Strong Steam, Weak Patents, or,

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

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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":

> It was not merely that they could not use the separate condenser. Watt held that the patent covered every one of his 'principles,' whether used together or separately, so, for instance, they were precluded from putting a cover to the cylinder and using steam instead of the atmosphere to press on the piston.

Economic historians, including John Kanefsky (1978), Joel Mokyr (1990), and Alessandro Nuvolari (2004), have drawn similar conclusions. Mokyr, for example, states (1990, p. 247 n.9) that Watt's patent "effectively blocked the development of a high pressure engine, even though Watt himself firmly opposed such engines." Cultural historian Ben Marsden (2002, p. 99), finally, 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 the extension of their monopoly rights "was disastrous for their opponents, stifling competition—and…hampering or altogether blocking technological progress."

It is hardly surprising, therefore, that Michele Boldrin and David K. Levine should open their recent assault on patents and other forms of "intellectual monopoly" with an account of Watt's story. According to Boldrin and Levine (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).

But plain as the evidence for it may seem, we intend to show that the common view of the consequences of Watt's patent is false. Although it's true that high-pressure steam technology developed only after the expiration of Watt's patent, the delay was due to factors other than that patent itself, including the widely-held opinion 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 would-be rivals to revive a supposedly obsolete technology so as to evade his patent.

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 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, in having the cylinder itself serve as a condenser, it wasted fuel, as the cylinder would have to be reheated to at least 212° after each power stroke. The invention that made Watt famous, by allowing steam power to be economically employed even in draining the copper mines of coal-starved Cornwall, consisted of an external condenser in which exhausted steam could be condensed without also cooling the engine cylinder.

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 exhausted steam was admitted to serve in place of the atmosphere to assist the piston's downward stroke.[1]

Besides making Watt's engines still more efficient 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. He did so, first, by applying it to his "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. Then, 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

[1] 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.

the steam when the piston had completed only part of its length, and then let the steam's continued expansion do the work needed to finish the stroke. For example, steam introduced at four times atmospheric pressure could be shut when the piston had risen one-quarter of the cylinder length. Since raising temperature (and hence the pressure) of steam was essentially costless, the savings in volume translated into a corresponding gain in fuel efficiency.

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 did not pursue this potential. 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 new plan for working steam expansively hardly compensated for the extra difficulties involved. Consequently Watt ended up equipping only a very small number of his engines for expansive working (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, still wasted fuel; and, second, that the creation of a vacuum remained essential to their 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.* 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 worth while 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.

Condensing engines were therefore especially unfit for locomotives and steamboats—two of the inventions that are supposed by Boldrin and Levine (p. 15 n.5) to have been "blocked" by Watt's patent.[2] But even in stationary applications with plenty of space at hand it was usually 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). Finally, condensing engines were usually uneconomical where abundant supplies of cold water were lacking.[3] Indeed, so exceptional was the use of condensers on stationary engines that, until at least the middle of the nineteenth century, the terms "low-pressure steam engine" and "condensing steam engine" were virtually synonymous.[4]

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).

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

[3] Just before 1808, 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, 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).

[4] 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).

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 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 begins by setting 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).

We must therefore ask whether these provisions of Watt's patents secured for him a monopoly, not only 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.

The answer, we intend to show, is a decisive *no*.

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. 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 could not reasonably have expected to secure a monopoly of the expansive working of steam 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.[5]

Second, to be patented an invention had to be new. Indeed, if any feature of the invention for which a patent was secured could be proven to have been known before the patent was sealed, a patent might be vitiated *in its entirety.* 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

[5] 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 the same basic idea, as embodied in his unique "compound" engine, the year before.

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 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. [6]

Both the abstract nature of Watt's specifications concerning the expansive working of steam and 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. Besides being extremely costly (owing to the need for testimony by expert witnesses), any such action might have resulted, not only in a judgment for the defense, but in the annulling of Watt's less legally-problematic monopoly rights, including those to his separate condenser. [7]

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[6] 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."

[7] The suits that Boulton and Watt did launch, described in the next section, are said to have cost the firm upwards of £10,000 in legal fees.

"The Stormy Sea of the Law"[8]

Consistently with the above argument, Boulton and Watt went to court to defend their firm's patents only against rivals whose engines employed separate condensers. 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 merely *threatened* to sue him, along with all other makers of engines featuring a "Piston pressed down by steam."[9] 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), called Boulton & Watt's bluff, and the rival firm never carried out its threat.[10]

Boulton and Watt did successfully oppose Hornblower's 1792 bid to have his 1781 patent extended. But by then Hornblower was equipping his engines with separate condensers, and Boulton and Watt carefully confined their testimony to this fact "without so much as hinting at a suspicion that Hornblower had pirated the principle of expansion from them" (Pole 1844, p. 31).

A year later, when Boulton and Watt did bring 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). Although two of the

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[8] The expression is from Watt's correspondence, Watt to George Hamilton, September 24, 1782, in Muirhead (1854, v. ii, p. 161).

[9] "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."

[10] Although the Hornblowers ignored Boulton & Watt's threat, it is conceivable that other would-be makers of non-condensing engines were deterred by it. Watt's patent may thus have indirectly impeded the progress of high-pressure steam, by contributing to the threat's credibility. Here it is perhaps desirable to distinguish between a patent's *de facto* and its *de jure* blocking power.

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, all four judges regarded the fourth article of Watt's specification, concerning the expansive working of steam, as an attempt to patent "mere principles," hence contrary to the statute. It thus appears that, had Bull merely employed steam expansively, without using a (separate) condenser, all four judges 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. Hornblower and Maberly.* 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 specification referring to his "contrivance" for condensing steam more efficiently, these alone having been found to fall "within the Statute of James."

To summarize: 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.[11] What's more, their would-be rivals understood it, however much they may have failed to take full advantage of the fact.

High Pressure Pioneers

Bull and the Hornblowers failed in not having made use of high-pressure steam, which would have allowed them to dispense with condensers. It 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 double-cylinder or "compound" engine, and as Richard Trevithick would do using a variant of Watt's single-cylinder design.

Trevithick's case is particularly instructive, because he is generally supposed to have been inspired to try high-pressure steam, despite the prevailing consensus that that technology was a dead end, by his desire to avoid running afoul of Watt's patent. According to Williams (1910, p. 112), for instance, after Bull was sued in 1793 Trevithick, who'd been his assistant, felt "obliged…to turn his attention to a different

[11] Concerning Watt's familiarity with English patent law, see Robinson (1972).

method, and probably, in part at least, in this way was led to introduce the non-condensing, relatively high-pressure engine."

Trevithick's experiments with high-pressure steam began a few years prior to the expiration of Watt's patent. Once the patent expired Trevithick was of course perfectly free to employ a condenser. Yet he chose not to, so as to make his engine more suited to places lacking abundant source of cold water for condensation (Pole 1844, p. 5). Trevithick's prototype "puffer," so-called because of its noisy disgorgements of waste steam, was erected 1814 and was tried in March 1816.[12]

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 by the mid-1820s experience had shown that the compound engine was less economical than its high-pressure, single cylinder counterpart. The design was therefore abandoned in England, although it continued to gain ground in France.[13]

Why the Delay?

If Watt's intellectual 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; Nuvolari and Verspagen 2004), the cause was a combination of a low estimate of the efficiency gains to be achieved through use of high-pressure steam, especially without the aid of a condenser, and a high estimate of the risks involved.

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[12] Later Trevithick would help develop the so-called "Cornish" engine—a hybrid made from condensing Boulton and Watt engines converted so as to make use of moderately high-pressure steam.

[13] Starting in 1839 James Sims attempted a British revival of the compound engine, using a version of his own design. But it, too, was eventually found to be less economical than rival single-cylinder designs. Boldrin and Levine's claim (2008, p. 4) that it was the compound engine, "and not the Boulton and Watt design, [that] was the basis for further steam engine development after their patent expired" is quite erroneous.

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. Those who, like Boldrin and Levine, insist on blaming the slow development of high-pressure steam technology on Watt's patents, tacitly assume that this "cultural conservatism" affected Watt alone, as if others inventors were immune. But they weren't, and the proof is that they didn't try the high-pressure gambit even though doing so would have steered them clear of Watt's rights.

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). In the U.S., where the technology was especially well adapted for low-drawing steamboats, steamboat explosions alone—233 of them in all—caused 2562 deaths and some $3 million in property damage between 1816 and 1848 (Leveson 1992, p. 3).[14]

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

[14] Nuvolari and Verspagen's (2004, pp. 12-13) seemingly contrary claim that "in Cornwall high-pressure steam was employed very safely throughout the first half of the nineteenth century" is readily accounted for by the fact that Cornish engines used steam at less than 50 psi, while true 'high pressure" engines used it at more than 100 psi. Although Cornish engines could be adapted to use steam at very high-pressure, few of them were so adapted until toward the end of 19th century.

> 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.

This, of course, is precisely why mine owners rushed to embrace Newcomen's radical and perfectly safe low-pressure technology, rendering Savery's obsolete, and removing 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 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 likewise frustrated by "his determined pertinacity in the use of his cast iron boilers" (Pole 1844, p. 53 n.96).

That Oliver Evans, who is widely considered the true inventor of the high-pressure stationary steam engine, erected his first successful engine around the same time as Trevithick, also suggests that factors apart from Watt's patent were behind the

late arrival of high-powered steam. Evans was, after all, an American, whose efforts could not possibly have been barred by any English patent.[15]

"Timid and Prejudicial Traditions"

In England high-pressure steam technology made little 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. There were a number of reasons for this. One was simply that, where low-pressure Boulton and Watt engines were already in place, it was often cheaper either to simply stick to them, as was done in Lancashire where coal was relatively cheap (Nuvolari and Verspagen 2004, p. 15), or to convert them into semi-high-pressure "Cornish" engines, using steam at about forty pounds per square inch, as was done in Cornwall, than to replace them with genuine high-pressure engines using steam of 100 psi or more.

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).

Inventor James Nasmyth likewise observed that it took until the late 1840s for Lancastrians to finally overcome their "timid and prejudiced traditions" favoring low-pressure steam (Nuvolari and Verspagen 2004, p. 11). However, at that late date Ernst

[15] Despite several attempts Boulton and Watt never managed to secure any patent privileges in America.

Albans (1848, pp. 13-14), then Europe's leading champion of high-pressure steam, was still able to complain 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 authority 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."[16] They then lobbied, unsuccessfully, to get Parliament to outlaw Trevithick's technology (Galloway 1881, p. 210).[17] 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 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).

[16] Watt even accused the rival inventor of manslaughter, declaring after the accident that "Trevithick wants hanging."

[17] 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).

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, and not because of any privileges granted him by the British government.

Conclusion

Whatever other effects it may have had, Watt's patent did not possess the "blocking power" often have attributed to it. The patent did not prevent rival inventors from building high-pressure steam engines, so long as they were non-condensing engines. And non-condensing high-pressure engines were generally more versatile than condensing ones. Watt's patent may not have been necessary to his own invention, or even generally beneficial; but neither was it the archetype of innovation-hindering monopoly.

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