Strong Steam, Weak Patents, or,

the Myth of Watt's Innovation-Blocking Monopoly, Exploded

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Revised
June 10, 2010

*Corresponding author. The authors are grateful to Michele Boldrine, Joel Mokyr, Alessandro Nuvolari, and participants in the Center for Law, Innovation & Economic Growth conference on "The Economics and Law of Innovation" (Washington University School of Law, April 2-3, 2009) and the 6th Beta-Workshop in Historical Economics, on the "Cliometrics of Creativity" (University of Strasbourg, May 14-15, 2010) for their helpful suggestions. We also owe special thanks to Jim Andrew of the Birmingham Science Museum for his expert advice on matters of steam engineering.

Probably more myths and half truths have grown around the subject of Boulton & Watt than around any of their contemporaries. Inaccuracies and overgeneralizations have been compounded through the years… .He who dares to question does so at his peril.

Jennifer Tann (1977-8, p. 41)

Introduction

Whether patent protection promotes or hinders technological progress is one of the great unsettled questions of political economy. But within the greater debate one fact at least appears settled, namely, that if the granting of patent protection has ever been counterproductive, it was so in the case of the British Parliament's decision, in 1775, to extend James Watt's 1769 steam engine patent for another quarter century.

This view has been held even by admirers of Watt, including those holding no brief against patents *per se*. For example, technology historians Henry Dickinson and Rhys Jenkins (1927, p. 299) claim that Watt's patent "completely blocked any progress by other engineers," while cultural historian Ben Marsden (2002, p. 99) observes that "Boulton and Watt deftly played the patent card to out-trump rival steam engineers—even, perhaps especially, those who promoted more efficient engines," and that extension of their monopoly rights was consequently "disastrous for their opponents, stifling competition—and…hampering or altogether blocking technological progress."

Numerous economic historians have taken a similarly dim view of Watt's patent. Thomas Ashton (1955, p. 107), for example, observed that, had Watt's patent expired in 1783, England might have had railways sooner. G.N. von Tunzelmann (1978, p. 293) endorses Ashton's view, while John Kanefsky (1978) , Joel Mokyr, and Alessandro Nuvolari claim somewhat more generally that Watt's patent "effectively blocked the development of a high pressure engine, even though Watt himself firmly opposed such engines" (Mokyr 1990, p. 247 n. 9), and that Watt's patent therefore "had a highly detrimental impact on the rate of innovation in steam technology" (Nuvolari 2004, p. 353).

That this negative appraisal of the consequences of Watt's patent also occurs in such a general survey as Deirdre McCloskey and Roderick Floud's *Economic History of Britain since 1700* (1994, i., p. 24) suggests that it is conventional rather than idiosyncratic. According to that source,

> Watt's engine had one dangerous competitor: the high-pressure engine. The idea of an engine that…utililized the difference between high pressure and the atmosphere (instead of that between the atmosphere and a vacuum) had been around for a long time, but Watt resisted it. Because he held a wide-ranging patent, he succeeded in blocking its development for many years.

It is hardly surprising, given such authoritative precedents, that Michele Boldrin and David K. Levine should treat Watt's patent as the principal exhibit in their recent indictment of patents and other forms of "intellectual monopoly." According to them (2008, p.1),

> During the period of Watt's patents the U.K. added about 750 horsepower of steam engines per year. In the thirty years following Watt's patents, additional horsepower was added at the rate of 4,000 per year. Moreover the fuel efficiency of steam engines changed little during the period of Watt's patent; while between 1810 and 1835 it is estimated to have increased by a factor of five.

"The key innovation responsible for these improvements," Boldrin and Levine add, was the use of high-pressure steam, "development of which had been blocked by Watt's strategic use of his patent" (ibid.):

> It appears that Watt's competitors simply waited until then [after 1800] before releasing their own innovations. This should not surprise us: new steam engines, no matter how much better than Watt's, had to use the idea of a separate condenser. Because the 1775 patent provided Boulton and Watt with a monopoly over that idea, plentiful other improvements of great social and economic value could not be implemented (ibid., p. 3).

"Quite plainly," the authors conclude, "Boulton and Watt's patent retarded the high-pressure steam engine, and hence economic development, for about 16 years" (ibid, n. 5).

The thesis of this paper is that, self-evident though it may appear, the common view of the blocking effect of Watt's patent is mistaken. Although it's true that high-pressure steam technology developed only after the expiration of Watt's patent, the delay was caused, not by Watt's patent, but mainly by inventors' failure to appreciate the thermodynamic advantages of high-pressure steam, together with the widely-held (and not unjustified) belief that high-pressure engines were excessively risky. Indeed, Watt's monopoly rights may actually have *hastened* the development of the high-pressure steam engine, by causing at least one of his rivals—Richard Trevithick—to revive a previously abandoned technology in order to avoid coming into conflict with Watt's monopoly rights.

In attempting to revise the record concerning the bearing of Watt's patent on the progress of steam technology, we do not wish to be understood as offering a general defense of that patent, much less of English patent law or patents in general. We seek only to make a small contribution to the larger debate concerning the desirability of patents, by showing that Watt's patent does not deserve the status Mokyr (2009, p. 350) and others have assigned to it as a "classic example" of a patent that stood in the way of the development of a markedly superior technology (Mokyr 2009, p. 350).[1]

Low Pressure Steam Engines

Prior to the expiration of Watt's patent, all working steam engines—that is, all engines save some experimental prototypes and models—used low-pressure steam, and relied, not on the pressure exerted by the steam itself, but on a vacuum created upon its

[1] Concerning the general influence of the English patent system on inventive activity during the Industrial Revolution see Dutton (1984), MacLeod (1988), and MacLeod and Nuvolari (2006); for the case of Watt's steam engine in particular see Scherer (1965) and Boldrin and Levine (2004 and 2008, chapter 1). Selgin and Turner (2006 and 2009) assess aspects of Boldrin and Levine's arguments apart from that considered here.

condensation, for their power stroke. In Thomas Newcomen's engine steam was allowed to fill the space below a piston resting at the top end of a cylinder, the upper part of which was open to the atmosphere. So long as the steam stayed vaporized, the piston rested at the top end of the cylinder, being suspended there from one end of a beam, the other end of which was held down by a weight and pumping equipment. But by introducing a jet of cold water into the cylinder, the engine operator (or the engine itself, if it was "self-acting") would cause the steam to condense, creating a vacuum under the piston, which was then driven down by the pressure of the atmosphere, raising the pump. Steam could then be readmitted into the lower chamber of the cylinder, which would at the same time be re-opened to the atmosphere so as to destroy the vacuum and restore the piston to its starting position.

The trouble with Newcomen's engine was that, even at its minimal working speed of about eight strokes per minute, the steam in its cylinder could only be cooled enough to generate a partial vacuum of about half the pressure of the atmosphere, limiting its power correspondingly. The invention that made Watt famous consisted of an external condenser that could be kept cool while the cylinder itself stayed hot. Steam exhausted into such an external condenser could be cooled quickly enough to create something approaching a perfect vacuum in the engine cylinder. This innovation made Watt's prototype engine as powerful as a Newcomen engine of twice the displacement. The resulting, substantial fuel savings meant that Watt's engine could be economically employed even in places, such as the waterlogged copper mines of Cornwall, where coal was hard to come by.

Steam Used Expansively

Although Watt's original engine design relied, like Newcomen's, on the "sucking" force of a vacuum alone for its power stroke, he understood that a piston might just as well be "pushed" by steam of sufficiently high pressure as "pulled" by a vacuum. His concern to avoid heat loss and conserve fuel led him to take advantage of this so-called "elastic" force of steam by making a new model with an enclosed upper cylinder, into which steam was admitted to serve in place of the atmosphere to assist the piston's downward stroke.[2]

Besides making Watt's engines still more powerful than Newcomen's, the employment of steam's elastic force might also have allowed Watt to increase his engines' power according to the pressure of the steam employed. But Watt did not take advantage of steam this way, his concern having been, in Marsden's (2002, p. 51) words, "not producing more work, but eliminating waste"—a preoccupation reflected in the title of Watt's original patent, for a "New Method of Lessoning the Consumption of Steam and Fuel in Fire Engines."

Watt did eventually make further use of the elastic force of steam. In 1777 he made his first trials of a new way of working steam "expansively." In Watt's original single-acting engines steam under pressure was first allowed to press upon the face of a piston opposite that against which a vacuum was established. That same steam was then admitted into the voided chamber, at atmospheric pressure, until the piston completed its length just as was the case in Newcomen's design. Watt's new discovery was that, by admitting steam of a higher pressure than that prevailing on the opposite side of the piston, he could cut off the steam when the piston had completed only part of

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[2] Strictly speaking, in the terminology of the day, this innovation marked the development of the true "steam" engine, as opposed to the Newcomen "fire" engine, which relied on atmospheric pressure alone.

its length, and then let the steam's continued ("excessive") expansion do the work needed to finish the stroke. Several years later, in 1782, he patented a "double-acting" engine in which the steam alternated with a vacuum both above and below the piston, thereby allowing the engine to work continuously instead of intermittently—an improvement that was crucial in employing steam power to turn machinery.

Later inventors would discover that the greatest efficiency gains from the expansive working of steam were to be achieved through the use of steam of considerably higher than atmospheric pressure. But Watt himself never pursued this alternative. Instead he was to maintain a lifelong aversion to what he called "strong" steam, relying only on steam raised to a few pounds per square inch of pressure beyond that of the atmosphere. At such relatively low pressure the advantages of Watt's "excessive expansion" idea hardly compensated for the extra difficulties involved. Consequently Watt ended up employing it only in a handful of his engines (Muirhead 1854, iii, pp. 60-73).

Watt's aversion to high-pressure steam had at least two important implications. It meant, first, that in theory at least engines of Watt's design, despite their great advance in efficiency compared to Newcomen's, were nonetheless thermodynamically inefficient; and, second, that the creation of a vacuum remained essential to such engines' operation.

Strong Steam

In a high-pressure steam engine a vacuum is unnecessary, for the expansive force of steam alone is capable in such an engine of working a piston with a force proportional to the steam's pressure. It follows that *high-pressure engines don't require condensers, external or otherwise.* A condenser could, to be sure, contribute to the fuel efficiency of a high-pressure engine; but it need not and often did not contribute to its overall cost effectiveness. As Cardwell (1963, p. 81) explains,

> A condenser could, of course, be fitted to this type of engine, but the saving in fuel, or the increase in power, did not generally compensate for the added cost. Would it be, for example, really worthwhile to fit a condenser to an engine driven by steam at four atmospheres pressure? The gain in power could only be, at the very most, 20%, and this might well be offset by the cost of the condenser and its associated equipment, by the increase in bulk of the engine and by sacrifice of mobility.

In rotary applications especially, non-condensing engines dispensed with various components apart from condensers themselves, and therefore cost much less than condensing engines of the same horsepower.[3] Their compactness made them indispensible where mobility was essential and space was limited, as on locomotives and steamboats—two particular inventions that are sometimes said to have been "blocked" by Watt's patent.[4] But even in stationary applications with plenty of space at hand it was often more economical to employ waste steam as a source of heat than to condense it so as to reduce back pressure (and thereby achieve greater fuel efficiency).[5] This was especially so were fuel was relatively inexpensive, where abundant supplies of cold water were lacking,[6] or (since the fixed gain of about 8 lbs. p.s.i. from condensation

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[3] Halsey (1981, p. 732) puts the average fixed or "factory" cost per horsepower of an Oliver Evans-type high-pressure engine and a Boulton & Watt-type condensing engine at $174 and $512, respectively. The cost per horsepower of a Trevithick "puffer" would presumably have been close to that of Evans' engine, to which it bore a close resemblance.

[4] Condensers were nevertheless used on ocean-going steam vessels, for the purpose of generating a supply of fresh water.

[5] "In large cotton mills and weaving sheds considerable quantities of steam are required not only to heat the mill, but to supply the damp atmosphere requisite to the successful weaving of fine sized fabrics. In paper mills and calico printing establishments much steam is used in heating rolls, and the use of steam for warming water in brewing, etc., is very common" (Anonymous 1875, p. 40). According to Albans (1848, p. 243), "there are few [stationary] engines where there are not at least rooms to be heated, or water to be warmed, or something of that kind which will give a greater advantage from the waste steam than the application of a condenser."

[6] According to Morshead (1856, p. 39), to condense steam with an ordinary condenser typically required an hourly supply of 25 to 30 cubic feet of cold water per horsepower. Around 1807, however, the American Oliver Evans invented a "surface" condenser that did not require water or an air pump, and which was used in conjunction with Evans' high-pressure "Columbian" steam engines in circumstances,

becomes proportionately smaller as steam of higher pressure is applied) when steam of sufficiently high pressure was employed. Indeed, by the mid-19th century, when the advantages of high-pressure stationary engines had at last come to be widely appreciated, the incorporation of condensers on high-pressure engines was sufficiently unusual as to make the terms "low-pressure steam engine" and "condensing steam engine" virtually synonymous.[7]

In short, to employ Suzanne Scotchmer's (1991) terminology, high-pressure steam technology was not an instance of "cumulative" innovation in the specific sense of having depended on Watt's prior invention of the separate condenser. On the contrary: the advent of high-pressure steam came close to making Watt's invention irrelevant (Galloway 1881, p. 193).

A Monopoly of "All Kinds of Steam Engines"?

The fact that high pressure engines don't require condensers is alone sufficient to refute more naïve versions of the argument that Watt's patent delayed the advent of the high-pressure steam engine. But it leaves a more sophisticated version of the argument intact, because the separate condenser was only one of several innovations referred to in Watt's various patent specifications. The others included his previously mentioned designs for employing "the elastic force of steam." "I intend," Watt stated in the fourth head of his original (1769) patent specification,

> to employ the expansive force (pressure) of steam to press on the pistons…in the same manner as the pressure of the atmosphere is now employed in common fire

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like those prevailing in parts of the eastern United States after 1812, where cold water was not relatively available and fuel was relatively expensive (Halsey 1981, p. 740).

[7] To give one of many examples, Bourne (1853, p. 173) observes that "steam engines of every kind are divisible into two great classes—high-pressure engines and condensing engines." At one point Boldrin and Levine (2008, p. 15, n.5) themselves employ this conventional terminology, observing "that high pressure, non-condensing engines were the way forward," in apparent disregard of their claim elsewhere that all "new steam engines…had to use the idea of a separate condenser" (ibid., p. 3).

> engines. In cases where cold water cannot be had in plenty, the engines may be wrought by the force of steam only, by discharging the steam into the open air after it has done its office.

Watt's 1782 patent specification in turn sets out his novel way of working steam expansively:

> My first improvement in steam or fire engines consists in admitting steam into the cylinders…only during some certain part of portion of the descent or ascent of the piston…and using the elastic force, wherewith the said steam expands itself in proceeding to occupy larger spaces, as the acting powers on the piston through the other parts or portions of the lengths of the stroke of the said piston…whereby certain large proportions of the steam hitherto found necessary to do the same work are saved (Muirhead 1854, iii, p. 60).

Thus, according to Dickinson and Jenkins (1927, p. 299) as well as some other proponents of the "blocking power" thesis, so long as Watt's patent remained in force, his rivals were prevented, not merely from using condensers, but also from "putting a cover to the cylinder and using steam instead of the atmosphere to press on the piston."

But were they? Did Watt's patents in fact secure for him a monopoly, not merely of engines with external condensers, but of all engines "using steam as a 'working substance'," as Nuvolari (2004, p. 353) claims, if not indeed of "all kinds of steam engines," as Boldrin and Levine (n. 5) would have it? In truth, we hope to show, they did no such thing.

Watt's correspondence makes clear, first of all, that in casting his patent net widely he hoped, not to broaden his monopoly rights to cover every innovation he specified (as Dickinson and Jenkins, among others, have assumed), but to secure those concerning his principal invention, the separate condenser. Matthew Boulton and William Small together persuaded Watt to adopt this strategy in preparing his original, 1769 patent (Miurhead 1859, pp. 178-9), and Watt continued to heed their advice afterwards. Referring to his 1782 patent, for example, Watt wrote,

> As the general opinion of *schemists* seemed to be that they might make any use they would of our principle [the separate condenser] provided they did not make their engines *exactly* similar to those they had seen of ours, in order to cut off as much as might not have any such pretences, I took out a new patent for certain new pieces of mechanism applicable to steam or fire engines, which passed the seals last March….. In the specification of this patent I included all the improvements on our engines which we had not publically used and were thought worthy of notice (Watt to George Hamilton, Sept. 22, 1783, in Muirhead 1854, v. ii; emphasis in original).

That Watt's strategy was risky, and that he could not reasonably have expected it to secure him a monopoly of the expansive working of steam as such, becomes evident upon consideration of two fundamental provisions of English patent law, as set forth in the Statute of Monopolies (21 Jac. I, c. 3). The first of these was that no inventor could claim a monopoly right to an "abstract" principle or idea. Instead, an invention could be patented only if it was embodied, according to the patent specification, in "a manufacture," meaning something both "made by the hands of man" and vendible (Godson 1840, pp. 36-7). Even then other inventors remained free to secure a patent making use of the same principle or idea provided that the concrete details of their own specifications were sufficiently distinct.[8]

Second, to be patented an invention had to be new. Yet the idea of powering an engine using the pressure of steam alone, unaided by a vacuum, long-predated Watt's original patent, and was indeed considered the only possible way of deriving power from steam until Newcomen came up with his then radical alternative. The idea had been suggested by Solomon De Caus in 1615, by Giovanni Branca in 1629, and by the Marquis of Worcester in 1663, among others. In 1698 Thomas Savery patented a full-scale working model of an engine that employed steam both expansively and to produce

[8] It was by virtue of this provision of the law that Watt was able to patent, in 1782, his special approach to the expansive working of steam, despite Jonathan Hornblower's having patented his "compound engine," which made use of the same basic idea, the year before.

a vacuum; and a year later, in a move that was to inspire Boulton and Watt, Savery managed to have his patent extended by an Act of Parliament for a full third of a century. In 1707 Dennis Papin came up with several improvements to Savery's design. Finally, in 1720, the German physicist Jacob Leupold also succeeded in building a working high-pressure engine, powered by two cylinders, which he described in detail in his *Theatri Machinarum Generale*, published several years later. [9]

The abstract nature of Watt's specifications concerning the expansive working of steam, combined with the fact that the idea of working steam expansively was not original to Watt, would have made it exceedingly risky for Watt to sue or to seek an injunction against any manufacturer of a non-condensing steam engine, for any such action, besides being very costly and time consuming, could well result, not only in a judgment for the defense, but in the loss of Watt's less legally-problematic monopoly rights, including those to his separate condenser. For the law held that, if *any* part of the specification upon the basis of which a patent had been secured could be shown to be contrary to the statute, the patent might be vitiated *in its entirety.* Thus when, in 1781, Richard Arkwright took nine mill owners to the Court of Common Pleas for infringing on the spinning process he'd patented in 1775, he lost his case on the grounds that many of the components it involved were borrowed from other inventors. The patent was thereupon declared null and void. In June 1785, a conflicting verdict in a separate trial caused the matter to be brought before the King's Bench, where the verdict once again went against Arkwright.

[9] Watt was perfectly aware of these predecessors, thanks mainly, according to Marsden (2002, p. 31) to the efforts of fellow Glasgow College student John Robinson (1739-1805), who "would scan the libraries to satiate Watt's hunger for steam." According to Hoblyn (1842, p. 36), Watt himself built a model high-pressure engine, based on one of Papin's designs, in the early 1760s, but then abandoned it in favor of modifying Newcomen's atmospheric engine , "owing to the danger of bursting the boiler, the difficulty of making the joints tight, and the loss of a great part of the power of the steam from the non-production of a vacuum."

Watt, having testified for Arkwright, was well aware of the decision's implications. In 1783 he wrote to Boulton, "I don't like the idea of setting aside patent through default of specification. I fear for our own" (Miller 2000, p. 5); and two years later he told Soho's London banker that he "had no doubt but we shall be next set up as a mark to be shot at and ruined if possible" (Dutton 1984, p. 37).

"The Stormy Sea of the Law"[10]

As the preceding arguments might lead one to suppose, Boulton and Watt went to court to defend their firm's patents only against rivals whose engines employed separate condensers. Even then, and despite Boulton's substantial connections in high places, they proceeded with great reluctance, and quickly discovered that they had treaded onto thin ice.

Thus when, in 1782, Jonathan Hornblower erected his first compound engine at the Radstock Colliery—an engine that condensed steam, not in a separate vessel, but at the lower end of one of its cylinders—Boulton & Watt *threatened* legal action against him, along with all other makers of engines featuring a "Piston pressed down by steam."[11] But Hornblower, secure in his knowledge that the expansive use of steam as such was neither new nor patentable (Dickinson and Jenkins 1927, p. 304), publically called Boulton & Watt's bluff: in his and John Winwood's May 1788 "Address" to the Cornish miner he observed, concerning "The fourth Article of Mr. Watt's Specification relating to Steam on the Piston," that "so far from this Invention being new, it was made public at least fifty years since" (Nelson 1883, p. 59). In fact, despite their threats

[10] The expression is from Watt's correspondence, Watt to George Hamilton, September 24, 1782, in Muirhead (1854, v. ii, p. 161).
[11] "Advt. put in the Bristol papers, 1782," Draft by Watt. Cited in Dickinson and Jenkins (1927, p. 305). Other engine features proscribed by the ad were "Cylinder with closed top," "Steam case, or non-condensing casing to cylinder," "Separate condenser," and "Piston kept tight by oil and grease."

Boulton and Watt, as Hornblower was himself to observe some years later, "never meddled with" him (Torrens 1982-3, p. 196); and it appears (notwithstanding occasional claims to the contrary) that Hornblower went on making his compound engines even after his patent for them expired in 1795 (Torrens 1982-3, p. 195).

Boulton and Watt did, however, successfully oppose Hornblower's 1792 bid to have his 1781 patent extended by Parliament, as their own patent had been extended 12 years previously. Even then Boulton and Watt carefully confined their testimony to the fact that Hornblower had been equipping his engines with a separate condenser, without so much as hinting at a suspicion that Hornblower had pirated the principle of expansion from them" (Pole 1844, p. 31; also Nelson 1883, pp. 59-60).[12] Whatever the grounds for Boulton and Watt's opposition, to suggest that Hornblower's inventive prospects were hindered by the early expiration of his patent is to make an argument, not against Watt's patent, but in favor or Hornblower's.

A year later, when Boulton and Watt brought an action against Edward Bull, the initial verdict was for the plaintiffs, but was rendered "subject to the opinion of the [Chancery] Court as to the validity of the patent" (Muirhead 1859, p. 391). That court, by a divided opinion, refused "to confirm the validity of the amateurish, catch-all specification that was the 1769 patent" (Marsden 2002, pp. 143-4). Only two of the four judges, Rooke and Eyre, believed that those parts of the specification referring to Watt's new means for condensing steam were themselves sufficiently concrete to justify a verdict for the plaintiffs, while *all four judges* regarded the fourth article of Watt's

[12] According to Nelson (1883, p. 57), although Watt "claimed that he had conceived the idea of using the expansive power of steam as early as 1767…he had not been able to make a successful application of it" prior to Hornblower's having done so. Consequently there was "really no reason to doubt that Mr. Hornblower's was an independent discovery, and that he was the first to put the idea into practical form."

specification, concerning the expansive working of steam, as an attempt to patent "mere principles," hence contrary to the statute.

In short, it seems that, had Bull merely employed steam expansively, without using a (separate) condenser, the court would have found in his favor, and Boulton and Watt would have found themselves without a valid patent—and therefore without any prospect of recouping withheld engine royalties. Judge Eyre was particularly explicit in this regard. "If indeed the defendant could have shown," he observed,

> that he had not pirated the [separate condenser] invention, which is sufficiently specified, but that what he hath done hath a reference to another method of lessoning the consumption of steam, to which the questionable parts of the specification were meant to relate, the objection to the specification would have remained, and perhaps some other objections which have been alluded to, might have been taken both to the patent and specification (Davies 1816, p. 217).

Judge Rooke for his part defended his opinion by observing that "if he [Bull] has infringed these articles which are well specified, he shall not be excused from an action, because he has been guilty of an additional infringement on that which is specified as a matter of intention only" (ibid., p.188).

The split decision in *Boulton and Watt v. Bull* left that case in limbo, where it remained until a final verdict was rendered in the separate case of *Boulton and Watt v. [Jabez Carter] Hornblower and Maberly.*[13] That case, first tried in the Court of Common Pleas in December 1796, also resulted in an initial judgment for the plaintiffs, which was in turn challenged on the grounds that Watt's patent was invalid. The appeal on this occasion resulted, in 1799, in a unanimous opinion affirming the validity of Boulton & Watt's patent. But this opinion, like that of the judges who had sided with Boulton and Watt in their case against Bull, was grounded solely on those parts of Watt's

[13] Confusion of the two Hornblower brothers has occasionally been responsible for the mistaken claim that Boulton and Watt sued the inventor of the compound engine. In fact, Jonathan Hornblower appears to have had nothing to do with his brother's undertakings. For further details, see Selgin and Turner (2006, pp. 1344-5 and 2009, pp. 1102-3).

specification referring to his "contrivance" for condensing steam more efficiently, these alone having been found to fall "within the Statute of James."

In observing that the court saw merit only in the separate condenser component of Watt's patent, while finding fault with the rest, we don't mean to suggest that the court's ultimate verdict was justified. Many contemporary authorities believed that it was not, either because they believed that Watt's separate condenser itself failed to not meet the requirements set forth in the statute, or because they believed that the more dubious parts of the specification should have caused the whole patent to be voided. Even John Farey (1827, pp. 649-50), the great steam engine authority and Watt enthusiast, concluded that had "the ordinary practice of the courts of law in other cases" been adhered to in his own, "Mr. Watt's patent ought to have been annulled." [14]

If even Watt's separate condenser monopoly could prove so contentious, despite the invention's having undisputedly been Watt's own and despite the relative ease with which jurors and judges might conceive of a separate condenser as a "manufacture," Boulton and Watt could not reasonably have hoped to monopolize the expansive working of steam. Had they tried doing so, they would have found themselves without a legal leg to stand on. If the partners understood the English law of patents at all, they surely understood this.[15] What's more, their would-be rivals appear to have understood it, however much they may have failed to take full advantage of the fact.

High-Pressure Pioneers

Both Bull and Jonathan Hornblower failed in not having made use of high-pressure steam, which would have allowed them to dispense with condensers. It

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[14] Concerning the vagueness of Watt's original patent specification and the strategic considerations that led to its being so drafted see Hills (2002, pp. 389-91).
[15] Concerning Watt's familiarity with English patent law, see Robinson (1972).

remained for others to take this crucial step, as Arthur Woolf would do, to a limited extent, by making a high-pressure version of Hornblower's "compound" engine, and as Richard Trevithick would do using a variant of Watt's single-cylinder design.[16]

Trevithick's case is particularly instructive, because he was actually inspired to invent his high-pressure non-condensing "puffer" engine, despite the prevailing consensus that that high-pressure steam was a dead end, by his need to evade Watt's patent. Trevithick had been assisting Bull in erecting low-pressure condensing engines in Cornwall. But when, in 1796, Boulton & Watt obtained an injunction against the partners for infringing Watt's condenser patent, Trevithick turned his efforts toward making an engine that didn't need a condenser. It was then that he approached his friend Davis Giddy (who would later serve, under the name Davis Gilbert, as Royal Society president) to ask how much power would be lost by working an engine with steam at several atmospheres pressure, and then simply letting the steam escape. Gilbert answered that the loss would be only one atmosphere, and that this would be partly compensated by the savings from avoiding the friction of an air pump and the cost of delivering condensing water. "I never saw a man more delighted," Gilbert later wrote, "and I believe that within a month several puffers were in actual work" (Galloway 1881, p. 195).

Thus Trevithick, like Jonathan Hornblower, believed that, so long as he avoided using anything resembling a separate condenser, he needn't fear running afoul of Watt's patent. In fact, condensers were so unnecessary to his new invention that, even after Watt's patent expired, Trevithick generally refrained from using them even on his

[16] Hornblower had, in fact, been pointed in the right direction by his friend Davies Giddies (later Gilbert), who would later encourage Trevithick—successfully—along the same path. But as A.C. Todd (1959-60, p. 5) reports, Hornblower, instead of following Gilbert's advice, chose to devote all his effort to building the low-pressure, combination pumping and rotary engine that was eventually to "prove his undoing."

stationary engines, so as to make them fit for places lacking abundant source of cold water for condensation.[17]

Besides posing a special challenge to those who insist that Watt's patent stood in the way of a move to high-power steam technology, Trevithick's story also underscores the irony underlying the struggles of those inventors who found their way impeded by Watt's patent precisely because they, unlike Trevithick, *failed* to appreciate the advantages, both thermodynamic and legal, of high-pressure steam. As Civil Engineer and steam-engine historian Robert Stuart (1881, p. 455) notes, with only slight exaggeration,

> It is somewhat singular…that although during the thirty years that Watt's monopoly existed, the whole ingenuity of practical men appeared to be directed to form an apparatus, in which the use of the condenser was essential to its proper action, yet no sooner had this invention become public property—the same year—than a scheme was matured, and carried into effect, which, of all the applications of this power, as a whole, touches not in any point—does not even approximate to any of Watt's ideas as exhibited in his condensing engine.

Woolf's compound engine, which he patented in 1804, employed a condenser, so it could not have been legally produced, much less patented, before 1800. But Woolf did not think using high-pressure steam expansively in a compound engine until he'd seen one of Trevithick's puffers at work (Jenkins 1933, pp. 57 and 67). In any case by the mid-1820s experience had shown that the compound engine was less economical than

[17] According to Jenkins (1933, p. 67-8), although there is evidence that Trevithick did experiment with a few high-pressure condensing engines of his own, these engines appear to have been very short-lived. "Indeed," Jenkins adds, "it may be said that Trevithick's efforts in this direction served to retard rather than to advance the introduction of high pressure, at any rate for the large engines," for Trevithick's condensing engines proved so inferior to those of Boulton & Watt that they only served to reinforce the Cornish mine manager's prejudice in favor of low-pressure engines.

Although so-called "Cornish" engines, which Trevithick is often said to have invented, were equipped with condensers, that is because they were, not engines of Trevithicks's own design, but old Boulton & Watt condensing engines that had been fitted with Trevithick's improved boilers so that they might be worked using steam of higher pressure.

its high-pressure, single cylinder counterpart. Woolf's design was therefore abandoned in Cornwall, although it continued to gain ground in France.[18]

Although Trevithick's puffers were the first truly high-pressure steam engines to be erected in Great Britain, in the United States Oliver Evans independently invented his similar "Columbian" engine in 1801. That the timing of Evans' invention had nothing to do with the fact that Watt's patent had just expired, and that Evans might in principle have invented and sold his engines years before, should be evident from the fact that Watt's monopoly rights did not extend to the American market. Evan's case therefore highlights the importance of various "other" factors in delaying the advent of high-pressure steam, while serving as a warning to students of corresponding British developments to be wary of a tempting *post hoc* fallacy.

Finally, a word concerning William Murdoch, who anticipated Trevithick's locomotive by building a miniature, high-pressure "steam carriage" in 1781, and who is sometimes said to have had his own way blocked by Watt's monopoly rights. In fact Murdoch, a Boulton & Watt employee, at first received support, albeit grudging, from his employers, who took out a patent for his design in 1784, not to discourage him from pursuing it (as Boldrin and Levine, among others, have claimed), but simply to secure for the firm the benefits of its employee's invention, as firms routinely do. That Watt, despite having grave doubts, went on support Murdoch's efforts for some time after the patent was secured is evident from a 1786 letter of his expressing his "resolve to try to see if God will work a miracle for these [high-pressure] engines" (Carnegie 1905, p. 190).

[18] In 1845 William McNaught patented a new compound engine design that involved the addition of a second non-condensing high-pressure to an ordinary Boulton & Watt beam engine. The efficiency of this design caused many old Boulton & Watt engines, especially in Lancashire, to be "McNaughted" over the course of the following decade.

Not long afterwards, however, Watt decided to toss in the towel, declaring the challenge of constructing a practical carriage insurmountable, owing to the weight of water and fuel it would have to carry (ibid.). Murdock soon accepted Watt's verdict, though he might well have desisted anyway without his employers' support. Either way, it makes little sense to treat the outcome as evidence of the blocking power of Watt's steam-carriage patent, let alone of his main engine patent: it was a simply a matter of Boulton and Watt's determination that there were better, which is to say more lucrative, uses for their most talented engineer's valuable time.[19]

A Credible Threat?

Having shown that *known* pioneers of high-pressure steam were not deterred by Watt's actual or pretended monopoly rights, it remains for us to address the possibility that *unknown* inventors were so deterred, and particularly that some were discouraged by Boulton & Watt's 1782 Bristol newspaper advertisement threatening to sue anyone who so much as enclosed the top of an engine cylinder.

Although the possibility in question obviously can't be disproved empirically, its implausibility can be established readily enough by appeal to the same game-theoretic considerations informing the modern theory of predatory pricing. According to that theory, as developed by Kreps and Wilson (1982) and especially by Milgrom and Roberts (1982), in the presence of uncertainty regarding whether an incumbent firm will find it worthwhile to prey on a new entrant, a "weak" incumbent—meaning one for which the short-run payoff from sharing exceeds that from preying, may still find it worthwhile to prey upon a new entrant so as to intimidate others. However, this will

[19] For further details concerning Boulton and Watt's grudging support of Murdoch's steam carriage project see Smiles (1890, pp. 133-6).

only be the case when the dynamic gains from reaping monopoly rents will at least make up for any short-run losses. Otherwise the incumbent firm has no choice but to reveal its weakness by sharing from the start, thereby undermining the credibility of its threat. As Milgrom and Roberts themselves (ibid., p. 299) put it, "if the established firm ever fails to prey, then there must be entry and sharing at every later stage."

We hold analogously that, because it was unlikely to win a suit brought against any rival that did not employ Watt's separate condenser, Boulton & Watt's position was that of a "weak" incumbent, whose threat was credible *only* if carried out at least once. By failing to do sue any maker of a non-condensing engine, and especially by failing to sue Jonathan Hornblower despite his direct calling of their "bluff," Boulton & Watt revealed their weakness, assuring other such rivals that they needn't fear molestation. Boulton & Watt did, on the other hand, sue rivals who used condensers, thereby intimidating others who might have done so, because they judged the probability of success high enough in these instances to make the gambit dynamically (if not immediately) worthwhile.

Why the Delay?

If Watt's monopoly rights didn't delay the advent of the high-pressure steam engine, what did? According to the more authoritative histories of the progress of high-pressure steam technology (e.g., Pole 1844; Albans 1848; Hills 1989), the cause was a combination of a low estimate of the thermodynamic advantages to be achieved through use of high-pressure steam, and a high estimate of the risks involved.

These were of course the reasons for Watt's own "continued refusal to admit the importance, or even the utility, of high-pressure steam" (Cardwell 1963, pp. 80-1). But Watt's Achilles Heel was hardly unique to him. It was also the Achilles Heel of Bull and of the Hornblowers and of practically every engine inventor and builder of Watt's era, all of whom inherited the "culture of low-pressure steam" (Marsden 2002, p. 124) established during Newcomen's long reign. To insist on blaming the slow development of high-pressure steam technology on Watt's patents is to tacitly assume that this "cultural conservatism" affected Watt alone, as if others inventors were immune. But they weren't, and the proof is that, until Trevithick, none tried the high-pressure gambit, even though doing so could have steered them clear of Watt's monopoly.

Nor was their conservatism unjustified. The dangers of high-pressure steam were real enough during the reign of Watt's patent, and continued to be so for some years afterward. In England 1046 boiler explosions killed 4067 persons and injured another 2903 between 1800 and 1866 (Marten 1872, p. 7).[20] In the U.S., where the technology was especially suited for low-drawing western steamboats, steamboat explosions alone—233 of them in all—caused 2562 deaths (and 2097 injuries) along with some $3 million in property damage between 1816 and 1848 (Leveson 1992, p. 3).[21]

High-pressure steam did not begin to gain ground against low-pressure alternatives until after 1800—and in England *well* after 1800—not because Watt's patent had stood in the way of its development, but mainly because state of the art of boiler design and engine component manufacturing lagged behind Savery's experiments with high-pressure steam by almost exactly one century. "It must be remembered," Donald Cardwell observes (1963, pp. 15-16),

[20] Nuvolari and Verspagen's (2009, p. 699) seemingly contrary claim that "in Cornwall high-pressure steam was employed very safely throughout the first half of the nineteenth century" is accounted for partly by the fact that most "Cornish" engines were equipped with Trevithick's improved, cylindrical boilers, and partly by the fact that these engines typically employed steam pressures at 50 lbs. psi or less, while true high-pressure engines exceeded 100 lbs. psi. Although Cornish engines could also be adapted to use steam at very high pressure, few were so adapted until toward the end of 19th century.
[21] According to Langlois, Denault, and Kimenyi (1994), the number of steamboat explosions per passenger mile declined more-or-less steadily during the period in question, thanks largely to improved boiler technology and new engine safety features.

> that as no-one had ever wanted great quantities of steam at high pressure before Savery came along, there were no high-pressure boilers available. No-one had developed the engineering and metallurgical techniques to make them. The result was that boilers available would not stand the high-pressure, and therefore high-temperature, steam. If the steam did not actually burst the boiler it forced its way out between the joints and seams. It even melted the solder; and…the relatively poor iron of the day would not stand up to sustained high temperatures for long…. Operating an early Savery engine must have been indeed an alarming occupation.[22]

This is precisely why mine owners rushed to embrace Newcomen's radical and perfectly safe low-pressure technology, having "eschewed" Savery's alternative (von Tunzelmann 1978, p. 16). By so doing they removed for the better part of a century whatever small incentive there had been for engineers to develop more pressure-resistant engine parts.

So when Trevithick decided to revisit the high-pressure option, he encountered the same equipment problems Savery had (cf. Trevithick 1872, v. ii, p. 78), and was forced to improvise. According to his son Francis,

> When the strained boiler and flinching rivets allowed the boiler-house to become full of dense steam, Trevithick told them [his crew] to cover it up with ashes, they would not see it quite so much then, and it would keep the heat in the boiler. Bran or horse-dung inside was a good thing as a stop-gap, though it added not to the strength of the boiler. Trevithick was himself in a cloud of steam in the engine-house (Trevithick 1872, ii, p. 78).

Trevithick, however, persisted, eventually coming up with his cylindrical "Cornish" boiler, constructed using wrought-iron plates and based on a design he first employed for his locomotive engine (Galloway 1881, p. 210). Woolf's early attempts to use high-pressure steam were, in contrast, frustrated by "his determined pertinacity in the use of his cast iron boilers" (Pole 1844, p. 53 n.96). Despite the relatively modest steam pressures his engines employed (around 40 psi), Woolf by his own account spent "many a sleepless night…repairing the many breakages of engines and boilers, caused by the

[22] Hills (1989, p. 19) observes, however, that Savery limited his engine's pressure to three atmospheres, implying a temperature too low to have actually melted soft solder, though perhaps high enough to render it pasty and deprive it of strength.

boilers being too weak for the strain attempted to be used, and the material of the engine not being strong enough for the concussion given by the sudden admission of much higher steam on the piston than was originally intended" (Jenkins 1933, p. 68).[23]

"Timid and Prejudicial Traditions"

In England high-pressure steam technology made slow headway even after reliable boilers became available. As Nuvolari and Verspagen (2009) note, a substantial improvement of British engine performance, based on the use of high-pressure steam, began only in the mid 1830s; and it was only in the ensuing decades, when it became British manufacturer's preferred power source, that steam power began to make s very substantial contribution to British productivity growth (Crafts 2004).

There were a number of reasons for this. One was simply that, where low-pressure Boulton & Watt engines were already in place, it was often more economical either to simply stick to the old engines (as many Lancashire textile mills chose to do with their old Boulton & Watt "rotative" engines) (Nuvolari and Verspagen 2009, p. 706), or (and especially where coal was relatively expensive) turn them into semi-high-pressure condensing engines (as Cornish miners did after 1810 with their huge reciprocating engines), than to switch to new high-pressure technology.[24] Elsewhere, in

[23] Jenkins (1933, p. 65) adds that, "even if the Woolf boiler was free from danger of explosion, it had serious drawback in continuous work; the expansion and contraction of the parts put a considerable strain on the necks between the tubes and the barrels, with the result that the joints were constantly leaking; to remedy the defect it would be necessary to stop work and draw the boiler fires. This was a very important consideration from the mine manager's point of view, so the Woolf boiler went out of favor."

[24] Whether Cornish mine owners might have profited by so modifying their engines before 1800, had the necessary boilers been available then, remains an open question: in principle Boulton & Watt was entitled to royalties equal to one-third the value of fuel savings attributable to their engine design, and not to those attributable to other improvements. In practice, however, it would have been very difficult and perhaps impractical to attempt to untangle the distinct sources of savings. It is also conceivable that Boulton & Watt would somehow have been able to refuse permission to modify their engines. In the latter cases, Boulton & Watt's peculiar way of profiting from their monopoly (by assessing royalties rather than selling their engines outright), rather than the monopoly *per se*, would have constituted a barrier to innovation. (We thank Alessandro Nuvolari for sharing his conjectures on this matter.)

contrast, the progress of high-pressure steam was relatively rapid: in Birmingham, for example, by the late 1830s high-pressure engines already accounted for more than half of all horsepower additions (von Tunzelmann 1978, p. 89). The slow diffusion of high-pressure steam technology in some regions of Great Britain relative to other regions, and also relative to America, thus reflected in part an adoption "threshold" rendered high by the very same sunk-cost considerations that had limited the uptake of Watt's own invention during the previous century (von Tunzemann 1978, pp. 75-77). To paraphrase von Tunzelmann (ibid., p. 76), substituting "Boulton & Watt" for "Newcomen," "low-pressure" for "atmospheric," and "high-pressure" for "Boulton & Watt," "If [a factory or mine] already had a Boulton & Watt engine installed, it would pay to scrap the low-pressure engine only when its variable costs rose above the *total* costs of the new high-pressure engine."

Second, the belief that high-pressure steam was excessively dangerous persisted despite substantial safety improvements. "It seems," James Renwick observed three decades after the expiration of Watt's patents,

> to be *now* conceded, that with proper precautions, boilers generating high steam may be rendered as safe as any others; and hence the conclusion has been drawn that high steam, acting expansively, as it is the most powerful application of steam, will, whenever circumstances will admit, supersede all other methods (Renwick 1830, p. 228, our emphasis).

According to inventor James Nasmyth, it took until the late 1840s for Lancastrians to finally overcome their "timid and prejudiced traditions" favoring low-pressure steam (Nuvolari and Verspagen 2009, p. 698). Elsewhere resistance persisted still longer. "We have often been surprised," steam engineer John Bourne observed in 1849, "at the tenacity with which some firms will stick to the old-fashioned low pressure steam, 4 or 5 lbs. p.s.i., even when the chance of putting in new boilers occurred" (quoted in von Tunzelmann 1978, p. 90). In the government dockyards alone, Bourne continued, "thousands of pounds per annum are wasted by the high-pressure-phobia of the authorities," who appear to have endured "a severe pang" in allowing as much as 16 lbs. p.s.i. in their faster mail boats (ibid.). Ernst Albans (1848, pp. 13-14), then Europe's leading champion of high-pressure steam, likewise complained in 1843 that, despite having been around for four decades, high-pressure engines "are treated as if already condemned: their advantages are generally doubted, or conceded only in a slight degree, and for certain applications; an outcry is made as to the great danger with which their use is attended."

Finally, Watt's reputation and influence among other engineers and inventors undoubtedly played a part. "It is *never* advisable," he once wrote (in Pole 1844, p. 49; our emphasis), "to work with a strong steam when it can be avoided, as it increases the leakages of the boiler and joints of the steam case, and answers no good end"; and Watt never ceased to campaign against the rival technology. In this he resembled Thomas Edison, who would similarly campaign against high-voltage electricity and in favor of his own low-voltage alternative. Nor was Watt averse to manipulating facts to suit his goals, as he and Boulton did in 1803, following the explosion of one of Trevithick's boilers. The partners misrepresented the cause of the accident, which appears to have been, not any flaw in Trevithick's design, but what is nowadays labeled "human error."[25] They then lobbied, unsuccessfully, to get Parliament to outlaw Trevithick's technology (Galloway 1881, p. 210).[26] It perhaps owed in part to Watt's looming authority, and not just to their own unhappy experience with frequent engine failures, that Cornish mine

[25] Watt even accused Trevithick of manslaughter, declaring that he "wants hanging."

[26] However unscrupulous Watt may have been, his horror of high-pressure steam appears to have been perfectly sincere. He even went so far as to include a clause on the lease of his house "providing that no steam carriage should under any pretext be allowed to approach it" (Williams 1910, p. 104).

owners resisted the employment of steam at very high pressure in their pumping engines, despite the greater duties, and corresponding savings, they might have achieved that way (Trevithick 1872, v. ii, p. 74).

So Watt may, after all, have hindered the progress of high-pressure steam power. But if he did so, it was through the authority he commanded as an engineer and inventor, if not as a "philosopher" or scientist, and not because of monopoly rights granted him by the British government. [27] The two channels of influence must not be confused if correct inferences are to be drawn concerning the influence of Watt's patent, or of patents more generally, on technological progress..

Conclusion

James Watt's famous steam engine patent did not possess the extreme legal "blocking power" that has so often been attributed to it. Although the patent did prevent rival inventors from building atmospheric or low-pressure engines that improved on Watt's design, or from building any sort of engine that employed a separate condenser, the patent did not prevent rival inventors from building non-condensing high-pressure steam engines, which were to be the basis for the dramatic diffusion of steam power during the 19th century, and the only type applicable to locomotives and boats. Watt's patent may have been legally unsound, and it may not have been beneficial on the whole. But whatever its true shortcomings may have been, the patent does not deserve the reputation it has garnered as a "classic" instance of an innovation-blocking intellectual monopoly.

[27] Compare Matthias (1969, p. 123) and von Tunzelmann's (1978, p. 89) (who refers to the influence of Watt's "heavy hand.") D.P. Miller (2000) offers a fascinating look at the bearing of Watt's reputation on Boulton & Watt's commercial success, albeit one that stresses the role Watt's status played in the successful defense of his patent rather than in discouraging other inventors from trying high-pressure steam.

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