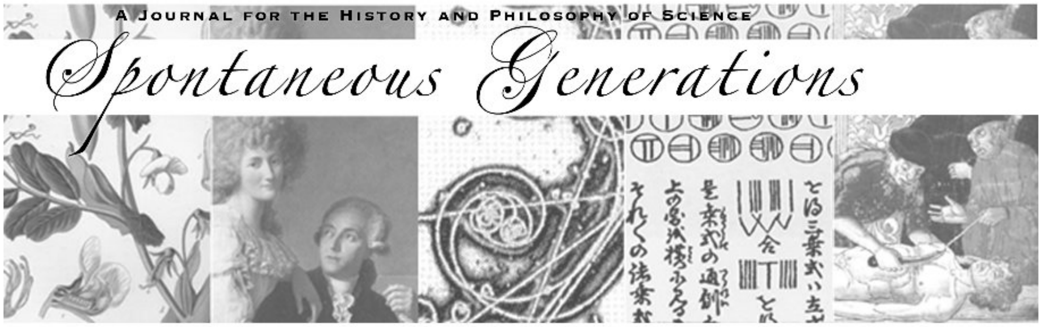

Domesticating the Magnet: Secularity, Secrecy, and Permanency as Epistemic Boundaries in Marie Curie's Early Work

Author(s): Graeme Gooday

Source: *Spontaneous Generations: A Journal for the History and Philosophy of Science*, Vol. 3, No. 1 (2009) 68-81.

Published by: The University of Toronto
DOI: 10.4245/sponge.v3i1.10615

Domesticating the Magnet

Secularity, Secrecy, and Permanency as Epistemic Boundaries in Marie Curie's Early Work[*][†]

Graeme Gooday[‡]

This paper investigates the magnet as a classic "boundary object" of modern technoscientific culture. Equally at home in the nursery, in the dynamo, in measuring instruments and in the navigational compass, its capricious performance nevertheless persistently eluded the powers of nineteenth-century electromagnetic experts in pursuit of the completely "permanent" magnet. Instead the untamed magnet's resilient secularity required its makers to draw upon ancient techniques of chemical manipulation, heat treatment, and maturation eventually to render its behaviour sufficiently stable for orderly use in modern engineering. The precise methods for accomplishing this quasi-permanence were typically protected by trade secrecy–that is, until Marie Sklodowska Curie's first research publication in 1898 opened up this topic for rigorous comparative research. Over the next quarter century, her work in this field was gradually eclipsed by heavily gendered citation practices; the futility of attempting to establish complete permanency in magnets was eventually substantiated by Sydney Evershed in the 1920s.

Long an ornamental accessory to global cultures and a life-saving tool for compass-based navigation, the magnet arguably became a paradigmatic boundary object in the nineteenth century (Star and Griesemer 1989). For children, it was an amusing toy; in the scrap yard, an industrial lifting tool; for power engineers, the driving force in the dynamo; for laboratory researchers, the means of directive control. And

---

[*] Earlier versions of this paper were presented in seminars at the University of Leeds and University of Cambridge. I am especially grateful to Soraya Boudiya, Matthias Dörries Patricia Fara, Sophie Forgan, and Vivien Hamilton for their constructive comments and to Chris Baxfield and Berris Charnley for their editorial assistance.

[†] Received November 2009.

[‡] Graeme Gooday is a Professor of History of Science and Technology at the Centre for History and Philosophy of Science, Department of Philosophy, University of Leeds. Following *Domesticating Electricity: technology, gender and uncertainty 1880–1914* (Pickering and Chatto, 2008), his current research focuses on historicizing issues of knowledge management ("intellectual property"). The project he leads, "Owning and Disowning Invention," is developing revisionist accounts of patenting, secrecy and public research in relation to the changing social contract for technoscience in the period up to and including World War 1–see owninganddisowninginvention.org.

for most instrument makers and users, the main constituency discussed in this paper, the magnet was the controlling force in measurement devices needed to manage the electrotechnology of modernity (Gooday 2004). For many of these purposes the so-called permanent magnet was expected–the idealized magnet that did not capriciously change its strength, but sustained its powers without regulation, epitomizing the much-fantasized about inorganic constancy of modern industrial culture. In theory, such magnets would lie at the core of reliable devices, invulnerable to the chaos of error and technical breakdown threatened by impermanent (and thus unreliable) performance.

This aspiration to permanence was problematic for Victorians. Not only was it difficult in practice to tame magnets to such orderliness, but there were no theoretical resources available to help with this task. Indeed, as Pierre Duhem archly noted in 1915, the permanent magnet was actually a theoretical *impossibility* in the Maxwellian theory of electromagnetism; so much the worse for Maxwell and his followers (Duhem 1996, 268). Most inconveniently of all, there was no reliable short-term laboratory test of permanence; only an elapse of years, or even decades, would reveal whether or not expectations of orderly behaviour were upheld or confounded. Modernity and electrotechnology therefore had at their interface a recalcitrant, un-modern entity that epitomized ancient interpretations of the magnet as bearing organic qualities of variability, vulnerability, and secularity (Fara 1996). The latter point is the most subtle, as it is bound to the slow unfolding and understanding of phenomena that evolved over extended periods and were therefore only properly comprehensible in the *longue durée*.

This theme was articulated most eloquently by Ralph Waldo Emerson in 1844:

> Geology has initiated us into the secularity of nature, and taught us to disuse our dame-school measures, and exchange our Mosaic and Ptolemaic schemes for her large style. We knew nothing rightly, for want of perspective. Now we learn what patient periods must round themselves before the rock is formed, then before the rock is broken, and the first lichen race has disintegrated the thinnest external plate into soil, and opened the door for the remote Flora, Fauna, Ceres, and Pomona, to come in. (Emerson 1876, 147)

During the latter part of the nineteenth century, this type of theme was adopted by those in the natural sciences and engineering who found that even their most cherished materials were not entirely immune to gradual change, and indeed typically drifted from prior calibration. Accordingly, those instrument makers who thought they had the optimum solution to this problem of permanent magnetism kept their methods protected as trade secrets. I show that these issues were first openly subjected to systematic treatment in Marie Sklodowska Curie's very first research paper of 1898, albeit in ways that were subsequently erased from the genre of magnetic scholarship that she helped to create. In addition to the now well-established boundaries of gender that have recurrently marginalized women's original research in technology and science, this paper explores three further epistemic boundaries: the permanent magnet as beyond the reach of theory, public scrutiny, or laboratory validation.

I. CRAFT SECRETS V. ENGINEERING EXPERTISE IN TAMING THE "PERMANENT" MAGNET

The first English language treatise on the making of permanent magnets, William Gilbert's *De Magnete* in 1601, drew heavily upon the expertise of the unlettered craftsmen who made compass needles using techniques that were already centuries old (Gilbert 1958; Pumfrey 2001). In the ensuing decades, instrument makers borrowed from Gilbert's epitome and used particular chemical forms of steel and specialized methods of quenching and heat treatment to make magnets with a minimal tendency to lose strength either over time or from exposure to other magnets. It was also gradually noted over the centuries that older magnets tended to become more stable over time, yet became weaker as they grew more stable. Subsequently, instrument makers introduced thermomechanical techniques–wryly anthropomorphized as artificial aging or maturing–to hasten the more sedate reliability of vintage magnets.

The advent of new forms of electric power and lighting after 1878 (e.g., Jablochkoff arc lights and Edison and Swan incandescent lamps) prompted instrument designers and manufacturers to devote renewed attention to the problem. Some regarded permanent magnets as ideal for new instruments that needed to measure currents much stronger than those used in telegraphy. Yet even they soon discovered that in engineering environments such instruments could overestimate readings by up to 50 percent as their readings decreased and vice versa. Therefore, some preferred to use instruments with springs or electromagnets less inclined toward capriciousness as a result of the harsh material conditions of electrical power technology (Gooday 2004, 128-71).

The problem discerned by the genteel consultant engineer James Swinburne was magnetic "memory"–a mark of lingering anthropomorphism in the characterization of the decidedly un-modern performance of the magnet (Swinburne 1888, 25-56). During the 1880s

Alfred Ewing in Tokyo and Emil Warburg in Berlin showed that all magnets–to a greater or lesser extent–bore traces of recent encounters with magnetic influences (Dörries 1991). Ewing and his Japanese assistants adopted the Greek term *hysteresis* to characterize this feature, then mapped out the *desiderata* of a permanent magnet (Ewing 1883; Ewing 1886; Ewing 1939). As specified by John Hopkinson in 1885, the key requirement was not just to make a magnet as strong as possible; rather, maximizing its coercitive force–the magnetic field required to demagnetize it–would limit the exasperating technological effects of magnetic memory[1] (Hopkinson 1901, 455-69). Determining how magnets could be constructed to meet these two theoretical *desiderata* was thereafter the key empirical challenge for magnet makers, though unaided by any accepted theory of the operation of magnets.

By 1890, such was the apparent progress made by one Edward Weston's instruments in the United States that one devoted New York user argued against "the general distrust of permanent magnet instruments." Weston's instruments were now reliable within a 0.1 percent margin for controlled laboratory work and 2 percent for engineering projects, demonstrating "substantial evidence of a reformation of their past character"[2] (Colby 1890, 279). The British instrument maker Sydney Evershed, however, was slightly more sceptical. In his first public comment at the Institution of Electrical Engineers (IEE) a year later, he commented that had he been asked 10 years before whether anything was permanent in the world, he would have said he did not know but "certainly not permanent magnets." Evershed admitted that most instrument makers–like Weston–could now "trust" permanent magnets if they were just "left alone" to age; yet after a recent relocation from central to West London, Evershed reported that at least one of his instruments had become rather less trustworthy (Sankey and Andersen 1892, 569-71). It suffices to say that, for the next 40 years, neither Evershed nor his fellow-instrument makers left such magnets alone in their ongoing project to bring some kind of permanence to so-called permanent magnets.

Until Marie Sklodowska Curie's research was published in 1898, the details of the proprietary techniques for maximizing the permanence of magnets were to a certain extent protected by conditions of trade secrecy, especially for the third stage of artificial aging. As general techniques had been public knowledge since Gilbert's time, they could not be patented. So

---

[1] Ewing and Hopkinson developed the two-dimensional hysteresis diagram to represent how magnets changed strength in response to external magnetic influences, with distinctly different "ideal" forms of steel used in permanent magnets and in dynamo construction.

[2] See also "Notes", *The Electrician* 126(1890) 128.

makers protected their special methods in conditions of secrecy instead. This secrecy prevented both rival manufacturers stealing their methods and prospective customers from critically analyzing their results. However, the gentleman instrument maker Kenelm Edgcumbe claimed in 1904 that the level of secrecy involved had been somewhat overstated:

> The aging process is looked upon by nearly every maker as his own "trade secret," but as a matter of fact every other maker knows precisely the method he employs, and is at the same time quite confident that his own method is the only correct and infallible one. (Edgcumbe and Punga 1904, 625)

Occasional hints had by then emerged in print about artificial aging. James White's company in Glasgow, Scotland, which made magnets for Sir William Thomson's patent instruments, subjected them to "rough usage," mostly repeated boiling and cooling (Thomson 1888, 545; Edgcumbe 1918, 66). To counter the broad prejudice against permanent magnets, Swinburne's 1888 manual reported other common techniques of artificially aging magnets, including hammering, dropping, heating to various degrees, and exposure to other magnets to partially demagnetize then remagnetize. Yet neither Thomson nor Swinburne divulged in print the exact temperatures, configurations, and durations of the processes involved, which would have enabled rival makers or consumers to reconstruct their precise proprietary methods (Swinburne 1888, 27). Indeed very few scholars or industrial researchers in the 1880s published any general recommendations on the three key processes of magnet making; any published guidelines available were not based on any protected company techniques (Barus and Strouhal 1885).

By the 1890s, stories of secret French developments in the chemical manipulation of magnet steel were circulating in the United Kingdom. In 1890, William Preece, Chief Electrician of the British Post Office, voiced concerns about the deteriorating quality of the British-made magnets used by telegraphists in his jurisdiction (Preece 1890a, 320-21). Having secured a range of French magnetic steels from his counterpart in France, Preece found these were 50 percent more reliable than the best British samples. One instrument-making consultant, John Perry, also speculated openly that certain French steel makers had a secret technique of tempering steel that was yet to be divulged to British practice (Preece 1890b, 546-49). When the Parisian metallurgist Floris Osmond spoke about this issue to the Physical Society of London in April 1890, critics attacked his silence on the marked effects of tungsten in the best French magnetic steels (Osmond 1888, 282-86). Therefore, it was with great interest that Preece and others read the most comprehensive study to come out of France in

1898–99: Marie Sklodowska Curie's study of the magnetic properties of heat-treated steels of French manufacture and design.

II. MARIE SKLODOWSKA CURIE'S STUDIES ON PERMANENT STEEL MAGNETS 1895-98

In 1894, there were few employment prospects open to Marie Sklodowska as she approached the end of her studies in the theory and practice of magnetism and electromagnetism under Gabriel Lippmann at the Sorbonne in Paris, France. Through Lippmann's patronage, however, she soon secured a commission from the Société pour l'Encouragement de l'Industrie Nationale (SEIN) to produce a systematic study of the best techniques and materials for producing "des bon aimants permanents" (Letté 2004, 65, 89-90). Supplied with forty-seven samples of magnetic steel from France's leading manufacturers, she soon found the scale of her task impractical in Lippman's laboratory[3] (Curie 1898a, 3). Through a mutual acquaintance she met Pierre Curie who invited her to work in the corridor of his laboratory at the école de Physique et Chimie, where they would later collaborate as a married couple on radioactivity research (Curie 1938, 102).

Having familiarized herself with the small corpus of published studies on magnet-making, and adopting the standardized phenomenology of hysteresis, she began work on her four-year industrial project.[4] Her results confirmed the unusually effective qualities of tungsten; she went on to specify an optimum amount of tungsten of 5.5 percent–a proportion that soon became standard in UK magnets thereafter. Her most novel claim, however, was that the best permanent magnets used steel alloys with 1.2-1.7 percent molybdenum. This was a striking discovery, as molybdenum steel had not previously been used for commercial magnet making. Her next discovery was more radical still, refining magnet makers' practice of hardening magnet steels by plunging them from a red heat into a cold liquid. Sklodowska borrowed from John Hopkinson's 1890 paper and Pierre Curie's 1895 doctoral thesis concerning the demagnetization of steel above a certain critical temperature[5] (Hopkinson 1890, 442-46); she

---

[3] She also received advice from metallurgist Georges Charpy on metallurgical furnaces–very different from the heating techniques used by Pierre Curie in his contemporary doctoral research on paramagnetism.

[4] For a study of Marie Curie's later industrial-scale researches on radio-activity, see Boudiya (2001). I am grateful to Soraya Boudia for confirming that there are no extant notes from Marie Curie's steel research.

[5] Pierre identified two temperatures, the upper Curie point, the temperature at which metals lost their ferromagnetic properties, and the lower Curie point, the temperature at which cooling metals returned to ferromagnetic conditions. See Pierre Curie's 1895 PhD thesis published as "Propriétés magnétiques des corps a diverses températures" (Curie,

claimed that the most effective permanent magnets were made from steel heated to the uppermost critical point then quenched before they cooled to their lowest critical point, The strict necessity for this, however, was soon contested by Osmond and the American metallurgist Henry Howe, both evidently somewhat resentful at her incursion into their specialist area of expertise.[6]

In 1897, during the final phase of Sklodowska's research concerning artificial aging of magnets, she suffered daily pregnancy-related attacks of dizziness. Her work at this time built on Barus and Strouhal's work for the US Geological Survey: for ordinary purposes they had recommended reheating hardened steel at about one hundred degrees Celsius (sixty degrees for magnets in precision instruments) for long periods of time before magnetization, and again for a short period after magnetization (Barus and Strouhal 1885). After days of repeatedly baking and hitting a variety of magnets, Sklodowska concluded that all forms of steel should be heated to no more than sixty to seventy degrees Celsius, for about forty-eight hours; further, they should be magnetized to saturation then demagnetized by 10 percent by non-percussive means. Revealingly, at the very end of her paper she apologizes for not completing any long-term trials on the permanency of her magnets–and thus not confirming her claims for the permanency of their strength. She does show, however, that from July to September magnets made to her specifications did not detectably change in strength. The last such measurement took place on September 18th, four days after giving birth to Irène, her first child with Pierre (Quinn 1995, 130).

Upon receiving her work in December 1897, the SEIN immediately announced that Skolodowska Curie's paper was "important," publishing all forty pages in three distinct forms over the next four years. It was soon abstracted and translated for journals of metallurgy and electrical engineering, not only in France but also Britain and the United States under the English title, "Magnetic Properties of Tempered Steel."[7]

1908).

[6] Osmond complained that Marie Skolodowska Curie did not mention any of his work in her paper. Like Howe, he also challenged her claim that it was necessary to heat steel to a non-magnetic condition before quenching in order to attain permanent magnetism. See correspondence in *The Metallographist* 1 (1898) 266-70.

[7] The SEIN published an abstract for its Bulletin for December 1897, followed by the forty page paper in 1898. Such was its enthusiasm that the SEIN also published it as an independent monograph in 1898. A short version of the paper focusing on the comparative merits of tungsten and molybdenum steels was published in an 1897 issue of *Comtes Rendues* (125: 1165-69), and the Academie des Sciences awarded her a prize for the paper. See also version in *Metallographist* published above; and Curie (1899). A copy of her paper was also sent to the Iron and Steel Institute: see *Journal of the Iron and Steel Institute* 53 (1898), 504-05.

Sklodowska Curie did not thereafter publicly discuss her research, nor did she defend it against criticism–she and Pierre were far too busy pursuing a new subject: radioactivity (Curie 1923; Curie 1898b; Curie 1989b; Wolke 1988; Pycior 1993; Pycior 1996). Nevertheless, the appropriation of her work by others sheds valuable light on the shifting epistemic boundaries of permanent magnets, as well as the gender issues surrounding recognition of her expertise.

III. BOUNDARIES RESOLVED AND REMADE: THE RECEPTION OF MARIE CURIE'S WORK ON MAGNETS

In January 1899, the London technical periodical *Electrical Review* acknowledged Mme Curie's paper as one of "the most important" recent contributions to the study of permanent magnetism. Yet the review was somewhat ambivalent about her originality, complimenting her for "patient and systematic work," but initially contending that she did not offer anything new, just information that was "more extensive, varied and exact" than anything previously published. The breadth of this research lent Sklodowska Curie, the first female researcher in magnetism, the status of an authority on permanent magnets; to avoid this uncomfortable implication, the editor contended that she had merely publicized rules long-known but kept secret by instrument makers (Steel for permanent magnets 1899, 33-35). Yet such patronizing suspicions did not prevent the *Electrical Review* from extensively editorializing her work or reproducing a nearly complete translation of her paper over the following three weeks (Curie 1899, 75-76, 112-13).

The significance of her work on steel remained unresolved even after she won her first Nobel Prize with Pierre Curie and Becquerel for their research on radioactivity in 1903. The following year, Kenelm Edgcumbe (later the Earl of Edgcumbe) of the company Everett-Edgcumbe and his assistant presented a paper on electrical switchboard instruments at the IEE, during which they spoke as though the problem of permanent magnets had been solved. Yet they did not specify how, when, or by whom (Edgcumbe and Punga 1904, 625). In the ensuing discussion, however, two commentators pinpointed Sklodowska Curie's work as crucial to the solution. Rookes E.B. Crompton, veteran of Indian colonial service and dynamo manufacturing who had anathematized permanent magnets twenty years before, now saw much of value in her analysis of critical temperatures:

> All instrument-makers are deeply indebted to Marie Curie for the excellent work she has published in regard to the saturation and persistence of magnetism in steel bars. Madame Curie

> has pointed out how much depends on the exact temperature to which the magnet steel must be heated before being plunged, and if her directions are closely followed excellent and concordant conditions invariably follow. The work that she has given to the world in this respect is almost unique in its character and accuracy. This accuracy in the production of permanent magnets has been a great boon to instrument makers. (Edgcumbe and Punga 1904, 656-57)

Further positive comments on Sklodowska Curie's work came from Sydney Evershed. His experience with taming magnets came from developing the globally successful "Megger," a portable ohmmeter for resistance measurements.[8] Evershed claimed her results to be "very valuable," although not quite sufficient to prepare magnets that maintained complete permanence. Importantly, he was rather guarded about revealing what–if anything–needed to be added to her methods in order to achieve this goal. Evershed thus upheld the boundary-maintaining tradition of trade secrecy in such matters (Edgcumbe and Punga 1904, 663-64).

The most powerful endorsement of Sklodowska Curie's work came from Silvanus Thompson in a paper he read at a meeting of the IEE in Glasgow in 1912. Thompson knew Sklodowska Curie personally and was highly sympathetic to women's participation in electrical work.[9] He cited her paper frequently in his lecture and was evidently impressed by the originality of her analysis of alloy steels, especially molybdenum and tungsten varieties. Thompson's recurrent use of graphs based on her figures, which he explicitly cited as her work, was evidently an attempt to persuade engineers and magnet makers that her work was authoritative. As did Evershed and many others, he concurred that Sklodowska Curie's recommendation of 6 percent tungsten steel was ideal; like Crompton, he reiterated her advice about critical temperatures and rapid quenching in making magnetic steels (Thompson 1913, 85,

---

[8] Evershed started his career in 1885 as a manager of a small London electrical instrument manufacturer, Goolden & Trotter. Evershed's work continued despite the move to the suburbs of West London in 1895; at that point, with his assistant, he took over and renamed the company Evershed & Vignoles. From 1903 onward, the company's location became the Acton Lane Works in Chiswick. In this setting, Evershed & Vignoles developed the "Megger" resistance testing set that became world famous–distributed along with the company's ammeters, not only across the British Empire but in Argentina, Denmark, France, Germany, Holland, Hungary, Italy, Japan, Java, Spain, Sweden, and the United States–along with other related equipment. See "*Eversheds": Their Place in British Industry* (1932).

[9] As President of the IEE in 1900, Thompson had overseen the election of Hertha Ayrton as its first woman member. See Thompson and Thompson (1920) and Sharp (1926).

87-88, 106-7, 110-11, 127-8). Nevertheless he complained that some magnet makers still had not adopted her recommendations, and instead pursued their venerable habits–for example, the "quite absurd" use of stale beer in quench-hardening (Thompson 1913, 104).

After Thompson's piece was reprinted in the IEE's journal the following year, it became the standard reference work on permanent magnets. Most authors thereafter referred to Sklodowska Curie's results by citing Thompson rather than referencing her original paper. While effectively assimilating the results of Curie's work into mainstream research on magnets, Thompson's work rather ironically upstaged it. For example, in 1914 Dr. Margaret Moir, research fellow at the University of Glasgow, published a piece on tungsten and chromium magnets that was primarily a response to Thompson's work, simply commenting in passing that her work refined that of "Mdme (sic) Curie" by noting that the optimum proportion of chromium for permanence depended on a magnet's length to breadth ratio (Moir 1914-15, 385-86). By contrast, in his revised treatise on electrical instruments published in 1918, Edgcumbe directly quoted data produced by Sklodowska Curie on tungsten steels yet cited no other source than Thompson's lecture (Edgcumbe 1918). As such, Marie Sklodowska Curie's expertise in the making of permanent magnets was all too easily marginalized by a male-dominated culture of electromagnetic technology unaccustomed to attributing authority to a female practitioner.

Sydney Evershed's two monumental papers from 1920 to 1925, "Permanent Magnets in Theory and Practice" (parts one and two), which eventually replaced Thompson's piece as the canonical texts, were the last publications in magnetism to cite Sklodowska Curie's name explicitly as an authority on magnetism (Evershed 1925, 769-70, 810-21). His company's intensive practice of employing women perhaps made him more receptive than many others to the expertise of women as major contributors to the production of magnets ("Eversheds" 1932; Morrison-Low 1991, 89-117). Evershed not only cited Sklodowska Curie's recommendations about tungsten steels, but from them drew further information that informed his important new guidelines on the relationship between carbon content and critical temperature. Indeed, Evershed's main point, beyond Sklodowska Curie's account, was that the metallurgical key to permanency in magnetism lay in distributing carbide molecules within steel to prevent microscopic magnetic elements moving out of alignment (Evershed 1925, 799-800). Yet by doing so he acknowledged that strict permanence was unattainable as carbide molecules simply could not be made to stay in fixed positions indefinitely. As Evershed stoically observed after a lifetime of research on the subject of permanence, after seeing the ideal elaborate molecular pattern of permanent magnetism "slowly [fall] to pieces," it seemed only natural that the word *permanent* should lose something of its force when applied to hardened steel:

> But after all, even permanence is relative. It may be said that a permanent magnet is nothing apart from the man who makes use of it, and from that point of view perhaps it is enough the magnet should be rather more permanent than the man. (Evershed 1925, 800)

Therefore, it was as Evershed concluded: the making of magnets contrasted "unfavourably with the precision and uniformity" attained elsewhere in "modern engineering practice." The "mediaeval art and mystery" remained at the heart of the impossible modernist ideal of the completely tamed magnet (Evershed 1925, 799-800, 810).

IV. CONCLUSION

> Magnet, n. Something acted upon by magnetism.
>
> Magnetism, n. Something acting upon a magnet.
>
> The two definitions immediately foregoing are condensed from the works of one thousand eminent scientists, who have illuminated the subject with a great white light, to the inexpressible advancement of human knowledge.
>
> Ambrose Bierce, *The Devil's Dictionary*

This paper might give readers sympathy for the sardonic judgement of American humorist and journalist Ambrose Bierce of the epistemic limits that afflicted technical experts' knowledge of magnets (1911). But it is too crude an account. What we have seen is that while Marie Sklodowska Curie's expertise finally broached the gendered epistemic boundaries of secrecy that long surrounded the production of magnets, Sydney Evershed eventually established that the theoretical and practical epistemic boundaries to achieving *permanent, unvarying* magnetism could not be surpassed. With that, the question of how to develop laboratory techniques for validation of permanence also died–even the most permanent magnet was an irredeemably secular entity in ways that no theory or technology premised on conventional epistemology of instantaneous revelation could ever hope to overcome.

GRAEME GOODAY
Centre for History and Philosophy of Science
Department of Philosophy
Woodhouse Lane
University of Leeds
Leeds, LS2 9JT, UK
g.j.n.gooday@leeds.ac.uk

REFERENCES

Correspondence: Magnetic Transformation and Hardening of Steel. 1898. *The Metallographist* 1: 266-70.

Eversheds: their place in British industry. 1932. London: Evershed & Vignoles Ltd.

Barus, Carl and V. Strouhal. 1885. The electrical and magnetic properties of iron carburets. *U.S. Geological Survey Bulletin* 14: 1-238.

Bierce, Ambrose. 1911. *The Collected Works of Ambrose Bierce*, *Volume VII: The Devil's Dictionary*, New York: The Neal Publishing Company.

Boudia, Soraya. 2001. *Marie Curie et son laboratoire: sciences et industrie de la radioactivité en France*. Paris: éditions des archives contemporaines.

Colby, Edward F. 1890. Permanent magnet voltmeters [letter to the Editor]. *The Electrician* 126: 279.

Curie, Eve. 1938. *Madame Curie*. Paris: Gallimard.

Curie, Marie Sklodowska. 1898a[1954]. Propriétés magnetiques des aciers trempés. In *Prace Marii Sklodowskiej-Curie*, ed. Iréne Joliot-Curie, 3-42. Warsaw: Polska Akademia.

Curie, Marie Sklodowska. 1898b[1954]. Rayons émis per les composés de l'uranium et du thorium. In *Prace Marii Sklodowskiej-Curie*, ed. Irène Joliot-Curie, 43-5. Warsaw: Polska Akademia.

Curie, Marie. 1899. Magnetic properties of tempered steel. *Electrical Review* 44: 40-2, 75-6, 112-3.

Curie, Marie. 1923. *Pierre Curie, with the autobiographical notes of Marie Curie*. Trans. C. Kellogg and V. Kellogg. New York: Macmillan.

Curie, Pierre. 1908. *Oeuvres de Pierre Curie*. Paris: Gauthie-Villars.

Dörries, Matthias. 1991. Prior history and after-effects: Hysteresis and nachwirkung in 19th-century physics. *Historical Studies in the Physical and Biological Sciences* 22: 25-55.

Duhem. Pierre. 1996. Some reflections on German science (1915). In *Essays in the history and philosophy of science*. Trans. and ed. Roger Ariew and Peter Barker, 251-76. Indianapolis: Hackett Publishing Company, Inc.

Edgcumbe, Kenelm and Franklin Punga. 1904. Direct reading instruments for switchboard use. *Journal of the Institution of Electrical Engineers* 33: 620-55, discussion 655-93.

Edgcumbe, Kenelm. 1918. *Industrial electrical measuring instruments.* London: Constable & Co.

Emerson, Ralph Waldo. 1876. Nature. In *The complete works of Ralph Waldo Emerson: Comprising his essays, lectures, poems, and orations*. London: G. Bell.

Evershed, Sydney. 1925. Permanent magnets in theory and practice [part two]. *Journal of the Institution of Electrical Engineers* 63: 725-810, discussion 810-21.

Ewing, James Alfred. 1883. On effects of retentiveness in the magnetisation or iron and steel. *Proceedings of the Royal Society* 34: 39-45.

Ewing, James Alfred. 1886. Experimental Researches in Magnetism. *Philosophical Transactions of the Royal Society* 176: 523-640.

Ewing, Alfred W. 1939. *The man of room 40: The life of Sir Alfred Ewing.* London: Hutchinson.

Fara, Patricia. 1996. *Sympathetic attractions: magnetic practices, beliefs, and symbolism in eighteenth-century England.* Princeton, NJ: Princeton University Press.

Gilbert, William. 1958. *De magnete*. Repr. New York: Basic Books.

Gooday, Graeme. 2004. *The morals of measurement: irony, accuracy and trust in late Victorian electrical practice.* Cambridge, MA: Cambridge University Press.

Hopkinson, John. 1885. Magnetisation of iron. *Philosophical Transactions of the Royal Society* 176: 455-69.

Hopkinson, John. 1890. Magnetism and recalescence. *Proceedings of the Royal Society* 48: 442-46.

Hopkinson, John. 1901. Magnetisation of Iron (1885). In *Original Papers by the late John Hopkinson, Vol.2: Scientific papers,* ed. Bertram Hopkinson, 154-77. Cambridge, MA: Cambridge University Press.

Joliot-Curie, Irène, ed. 1954. *Oeuvres de Marie Sklodowska Curie*. Warsaw: Panstwowe Wydawnictwo Naukowe.

Letté, Michel. 2004. *Henry Le Chatelier (1850-1936) ou la science appliqué l'industrie.* Presses Universitaires de Rennes: Rennes.

Moir, Margaret. 1914-15. Permanent magnetism of certain chrome and tungsten steels. *Electrician* 74: 385-86.

Morrison-Low, Alison. 1991. Women in the nineteenth-century scientific instrument trade. In *Science and sensibility: gender and scientific enquiry, 1780-1945*, ed. Marina Benjamin, 89-117. Oxford: Basil Blackwell.

Notes. 1890. *The Electrician* 126: 128.

Osmond, Floris. 1888. Considerations on permanent magnetism. *Proceedings of the Physical Society of London* 10: 382-86.

Preece, William, 1890a. Discussion of the President's address on magnetism. *Electrician* 24: 320-21.

Preece, William. 1890b. On the character of steel used for permanent magnets. *Electrician* 25: 546-49.

Pumfrey, Stephen. 2001. *Latitude and the magnetic earth: the true story of Queen Elizabeth's most distinguished man of science.* Cambridge: Icon Books.

Pycior, Helena M. 1993. Reaping the benefits of collaboration while avoiding its pitfalls: Marie Curie's rise to scientific prominence. *Social Studies of Science* 23: 301-23.

Pycior, Helena M. 1996. Pierre Curie and His Eminent Collaborator Mme. Curie: complementary partners. In *Creative couples in the sciences*, eds. Pycior, Slack and Abir-Am, 39-56. New Brunswick: Rutgers University Press.

Quinn, Susan. 1995. *Marie Curie: a life*. London: Heinemann.

Sankey, Capt H.R. and F.V. Andersen. 1892. Description of the standard volt- and ampere-meter used at the ferry works, Thames Ditton. *Journal of the Institution of Electrical Engineers* 20: 516-90.

Sharp, Evelyn. 1926. *Hertha Ayrton 1854-1923: a memoir*. London: Edward Arnold & Co.

Star, Susan Leigh and J.R. Griesemer. 1989. Institutional ecology, "translations" and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science* 19: 387–420.

Steel for permanent magnets [Editorial]. 1899. *Electrical Review* 44: 33-35.

Swinburne, James. 1888. *Practical electrical measurement*. London: Alabaster & Gatehouse.

Thompson, Jane Smeal Henderson and Helen Gertrude Thompson. 1920. *Silvanus Phillips Thompson: his life and letters*. London: T. Fisher Unwin.

Thompson, Silvanus Phillips. 1913. The magnetism of permanent magnets. *Journal of the Institution of Electrical Engineers* 50: 80-142.

Thomson, William. 1888. On his new standard and inspectional electrical measuring instruments. *Proceedings of the Society of Telegraph Engineers and Electricians* 17: 540-67.

Wolke, Robert L. 1988. Marie Curie's doctoral thesis: Prelude to a Nobel Prize. *Journal of Chemical Education* 65, no. 7: 561-73.