variables, and the concepts of standardisation and interchangability between engines of the same horsepower by the same and different manufacturers; we consider what constituted precision in steamboat testing and the extent to which validity was demonstrated in the formative period of steamboat development, when the trajectory for coastal shipping was evolving.

Without the vast rivers and lakes of North America, where the predominant use of steam vessels was passenger transport (Flexner,c.1978), the case for steamboats in Europe was made on a comparative use basis –for packet boats in coastal waters, river estuaries and larger rivers and also for port-based tugs and Channel-crossing packets. BW & Co, while not the first to develop marine engines (Fletcher, 1910; Hunter, 1949; Spratt, 1958 Williamson,1904), took a major initiative in buying a ship specifically for the purpose of conducting steamboat trials.

## Technology testing

Historians and philosophers of science have problematized experimentation in the relatively controlled conditions of a laboratory (Collins, 1985; Shapin & Schaffer, 1989) but in the technical world of the workshop, factory or field it was even more of an imprecise art. Machinery was often large and cumbersome and frequently assembled at the user’s site, making it particularly difficult to control for externalities

(Linqvist, 1990).[5] Observation and measurement, nevertheless, began to be applied to technology during the eighteenth century, the techniques being borrowed from experimental natural philosophy; members of the Lunar Society of Birmingham were amongst the most articulate on the subject of technology experiments (Schofield, 1963). It was common practice for machinery to be tested initially on a scale model. This reduced the difficulties of controlling for external factors (eg wind speed/direction in the case of windmills, or river bed profiles/currents in the case of waterwheels), and internalities such as differently sourced engine parts and engine maintenance in the case of steam engines (Musson & Robinson,1969; Tann,1974), but subsequent scaling-up was not without its problems and testing on scale models did not appear to be a satisfactory predictor of problems encountered in the field in the early 19th century (*ibid*), let alone at sea.

The laboratory in the field 'demanded a much larger spatial and temporal dimension than the (indoor) laboratory; it was beyond the means of individuals to embrace the technical reality in time and space' (Linqvist, 1990). Cardwell (1972) identifies 1790-1825 as a turning point in the course of technological history with the emergence of institutions, such as military academies, arsenals, dockyards, mining, and major civil engineering projects (for example, canals) in which the application of quantitative methods to technology could be controlled.  Wise (1995, 6-9) distinguishes between precision and accuracy, asserting that precision needs to be established as a matter of credibility and trust. Precision  requires agreement about standards of comparison and is more than merely the product of an individual using a carefully constructed

[5] Stationary engines, for example, were transported in sections to the customer and, until the opening of Soho Foundry in 1796, Boulton Watt & Co (as the firm was known from that date) subcontracted the majority of engine parts to a range of specialist founders and fabricators. Even after 1796 some engine parts were subcontracted (Tann, 1978;  Roll, 1930).

instrument (accuracy), for successive measurements should yield very nearly the same result . Precision, besides being concerned with measurement, machinery and mathematics, is also a cultural value, a form of knowledge sanctioned by community norms (Porter, 1995, 191). In the late eighteenth and early nineteenth centuries, when technologies were largely developed by trial and error, with the science following the technology rather than the reverse, learning from tests and trials was similarly inductive. While classification existed, there was an absence of standardisation for certain measures, such as distance at sea (Bowker & Star, 2000, 10-11; Sharp, 1999, 5-9) and measures of volume such as bushels.[6] This further impeded meaningful technology trials, prompting questions of reliability and challenges to the reputation of engineers by peer competitors, governments and customers. Any field test or trial was open to challenge, just as any laboratory experiment was, and particularly at sea. Indeed, more so.

As Mackenzie (1989, 412-417; 1996, 1-8) points out, the validity of experimental procedures can be variously challenged and, since successful experiment or test requires a variety of procedures, each one can be subject to interrogation; 'the only way of knowing whether an experiment has been competently performed is to know whether it produces the right result'. But what was the right result? If the result was contested, the procedures and instruments employed were likely to be subject to scrutiny. Moreover, one of the easier ways of calling techniques into question was to criticise the capabilities of the performers. Where techniques involved tacit, rather than explicit, knowledge the procedures were judged by whether the tests/trials met

[6] The bushel, a measure of volume for grain, was a measure of different capacity in different parts of Britain. The Winchester bushel was gradually adopted as the standard in the late eighteenth century and was used by B & W who took care to insert the prefix 'Winchester' in specifying corn mill engine capacity.

the expectations of those conducting them and, secondly, whether they were accepted by a wider peer group. The written account of a technology trial was a powerful (and not necessarily unbiased) weapon with which to seek to persuade individuals, partnerships, companies or government departments of the benefits to be derived from purchasing a particular technology (Mackenzie, 1989, 412-17).

Mackenzie (*ibid*) draws attention to the issue of selectively dropping 'modalities' in order to demonstrate acceptable testing. By this means acceptable levels of validity and reliability may be achieved, allowing the comparison of results. Typical modalities which could be removed or altered include the individuals performing the test, as well as the context of time, place and circumstances (eg weather conditions) when the test was undertaken. These modalities are external to the technology being tested and beg the question regarding standardisation of a single manufacturer's machines/engines of similar size/power,[7] let alone machines/engines of similar size/power of different provenances. Lindqvist (1990, 291-314) draws attention to control as a distinguishing feature of effective technology experimentation, suggesting four means by which technology testing in 'the laboratory in the field' could be more effectively controlled, although he provides no empirical evidence for these practices. First, 'institutional' rather than individually conducted tests; second, greater rationality/objectivity; third, power to control the physical and social environment (modalities) in the field; and fourth, authority based on competence. If tests of marine engines were, indeed, undertaken in ways identified by Lindqvist, the results might have been accepted by engineers and their customers, even in situations where

[7] While BW & Co recognised the advantages of standardisation of engine parts (greatly assisted by Abraham Storey who joined Soho Foundry from John Wilkinson's Bersham Foundry), this was not fully achieved until well into the nineteenth century.

modalities were dropped. At all events, as with steam engine tests on land, the emergence of a new body of knowledge would underpin incremental innovation.

<u>Early British marine engineers</u>

The key stages in the development of steam navigation are well known. So, too, are the contributions of some of the key players (Hunter, 1949, 121-80; Spratt, 1958, 17-116). The entry route to marine engineering was largely via the manufacture of stationary land engines, although only a minority of land engine manufacturers diversified in this way. Fenton, Murray & Wood of Leeds, Butterley Co of Derbyshire and some of the Clydeside steam engineering firms were early on the scene (Riden, 1973, 42, 74, 145; Williamson, 1987, 1-43). But two manufacturers of land engines, Maudslay Sons & Field and BW & Co, were the leading marine engineers of the 1820s and 1830s, and by the mid nineteenth century marine engines were the prime focus of Maudslay's (but not BW & Co's) business (Cantrell & Cookson, 2000, 171; Petree, 1956). Both firms were initially technological followers, in the sense that steam navigation had been successfully demonstrated by others before either firm seriously entered the market; both, however, developed significant innovations in marine engineering (Macleod et.al, 2000, 311-12).

BW & Co manufactured their first engine for marine use in 1804, the customer being Robert Fulton who specified the need but did not materially contribute to the engine design, a bell crank engine being supplied (B&W MSS, Order Bk; Flexner, c.1978).
B W & Co, did not, apparently, perceive the marine engine market to be a potentially fruitful one until Fulton ordered a second engine in 1811. From then on, marine

engineering trajectories in North America and Europe diverged. The American steam boat market was far larger and, by 1820, steam had become the accepted solution for inland navigation (Hunter, 1949 61-112;  Lardner, 1840, 487). The inland waterways provided relatively smooth, calm conditions and fresh, rather than salt, water for boilers, which permitted longer and lighter vessels to be constructed. In Europe, on the other hand, rivers were shorter and narrower and the market for steamboats was mainly for estuary and coastal navigation and for limited ocean voyages. Vessels designed for these conditions were smaller and relatively weightier.

BW & Co's third steamboat engine was for John Molson, the Canadian brewer. In 1814 the firm received its first UK order (two 4hp engines for the *New Clyde Steam Boat Co*), and in 1815 its first Navy Board order for a marine engine; thereafter, the firm devoted increasing attention and resources to marine engine technology (Macleod et.al, 2000, 313-1; B&W MSS, Order Books).  BW & Co installed a pair of small beam engines in the *Princess Charlotte* in 1814, but it was not until 1817 that they moved almost wholly to the installation of  twin-engines (B&W MSS, Order Books). Besides greater efficiency and balance, paired engines provided security in the event of an engine failing. By the end of 1823, BW & Co had provided 69 engines for 44 vessels, the majority of vessels having a pair of engines, rather than a single one (ibid).

Henry Maudslay's entry to the marine engine market was almost certainly assisted by the arrival of his partner Joshua Field who had served an engineering apprenticeship at HM Dockyards – Maudslay, having provided machinery for Portsmouth and Woolwich dockyards, and probably others, besides being granted a patent (together with Robert Dickinson) for a method of purifying ship drinking water (Cantrell & Cookson, 2002, 14). Maudslay's first marine engine was for the River Thames-based *Richmond*. This was followed by an engine for a coastal vessel plying between London and Margate. Three overseas orders followed in 1817, one being for a 100 hp engine for a 500 ton Canadian river vessel, a boat engine size not reached by BW & Co for another decade. Until 1822 all Maudslay's engines were for river navigations or coastal waters (Petree, 1956).

There were strong challenges, however, from David Napier of Glasgow and Butterley Co of Derbyshire, as well as Seaward of London, while other provincial marine engineers such as Fawcett of Liverpool and Cook of Glasgow contended for coastal steam navigation business (Liverpool Maritime Museum Fawcett Order Books; Napier, 1912; Williamson, 1904, 24-43).[8] It was in this context that marine engineers increasingly focused on comparative steamship performance. Watt JrJr in 1817 for example, instructed an employee to 'take any trip you think likely to add to our knowledge of the vessels and engine(s)' from the port of Liverpool (B&W MSS, Watt Jr to W Creighton, 1817).

Of the engineers and mechanics who had contributed to the development of the Boulton & Watt low-pressure condensing (land) engine in the late 18$^{th}$ and early 19$^{th}$ centuries,[9] only the Creighton brothers translated their skills from land to marine engines. By the early 19$^{th}$ century William Creighton was head of the drawing and

[8] 'There is not a slip for building vacant in Liverpool and Fawcett's hands are more than full' (B&W MSS, Robert O'Brien to Watt Jr. 23 Nov 1824).

[9] Three skilled engineers all achieved promotion and some share in the business in the early nineteenth century, either (in Lawson's case) commission on sales or, in Southern and Murdoch's cases, a share in profits. James Lawson left the firm in 1811 to become engineer at the Royal Mint, John Southern died in 1815 and William Murdoch continued with BW & Co until 1830 (Roll, 262-263).

designing office at BW & Co's Soho works in Birmingham, while his brother Henry, at first an engineering representative in Scotland, was by 1815 based in Manchester (Tann, 1998, 47-72). Despite his inland work base, Henry Creighton paid a great deal of attention to calculating optimal steam vessel designs. He had become a shareholder in two steam vessels by 1813, advising his brother to do likewise: 'verily verily there hath been done nothing but steam boat scheming these last two months' (Houldsworth MSS, HC to WC, 21 July & 17 Aug 1813 ).

## Marine engine technology

A key issue for marine engineers in the early nineteenth century was that boat building and engine manufacture were distinct and, sometimes, geographically separate activities. It was due to this that landlocked engineering companies, such as BW & Co and Butterley Co, could compete for a while with engineering companies located on river estuaries, such as Maudsley Sons & Field on the Thames, and Fawcett on the Mersey. The early applications of steam power to drive boats involved the direct transfer of a single land beam engine to the vessel as, for example, for the Tyne Steam Packet Co's *Eagle,* and *The Congo*, BW & Co's first and unsuccessful venture with the Royal Navy. This latter vessel drew too much water (Watt Jr blaming the shipwrights), resulting in the boat's inability to move against the current, despite its powerful engine.[10] Proving to be unseaworthy, the vessel was converted to sail.

The development of the marine engine illustrates the dysfunctions that may arise from the direct transfer of an unmodified technology, developed for one application, to another. It also highlights the significance of incremental innovation underpinned by

[10] Naval historians have been less generous, pointing out that the engine was far too heavy.

‘trial and error’ as well as managed trials. The transfer of unmodified land engine technology to a boat proved largely unsuccessful for a number of reasons. First, the beam engine was insufficiently compact and stood too high in the vessel, contributing to instability, particularly in rough weather, besides making passage under river bridges hazardous. Moreover, at sea an engine above the waterline was vulnerable to attack in wartime. The traditional beam engine was, therefore, rapidly abandoned for marine use. Instead, a short-lived experiment with the bell crank engine took place, Henry Creighton, the B W& Co engineer, playing a significant role in its design. This was a small, more compact engine, also developed for land use, in which the beam moved sideways rather than up and down, thus allowing for some reduction in height and contributing to greater stability. Only two vessels were fitted with bell crank engines, one being Robert Fulton’s 1804 boat and the other a boat ordered by J. B. Humphreys, a British merchant who ‘hath got all the German rivers which run northward at his command’. Henry Creighton described to his brother William, how he had sent ‘a very learned 2 page close written dispatch illustrated by divers pretty sketches’ to Humphreys and receiving in reply ‘great applause’ (B&W MSS, Order Bks; Houldsworth MSS, HC to WC,14 Dec 1815). The bell crank was identified by Creighton as his ‘last scheme’ which ‘comes in exactly and good enough for Prussians –no fixture high up and passing Bridge; stop engine at bottom of stroke so that crossbar is below deck or down upon it at all events’ (Houldswoth MSS, HC to WC, 14 Dec 1815). The boiler chimney, too, could be lowered. Reference was made by Creighton to the possibility of an experimental boat being built on the Thames; and he reflected that, as the bell crank design ‘with long-linked motion’ could not ‘be avoided… in such situations, the question is how to make the best of them’(ibid, HC to WC 22 Dec 1815). However, Watt Jr did not favour the bell crank and it is likely to have been for this reason, besides the fact that it was only suitable for small vessels, that effort was put into the development of the side lever engine which rapidly superseded the bell crank. As Watt JrJr remarked ‘I was once a friend to bell cranks but have since grown wiser’ (ibid, HC to WC 24 Dec 1815).

Tredgold (Macleod et al. 2000, 315) suggests that the side lever engine, a modified inverted beam engine, was developed by BW & Co, and it is possible that the person responsible was William Creighton who, by January 1816 ‘hath got engine into so small a height it is of course quite unnecessary to think about bell cranks’ (Houldsworth MSS, HC to WC 4 Jan 1816). It was Creighton’s view that pairs of marine engines should be confined to two sizes, namely 14hp and 20 hp, the reason given being that ‘it is very desirable in most cases to keep below deck and as 3 ft stroke even will hardly do this in a moderately large vessel’ (ibid). A further reason would have been the economy of interchangeable parts for a small portfolio of marine engine sizes. Within a very few years closure had been achieved on the side lever engine on the grounds of compactness, greater stability in the vessel and effective connection to the paddle shaft. The side lever engine also became the mainstay of Maudslay Sons & Field’s early marine engine business.

Until the adoption of screw propulsion, all steam vessels were propelled by paddle wheels. The key design issues were paddle wheel diameter and width, the number and dip of blades, how far they were submerged, and the means of disengaging them rapidly in order that the wheels could ‘freewheel’, thus preventing them from acting as a brake. Major marine engineers designed and manufactured paddle wheels, devoting considerable effort to their improvement; Henry Creighton undertook a series of experiments between 1815 and 1818. ‘It would be a grand convenience’ he wrote, ‘if paddles could be raised or lowered while the engine is at work’ (Houldsworth MSS HC to WC, 17 Feb 1816, 9 March 1816, 4 March 1818). His brother volunteered: ‘the best surface for boat paddles will of course be that which has most resistance.’ He added ‘ought not Rees (author of Cylopaedia) (to) have had experiments on resistance?’ (ibid, WC to HC 24 Dec 1815). This provoked Henry Creighton to set out some alternatives (ibid, HC to WC Jan 1816):

> Some folks have imagined that setting the paddles oblique a little to throw or direct water away from stern, others the exact reverse considering it a benefit – now which is best, or is there any advantage over a flat one?

In January 1816 Henry Creighton speculated, ‘I guess…there is a huge waste of power from making paddles thin’, and in March he reported from empirical observation (ibid, HC to WC 9 March 1816):

> (I) hath been 9 hours this day hatching curves shewing routes of paddles… and suspecteth 16 ½ to be the best dip for paddle wheel 10.2 diam going 27 turns…as that part of the paddle which just touches water…gives something considerably like a whack – at all events the water does not get much into motion – suspect there is no advantage in not making paddles point to centre.

Henry Creighton discussed the matter with Peter Ewart, Lancashire engineer and friend of Watt Jr, reporting that ‘the power lost in kicking water back depends upon velocity of paddles…(he) made a table in which theory and fact agree wonderfully’.[11]

[11] Creighton transcribed the table and beneath it states:
‘This table is founded upon Col Beaufoy’s Expts –he found that a vessel having one sq foot of section, & shaped as a well formed vessel, required a force of abt 40llbs to move it 8 miles pr hour/the weight

Steam Boat trials

The measurement of a steamship's speed during the first two to three decades of the 19th century was no different from the method employed during the era of total sail. The method of calculation was crude, consisting of the log, line and glass timer. The log, a piece of wood, weighted with the intention that it remain stationary whilst floating, was connected to a knotted line which was fed out overboard and the speed calculated by the number of knots fed out in a given time, as measured by an hour glass. Variously said to have been in use since 1570 and 1607, it was in general use in the early to mid 19$^{th}$ century (Sharp, 1999, 5-17.[12] Smeaton (1814, 21) pointed out the difficulty of ascertaining the effect of currents on a mechanism designed to measure a ship's speed, adding that 'such a contrivance…even if brought to perfection, was likely to be received (with indifference) by seamen; who, in general, do not seem over fond of making trial of new instruments, especially if proposed by landmen, as, in derision, they are pleased to call us.'

A vessel for the Cork Steam Boat Co, powered by BW & Co engines, was estimated to have travelled 'by log 6 1/5 to 6 ¾  miles per hour= 7 ½  English' (Houldsworth MSS, HC to WC 1815). Leaving aside speculations about the difference between English and Irish logs, the system was, to say the least, imprecise.  There were discrepancies in the length of line used, the possibility that 'a great sea from the stern…will bring home the log' (it would overtake the vessel) (Encyclopaedia Britannica, 1771, 111) leading to an under-indication of speed by as much as 10%, or the hour glass could be inaccurate (Sharp, 1999).  While variants had been patented in

moving thro the same space -& the resistance being as the square of the velocy –the constant power reqd to overcome that resistance is as the cube  - or as v2v=03'  .(ibid, WC to HC 27 May 1817).

[12] The same methods could be found in the early twentieth century (Sharp, 1999).

the 18th century, and experiments were undertaken at British dockyards in the early 19th century, the alleged improvements were 'subject to other inconveniences which will not render them a proper substitute for the common log' (*ibid*). Where measurement of a ship's speed was undertaken within sight of land, on a river or estuary, the speed of the vessel was measured by the time taken to pass a measured distance indicated by visible markers on the land; hence the term 'measured mile'.

There was no generally accepted mathematical principle in use to determine the velocity of a ship. Nevertheless Henry Creighton, informed by Beaufoy's unpublished work, articulated a general principle. 'Reckoning_the supposition of resistance being as the square' he calculated that a common canal boat of 8 ft width, drawing 2 ft or so of water, could be drawn by two horses at about 4 mph 'being what is done every day and agreeing with fact' (Houldsworth MSS, HC to WC 10 Jan 1816). Seventeen years later John Farey (1833, 111) asserted that 'a general rule is greatly wanted…. notwithstanding the great experience which has been acquired in constructing steam vessels, few engineers possess any rule for determining, *a priori*, what will be the speed of a new vessel'. Farey claimed that he had 'kept the subject in view from the first establishment of steam vessels', stating that almost all experiments 'shew that the resistance increases as the square of the velocity'. This became Farey's first proposition. His second was that 'the exertion of mechanical power, or forcible motion, must progress according to the cube of the velocities' (*ibid*). Farey is likely to have known of Beaufoy's experiments conducted at Greenland Dock in 1793-8, but only published in 1834 (ODNB, 'Mark Beaufoy'). By this time, the size of vessels had considerably increased, but Farey posited that, in regard to the first assertion, larger vessels 'all concur in very nearly the same result';

and with respect to the second assertion, 'it will be found to give results which approximate to the actual performance of steam vessels in common use.' Farey's short communication provided six practical examples of vessels large and small, older and newer, which empirically demonstrated 'that the rate applies to cases where the difference of speed is very considerable'(Farey, 1833, 112).

Inland engine manufacturers were not unduly disadvantaged in the emergent period of steam navigation. The dominance of BW & Co in the early period of marine engineering was founded, in large measure, on their established position as steam engine manufacturers achieved during the extended period of Watt's patent, 1775-1800. But the separation of marine engineering and boatbuilding contributed to the difficulties of conducting experiments and trials. An engine might perform well in a works-based test but less well upon installation in a vessel. Once the engine was installed, tests could only be carried out with the acquiescence of the owners. And, if permitted at all, the time allowed was likely to be short. Henry Creighton, for example, conducted some trials on B W & Co engines installed in a boat on the River Tyne in 1816 and 1817. B W & Co's request for further trials was, not unexpectedly, thought to be unreasonable: 'The experiments would take a week – Tyne Co, blackguards and scoundrels as they are, were in the right to grumble at (our) using their boat for experiments and with sufficient cause too' (Houldsworth MSS, HC to WC, 23 Jan 1817). The contingent nature of this development period of steam boat and marine engine design prompted Henry Creighton to comment ironically in 1818: 'there never was a steamboat yet but would have done well if…[sic]' (ibid, HC to WC7 Jan 1818).

B W & Co's first trials of steamboat speed were conducted on the St Lawrence River by the Candian brewer, Molson, probably measuring time against distance between marked miles on the riverbank. Molson's vessel was found to travel 8.2 mph downstream and 3.6 mph upstream. On a second trial the vessel went 9 mph downstream and 5.3 mph upstream, a mean speed of 7.15 mph. Molson, apparently, claimed that the boat had gone downstream at 10.6 mph and 4.75 mph upstream, a result greeted with some scepticism by Henry Creighton at B W & Co (Houldsworth MSS, HC to WC, 10 Jan 1816, 9 March 1816). A similar method was used to calculate the mean speed of *Eagle*, owned by the Tyne Steam Packet Co (ibid., HC to WC, 9 March 1816 ). Whereas river trials had to contend with the current, estuary and sea trials additionally encountered tides, besides being more exposed to winds. At sea, unless a trial took place sufficiently close to shore for marked miles to be observed, recourse was had to the log. In one sea trial *Caledonia* was estimated to be travelling at 8.15 mph with the tide and 4.75 mph against it. Watt Jr was critical of the log but offered no alternative (B&W MSS, Watt Jr to WC, 1817). Of two Scottish vessels, *Argyle* and *Rothesay Castle,* the former was claimed to have achieved 7 mph and the latter 7.8 mph but, as Henry Creighton commented in 1817, 'they may have and doubtless do this <u>with the tide</u> & sometimes more as they will go to Greenock for 21 miles, sometimes in less than 3 hours…(but) I do not believe any boat has ever exceeded <u>6 mph</u>' (his underlining; Houldsworth MSS, HC to WC, 30 Oct 1817).

<u>Trials on *Caledonia*</u>

In 1817 BW & Co acquired a vessel, *Caledonia*, complete with fittings, paddle wheels, shafts, bearings and boiler chimney for the sum of £1200, from Henry Bell of Glasgow, a pioneer of early steamboats (Miller, 2004). Described as 'one of the worst sailors in the Clyde' (Houldsworth MSS, HC to WC) *Caledonia* was re-engined and re-fitted in order to become a floating laboratory for BW & Co (B&W MSS, Watt Jr to WC 19 April 1817). It was in this vessel that Watt JrJr crossed the North Sea to Rotterdam in 1817. This land-locked firm's knowledge of marine engineering advanced considerably with the acquisition of *Caledonia*. The boat was acquired, it appears, for five purposes. First, B W & Co needed to acquire tacit knowledge of the integration of steam engines with vessels; secondly, they needed to experiment with paddle wheel design and angle of dip; thirdly, they could establish their own ground rules for trials – it becoming clear that, for many customers, speed was an issue of prime importance; fourthly, only by owning a vessel could they conduct tests over as long a period as necessary – customers, understandably objecting to continued trials at their expense; finally, *Caledonia* could become a practical demonstration vessel, providing the opportunity for Watt JrJr's marine engine marketing campaign.

Fitted with a pair of 14 hp engines, *Caledonia's* first trials were undertaken in the Thames estuary, using both steam and sail. The vessel travelled at 8.5 knots per hour under both steam and sail and at 6.5 knots per hour with steam alone. Watt Jr noted that coal consumption was roughly double that of 14 hp land engines, a fact that he was unable to explain, although he suggested that poor coal and the need for a steam case to insulate the cylinder at sea possibly contributed; adding 'Experiments are requisite to find out the rest' (B&W MSS, Watt Jr to WC, 9 Sept 1817). On the Thames *Caledonia* performed well, 'though certainly too narrow & long for the sea – had no twitchings or wrigglings' (ibid., Watt Jr to J Brown, 23 Aug 1817). Several public trials were undertaken, the focus being on speed and coal consumption. On one occasion *Caledonia's* speed going downstream was measured against that of a raft secured by a rope to the river bank, but unfortunately the vessel ran over the raft with one of her paddle wheels, raising one side of the boat out of the water, but causing no structural damage (ibid). On a trial journey to Margate, Watt Jr experimented with different levels of paddle wheel immersion 'the greater dip did not appear to affect the speed of our Engines…as we think we have lost speed in the vessel by raising our paddles so much, we are now about to lower them gradually again, for there seems little doubt that if the Engines will make the same number of strokes with a deeper immersion, our speed through the water will be greater'.

*Caledonia*'s crew sought opportunities for gratuitous trials against other steam vessels in the Thames estuary. Finding *Thames* travelling in the same direction downstream, *Caledonia* gave chase: 'In one hour we passed the … boat which had started 44 minutes before us'. On another occasion, also in the River Thames, a challenge was given to *Sons of Commerce*; *Caledonia* gave it 10 minutes head start and, 'In 37 minutes we came up & passed them and shooting ahead tacked about, sailed round and repassed [sic] them on their other side…all this took place before we reached Woolwich and with most of their Proprieters on board.' Watt Jr, with no false modesty, told his father 'This settles the question of superiority in point of speed and from all I can collect their consumption of coal is more than double in proportion to ours' (ibid., Watt Jr to WC, 9 Sept 1817).

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In October 1817, Capt Wager, RN, approached Watt Jr, asking to be permitted to take *Caledonia* across the Channel to Rotterdam. He had undertaken a cross-Channel steamship journey in the previous year. Watt Jr, recognising the opportunity for trials in open sea, besides the possibility of taking steamboat orders on arrival in Holland, decided to go too. They were joined by a Mr Barker and James Brown (officially ‘mate’, who was later to head up BW & Co’s London office) whose ‘knowledge of steam packets & Engines’ made him ‘more peculiarly adapted for the situation than any other of our corps’ (B&W MSS Watt Jr to Watt Snr). Either or both of the Creighton brothers could have provided the requisite engineering knowledge but it is possible that Watt Jr favoured Brown as being a ‘safe pair of hands’ not only in the engineering sense, but also socially. The remainder of the crew comprised a steward/cook with experience of sailing on an East Indiaman (who would also act as a sailor when required), a pilot well acquainted with the Dutch coast ‘by a life of smuggling’, two ‘active steady’ sailors, a cabin boy and three enginemen (James Brown MSS, Diary). On hearing, after Watt Jr’s arrival in Rotterdam, that the crossing had been rough, James Watt showed fatherly concern on the one hand and a singular disregard for other human lives on the other: ‘we were all made very happy to learn …that you had escaped the perils of the seas and I earnestly pray that you may not again subject yourself to such risk as you must have run in a winter passage, but leave those matters to men of not so much consequence to society if it be necessary to encounter them’ (B&W MSS, JWatt to Watt Jr, 25 Oct 1817).

A close check was kept on coal consumption during the crossing. It was around 4.25 bushels per hour, ‘and the machinery acted perfectly well throughout. The vessel rode the waves extremely well and drew no more water than in her River navigation…[confirming Watt Jr’s opinion] of the possibility of adapting steam vessels to sea navigation in short passages and rendering them nearly equally safe with any other vessel’ (ibid., Watt Jr to WC, 17 Oct 1817 ; Watt Jr to Jwatt, 1 Feb 1818). Two disasters, one more serious than the other, befell *Caledonia* shortly after arrival in Holland. First, a pilot ran them aground and it took the entire population of the nearby community, 'male & female, young & old…with their parson at their head', plus four horses to pull the boat free (James Brown MSS, Diary). And then a beam of one of the engines broke, and 'finding there was nothing else for it I set myself resolutely to work with the men' (B&W MSS Watt Jr to J. Watt, 1 Feb 1818), and within four days a replacement had been fitted. Had this accident occurred anywhere other than in the proximity of a major manufacturing port, where a replica beam could be cast, the situation would have been much more serious. This incident emphasises the need to have engineering expertise to hand and, although vessels were, by 1817, almost routinely fitted with pairs of engines for other reasons such as balance, greater smoothness of ride and speed, a pair served as a form of insurance should such an accident occur at sea.

One engineman short on the return journey ('the charms of the gin of this place having proved too powerful'), James Brown graphically described his exhaustion: 'I felt myself much fatigued from my exertions in firing (over 30 hours) and was most anxious for our arrival at Gravesend.' But Capt Wager was equal to the task of motivating: 'seeing the fagged state of Taylor and myself [he] used every means of deceiving us as to the distance making it much shorter [than] it really was to buoy up our spirits.' On arrival Brown was unable to stand, 'owing to the fatigue having swelled both ankles' (James Brown MSS, Diary).

Further trials

An experiment conducted in September 1818, after their return to the Thames estuary, resulted in another accident on board. Watt Jr, having noticed that the wheels of one of the engines was making more noise than usual, directed the engineman to screw the bolts of the plummer blocks a little tighter - while the engine was running. On his own initiative the engineman went to tighten the pin of the connecting rod, 'in doing of which he let fall his hammer between the crank wheel and connecting rod, which broke the latter…and the piston being let loose struck…the cylinder & broke the crossbar…Both engines were instantly stopped.' No-one was injured but the lesson 'not to have anything done to the Engines without stopping them' was learned the hard way (B&W MSS, Watt Jr to J Watt, 1 Feb 1818). Repairs were quickly done, and a 'comparative Experiment of our speed and consumption of fuel with two & with one Engine' was undertaken. The results were 'curious. With one Engine we go 7 miles per hour burning 1.7 bushels of Wylam coal and with 2 Engines we go 8 miles burning rather more than 4 bushels' (ibid); no explanation was offered. It is likely that externalities such as tide, current and weather accounted for the unexpected results.

By 1819, Watt Jr, who had probably heard of Maudslay's higher powered marine engines, acknowledged that a speed of at least 9 mph was necessary for steam packets in the coasting trade (ibid., Watt Jr to WC, 23 July 1819). That this was by no means always attained is attested by William Creighton, who noted that the boat he referred to as '*the flying dutchman'* (probably *Moerdyke)* achieved only 6 mph, while in the same year *James Watt* achieved only 7 mph, a performance described by Creighton as 'miserable and the few strokes wanting of full speed seem unlikely to give it a quarter of a mile more' (ibid., WC to J Brown, 2 May 1822; WC to J Brown, 9 May 1822).

In 1827 a comparative speed trial was conducted by B W & Co on *Alban* and *Carron*, the former achieving 8 mph and the latter 8.75 mph . Indications of the Navy Board's interest in and desire for trials to be sufficiently controlled are shown in its request for information on wind direction, whether the sea trial was undertaken against a marked mile on shore or under other circumstances, and the identities of the personnel on board. To this end, the Admiralty asked the superintending master of Deptford Dockyard to mark off 2 nautical miles (together with half mile positions) on any part of the Thames bank best suited to ascertaining the speed of steam vessels (NA, ADM 106/2164C/76/29 14 March, 4 April, 29 May; Buchanan & Doughty, 1978).

The continuing difficulties of isolating different aspects of engine performance in tests were a source of frustration. Engines and boilers of similar capacity but different provenance performed differently. Performance was poor in the first trials of *City of Edinburgh* (with BW & Co engines) conducted in 1821, and difficulty was experienced in keeping up the steam. Watt Jr commented, 'it turns out as I feared it would, that we have not boiler or grate surface enough'. However, he was unable to explain how *Lightning,* made by Maudslay Sons & Field, with engines of the same size and similar boilerswas able to produce ample steam (B&W MSS, Watt Jr to WC, 25 May 1821).

The type of coal used was believed to influence the attainable speed of a steam vessel. Experiments were conducted on *Crocodile,* a Post Office vessel powered by a pair of 40 hp B W & Co engines, in 1825. The boat produced a speed of between 9.5 and 9.8 mph, coal consumption varying between 5.9cwt per hour and 6.4. In this experiment Wylam coal from Northumberland was used; Lambton Main coal from County Durham was found to evaporate slightly more water per cwt of fuel employed (ibid, Watt Jr to BW & Co, 12 April 1825). Watt Jr showed disappointment at the lack of steam on a journey in *Caledonia* from London to Sheerness 'despite' its use. 'Scotch' coal was also tried and found to be satisfactory.

Paddle wheels were an internal variable upon which it seemed possible to conduct repeatable trials under sufficiently similar external conditions as to be able to derive comparable results. Universally used until screw propulsion was developed, much attention was paid to the most effective design for paddle wheels, particularly with regard to the angle of dip and degree of immersion. Both BW & Co and Maudslay Sons & Field, as well as other marine engineers, integrated paddle wheel manufacture with that of marine engines. When, in 1820, *Sons of Commerce,* despite its new BW & Co engines, attained only 7.75 mph without passengers or other load, Watt Jr suggested that an alteration to the paddles might lead to enhanced speed. He deferred to William Creighton's concern that the paddles proposed for a Post Office vessel might overload the engines, suggesting that the width be reduced by 1 ft ( B&W MSS, Watt Jr to WC, 16 Aug 1820; 20 Aug 1820) . In June 1821 Watt Jr sent various papers concerning *Venus*, noting 'from all of which you will see the necessity of revising the construction of our paddle wheels' (ibid Watt Jr to WC 22 June 1821).

The late 1820s mark a period of intense Navy Board attention to paddle wheel design, for this began to emerge as significant in determining variance of speed in otherwise largely similar vessels. The largest category of steam-related inventions offered to the Royal Navy prior to 1832 comprised paddle wheels or some other method of ship propulsion. The Navy was offered 31 paddle wheel inventions, the editor of Galloway's *History and Progress of the Steam Engine* (1836), noting that while 'no less than 70 different inventions have recently been patented for the propulsion of steam vessels…it is a remarkable circumstance that, among the very numerous attempts to obviate…defect,…very few have been proposed that have not been calculated either to augment the evils, or to introduce others of greater magnitude' (Macleod et al, 2000, 323).

While many of the internal variables of the marine engine were, in principle, within the control of the engineer, the design (shape and weight) and manufacture of the vessel was in the hands of the shipbuilder. Problems occasioned, at least in part, by the separation of shipbuilding and marine engineering had begun to emerge as early as 1820. At least two vessels with B W & Co engines had an unequal draft between fore and aft. *Diana,* for example 'appears to me to have sunk in the middle as I cannot conceive her to have been built with the sheer she now has'; while the performance of the *Moerdyke* prompted Watt Jr to query its centre of gravity (B&W MSS, Watt Jr to WC, 9 Sept 1820; Watt Jr to J Brown, 26 Feb 1822). In such cases there was concern for the effect on speed as well as appearance. Watt Jr was also concerned that the speed of vessels intended for navigable waterways in continental Europe might be impaired by their flat-bottomed design, suggesting that the draught should be c.4 ft 'to give it any chance of equalling the others in velocity' (ibid., Watt Jr to J Brown, 26 Feb 1822). By the early 1820s BW & Co were moving towards a closer relationship with boat builders, being able to quote on (but not yet supply) an entire vessel package. Watt Jr became conversant with the prices of vessels and was able to suggest rough dimensions for a given speed and engine size, probably based on tacit knowledge, rather than informed by Beaufoy's theory, since there is little evidence that he was a theoretician.[13] In his relations with the Navy Board, Maudslay used greater initiative than BW & Co, besides providing larger engines. Having undertaken shipping-related business prior to commencing the manufacture of marine engines, Maudslay was prepared to focus his engineering output more exclusively on marine engineering than Birmingham-based BW & Co could afford to without re-locating. It is possible that Maudslay was no more integrated than B W & Co before the mid 1830s, save in the perception of the Navy Board (Macleod et al, 2000, 312, 317-18), but by appearing to rest on their reputational laurels inherited from the eighteenth century, BW & Co did themselves no favours (Tann *et al*, 2000).

Trials and tests were perceived to be a necessity both by marine engineers and their potential customers in the first decades of the steamship. For engineers they provided the data upon which new trajectories could be developed (eg beam to bell crank to side lever engine) or modifications (eg dip of paddle wheels) could be made. For potential customers the important aspect was the demonstration effect, together with a clarification of key criteria upon which to evaluate one vessel against another. While steam power on land was becoming a mature technology, in its emergent phase potential customers had found choice to be difficult (even Richard Arkwright elected to purchase an untried engine which was a failure). However the number of internal and external variables made it difficult to isolate any single one, in addition to which external variables, particularly at sea, could not be controlled with precision. Nonetheless, it was only by conducting tests and trials, however imperfect, that knowledge could be created which, cumulatively, could contribute to improvements in performance. Of all the variables, speed was the most clearly demonstrable

[13] Watt Jr's letters are largely general on the subject of technology (unlike those of his late half brother, Gregory). Even his letters to his father lack specific detail on technology. He clearly depended on well-trusted employees for engine details.

performance and one to which Watt Jr devoted much attention, whether against a personally set standard or in competition with another vessel.

Engine size was a key variable but, as the inconclusive results of trials show, although there was a slow increase in achieved speed through the 1820s, experiments with shutting down one of a pair of engines, or two vessels with similar-sized engines, sometimes produced unexpected results. The marine engineer faced a dilemma not encountered with stationary land engines, namely the relationship between engine size and weight. In principle, the larger the engine, the greater the ship's speed. This was, however, counteracted by the greater weight of engine(s) and boiler(s). Watt Jr conceded that engine weight could be taken out, although he warned 'by no means risk the safety of the engine for the sake of saving weight in this or any other boat engine' (B&W MSS, Watt Jr to WC, 6 Jan 1821). Moreover, size conflicted with the requirement of compactness. While attempts had been made to reduce weight, these had proved to be diseconomies, as breakages had occurred. Creighton conducted experiments on areas of weakness with the consequence that weight was added, rather than being reduced (ibid). On the whole, BW & Co favoured smaller engines, providing they could generate the requisite power with adequate strength in adverse weather conditions. Just as they were comparatively slow to manufacture large rotative land engines, BW & Co adhered to a policy of installing smaller marine engines than Maudslay but, despite this, there is no evidence that they were considered unfit for purpose.[14]

[14] In the 1840s and 50s BW & Co greatly increased the size of their marine engines, but by then they had all but lost out to port-based steam engineers.

With respect to fuel consumption, early steamboats were caught in a bind similar to that of early aeroplanes almost 100 years later This was the seemingly vicious circle of the relationship between fuel consumption and weight of the vessel for a specific journey- the longer the distance to travel, the more fuel was required, necessitating a larger and heavier vessel to carry it which, in turn, necessitated a larger engine to propel it (Gibbs-Smith, 1965, 46-61). Fuel economy was, therefore, a matter of importance and this depended, in part, on the type of coal used, besides boiler design, the management and skills of boiler stoking – important tacit knowledge to which J. R. Harris (1992) drew attention – and the management of salt accumulation, consequent upon the use of salt water.

The only control marine engineers had over external variables such as wind, current, tide and sea swell was to plan tests and routes so as to maximise performance – excepting opportunistic races in the Thames Estuary. As modalities, there was no possibility of removing one or more, so as to enhance the perception of precision. In this sense, steamboat trials were destined to fail one of Lindqvist's (1990) four measures of control. However there were opportunities for altering one modality, namely the individual performing the trial. Watt Jr was concerned to have James Brown on board for, despite his reliance on their experimental engineering knowledge, he did not invite the Creighton brothers to perform trials at sea or in the Thames Estuary, although Henry Creighton had been involved in pre-*Caledonia* trials on the River Tyne in 1816 and 1817. In this regard Watt Jr chose Brown's authority and competence (Lindquist, 1990) rather than the Creightons' competence and irreverence (Tann, 1998).

Both Cardwell (1972) and Lindqvist (1990) highlight the role of institutions in technology testing. The Navy Board intervened in testing to the extent that it specified that measured half mile lengths be laid out along an estuary for the purpose of speed trials; besides encouraging experimentation on methods of propulsion. But the Board did not undertake tests and trials, instead devolving responsibility and cost to the manufacturer to prove superiority of the technology in question (Macleod et al, 2000, 320-6).

## Conclusion

The difficulty that engineers had in isolating the many variables contributing to steamboat performance made comparison of the results of trials very difficult. When two vessels were entered together in a trial, external factors were self-cancelling, but there remained sufficient factors internal to the vessels for doubts to be raised concerning the causes of any perceived differences in performance. Nonetheless, there were some standards of comparison; and leading marine engineers established a basis for professional credibility and trust, thereby achieving a degree of precision (Wise, 1995). Steamboat trials contributed to the establishment of a cultural value (Porter, 1995) in which tests and trials played a part in public sector procurement (eg the Navy and Post Office), thereby setting a standard which was emulated by the larger companies in the mercantile marine. In addressing the issue of validity (Mackenzie, 1989) the question to be answered first is did steamboat trials produce the 'right 'result; and second, could trials be used for purposes of persuasion?

The first begs the question of what was a 'right' result? One of the easier ways of challenging a result was to criticise the capabilities of those who conducted the trial in question. Watt Jr, self-appointed keeper of the flame of his father's genius, was probably less liable to be criticised than others for this reason, and it may have been as much for his gravitas as his engineering ability that he chose to take James Brown on *Caledonia's* cross-Channel voyage. If trials and tests led to the identification of key areas for development – the bell crank engine being abandoned in favour of the side lever; the abandonment of a single engine in favour of linked pairs; or the most effective angle of dip for paddle wheels, for example--the answer to the question of whether early marine engine trials produced the 'right' result must be a qualified 'yes'. With respect to persuasion, the very public nature of steamboat trials excited attention and Watt Jr was fully aware of the opportunities for public persuasion, besides the marketing potential of *Caledonia's* voyage across the English Channel in 1817. The inductive approach to early marine engine trials and the attempts made to control for both internal variables and such external ones as it was possible to control, suggest that, despite their questionable accuracy, steamboat trials had a recognised validity.

# References

## Manuscript Sources

Birmingham City Archives, Boulton & Watt MSS (B&W MSS)

Glasgow Museum of Transport, Houldsworth MSS

Heriot Watt University Archives, James Brown MSS, Diary

National Archives, Kew (NA), Admiralty Papers

## Secondary sources


Armstrong, R (1974) Powered Ships, Ernest Benn, London

Bowker, Geoffrey C & Star, Susan Leigh (2000) Sorting Things Out; Classification and its Consequences MIT Press, Cambridge, MSS

Buchanan, R A & Doughty, M W (1978) 'The Choice of Steam Engine Manufacturers by the British Admiralty, 1822-52' The Mariner's Mirror, 64, 327-347

Cantrell, John & Cookson, Gillian (2002) (Eds) Henry Maudslay & the Pioneers of the Machine Age Tempus, Stroud

Cardwell, D.S.L. (1972) Technology, Science and History, London

Collins, H. M. (1985) Changing Order: Replication and Induction in Scientific Practice, London

Farey, J jr (1827, repr 1971) Treatise on the Steam Engine, David & Charles, Newton Abbot

Fletcher R A (1910) Steamships and their Story, Sidgwick & Jackson, London

Flexner, James T (c.1978 ) Steamboats Come True, Little Brown

Gibbs-Smith, Charles H (1965) The Invention of the Aeroplane 1799-1909 Faber & Faber

Harley, C. K. (1971) 'The Shift from Sailing Ships to Steamships, 1850-1890;A Study in technological Change and its Diffusion' in McCloskey D.N. (ed) Essays on a Mature Economy: Britain after 1840, London

Harris, J R (1992), 'Skills, coal and British industry in the eighteenth century', Essays in Industry and Technology, Ashgate, Aldershot

Hindle, Brooke & Lubar, Steven (1986) Engines of Change, The American Industrial Revolution 1790-1860, Smithsonian Institution, Washington

Hunter, Louis C. (1949, new edn 1993) Steamboats on the Western Rivers An Economic and Technological History, Dover, New York

Lardner, Dionysius (1840) The Steam Engine Explained and Illustrated, Taylor & Walton, London

Lindqvist, Svante (1990) 'Laboratories in the Woods: The Quantification of Technology during the Late Enlightenment' in Frangsmyr, T., Heilbron, J. L., Rider, Robin E. (Eds) The Quantifying Spirit in the Eighteenth Century, University of California Press, Berkeley

Roll, Eric (1930, repr 1968) An Early Experiment in Industrial Organisation, Being a History of Boulton & Watt 1775-1805, Frank Cass & Co, London

Mackenzie, Donald (1989) 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy', in Gooding, David, Pinch, Trevor, Schaffer, Simon (Eds) The Uses of Experiment, Studies in the Natural Sciences, Cambridge UP

Mackenzie, Donald (1996) Knowing Machines: Essays on Technical Change, MIT Press, Cambridge, Mass

MacLeod, Christine, Stein, Jeremy, Tann, Jennifer, Andrew, James (2000) 'Making Waves: The Royal Navy's Management of Invention and Innovation in Steam Shipping, 1815-1832' History and Technology (**16),** 307-33

Miller, David Philip (2004) Discovering Water: James Watt, Henry Cavendish and the Nineteenth-Century "Water Controversy", Ashgate, Aldershot

Musson, A E & Robinson, Eric (1969) Science and Technology in the Industrial Revolution, Manchester U Press

Napier, D D (1912) (Ed) David Napier, Engineer 1790-1869, An Autobiographical Sketch with Notes , Glasgow

Pearson, F H (1896, repr 1984) The Early History of Hull Steam Shipping, Smith Settle, Otley

Petree, J Foster (1956) Henry Maudslay 1771-1831, and Maudslay Sons & Field Ltd: A Commemorative Brochure, Alcester

Porter, Theodore M (1995) 'Precision and Trust: Early Victorian Insurance and the Politics of Calculation', in Wise, M. Norton, (Ed) The Values of Precision, Princeton UP

Riden, Philip (1973, 2nd ed 1990) The Butterley Company, Derbyshire Record Society XVI

Robinson, Eric & Musson, A E (1969) James Watt and the Steam Revolution, A Documentary History, Adams & Dart

Robinson, Eric & McKie, Douglas (1970) Partners in Science: James Watt & Joseph Black, Constable, London

Rowland, K T (1970) Steam at Sea A History of Steam Navigation, David & Charles, Newton Abbot

Schofield, R E (1963) The Lunar Society of Birmingham, Oxford

Shapin, Steven, & Schaffer, Simon (1989), Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life, Princeton, N.J.

Sharp, A.J. (1999) Distance Run: A History of the Patent Ship-Log, Brassbounders Publishing, Weymouth

Smeaton, John (1812) Reports of the Late John Smeaton F.R.S. Made on Various Occasions in the Course of His Employment as a Civil Engineer, Vol 2, Longmans, London

Smeaton, John (1814) The Miscellaneous Papers of John Smeaton Civil Engineer etc F.R.S. Comprising his Communications to the Royal Society Printed in the Philosophical Transactions Forming a Fourth Volume to His Reports, Longman, London

Spratt, H Philip (1958) The Birth of the Steamboat, Charles Griffin & Co, London

Tann, Jennifer (1992) 'Two Knights at Pandemonium: A Worm's Eye View of Boulton Watt & Co' History of Technology, 20, 47-72

Tann, Jennifer (1972) The Development of the Factory, Cornmarket Press, London

Tann, Jennifer (1978; 1994) 'Boulton & Watt's Organisation of Steam Engine Production before the opening of Soho Foundry', in Pollard, Sidney (Ed), The Metal Fabrication & Engineering Industries, Economic History Society, Blackwell, Oxford

Tann, Jennifer, Stein, Jeremy, MacLeod, Christine, Andrew, James (2000) 'Running out of Steam?' Paper presented to Economic History Society Conference, Bristol

Williamson, James (1904, repr 1987) Clyde Passenger Steamers 1812-1901, Spa Books

Wise, M. Norton (1995) (Ed) The Values of Precision, Princeton UP