

Edward John Dent's glass springs, archive and technical analysis combined.

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Introduction

Clockmakers have long pioneered the design and experimentation of new materials, often in response to demands from the state as well as the market. Late eighteenth and early nineteenth century research into the errors to which marine chronometers were liable is a superb example of this. Balance springs made of hard-drawn gold, resistant to oxidation, were used by John Arnold from the late 1770s, and subsequently by his son John Roger, until Arnold senior's death. In 1828, Johann Gottlieb Ulrich patented a non-ferrous balance, while, in Glasgow that same year, James Scrymgeour produced a flat spiral made entirely of glass.¹ It is the remarkable application of glass to the construction of balance springs that is the concern of this paper. Specifically, the efforts of the firm of Arnold & Dent, and later Dent alone, to secure the performance of their marine chronometers against variations in homogeneity, magnetism, temperature and elasticity, by using new materials for their balance springs.

In April 1833, virtuoso chronometer-maker Edward John Dent, then of the firm Arnold & Dent, chose the Admiralty monthly periodical for seafarers, *The Nautical Magazine*, to announce the first successful construction of a helical balance spring made entirely of glass. The editor of *The Nautical Magazine*, hydrographic officer Alexander Bridport Becher, marvelled at the innovation, confidently predicting that navigation hereafter would be carried out with glass-spring chronometers, to a greater degree of exactness than ever before. Indeed, Becher not only anticipated a major change in the composition and practice of horology, but also that glass springs would win the prized government contracts,² the highest standard of precision chronometry since the establishment of premium trials at the Royal Observatory in 1822.³ Yet by Dent's death in 1853, it seemed to those horologists who remembered the springs, as if the great expectations of government scientific administrators had come to nothing.⁴ The application of glass to balance springs appeared abandoned and all but forgotten. The gatekeeper to government contracts, Astronomer Royal, George

¹ Jonathan Betts, *Marine Chronometers at Greenwich*, (Oxford: Oxford University Press and the National Maritime Museum Greenwich, 2017), p.60.

² John Roger Arnold & Edward John Dent, Experimental Chronometers, Letter to the Editor, Alexander Becher, *The Nautical Magazine and Naval Chronicle*, (April 1833), 222-5.

³ Yuto Ishibashi 'A Place for Managing Government Chronometers': Early Chronometer Service at the Royal Observatory Greenwich, *The Mariner's Mirror*, 99:1, (2013) 52-66.

⁴ Second Extraordinary Meeting, *The Journal of the Society of Arts*, Vol. 1, No. 28, (3 June 1853), 325-336.

Biddell Airy, watched on silently, as Dent's glass springs were 'peremptorily denounced as *one of the puffs of the trade*.'⁵

Drawing on new primary evidence brought together with the first technical analysis of the springs, this paper argues that far from a technological dead end, Dent's glass researches played a pivotal role in the development of nineteenth century precision chronometry. In 1843, a decade on from Dent's first announcement in *The Nautical Magazine*, Airy would resuscitate the 1833 notice to attribute to the chronometer maker the discovery of 'middle temperature error'.⁶ Airy's judgment was retrospective, made after the fact, as he attempted to impose order on a clamour of makers, locked in ferocious competition seeking new design solutions to the problem of a losing rate at extremes of temperature. The episode is critical to understanding the legacy of the springs. Following Dent's announcement there were many claims both to the discovery of middle temperature error, and, separately, to the horological community's long-standing awareness of the phenomena. In keeping with an established museological patent culture, such claims took the mechanical features in exhibited work as evidence of priority.⁷ What is of interest here is not who said or did what first. Rather, it is to establish what it was Dent was doing when he made this extraordinary innovation in glass; what had changed such that, a decade on, credit for a refined temperature compensation had come to be so hotly contested; and how, despite competing prior claims, for Airy and for Dent, such contest could be resolved by the announcement of the application of glass to the balance-spring of the chronometer.

Figure 1. Edward John Dent's glass balance-spring with ebony stand, dated: 1835-40, displayed but not used in a mechanism, British Museum No. 1958,1006.3009. Copyright Trustees of the British Museum.

Figure 2. Glass balance-spring attached to glass balance disc, dated: 1836, previously incorporated into a chronometer and trialed, British Museum No. 1958,1006.3394. Copyright Trustees of the British Museum.

Figure 3. Flat spiral balance-spring made of glass fixed to three-ball mercurial balance. British Museum No. 1958,1006.3073. Copyright Trustees of the British Museum.

⁵ For quotation see Francis Herbert Wenham, 'Letter to the Editor', *The Journal of the Society of Arts*, Vol. 1, No. 29, (10 June 1853), 337-364, 361. For Airy's silent presence at the meeting, see Cambridge University Library (CUL), Royal Greenwich Observatory (RGO), Papers of George Biddell Airy (6), Papers on Chronometer Improvements (590).

⁶ Edward Dent to George Biddell Airy, 12 October 1843, CUL RGO 6 Claims for Chronometer Improvements (587) and Airy's annotations on copy of 'Glass Balance Springs to Chronometers' in CUL, RGO, 6, 587.

⁷ Sept-November 1843, Responses to circular by Airy dated 12 September 1843, CUL, RGO, 6, 587, 483-517.

Jonathan Betts, Curator Emeritus of Horology at Greenwich National Maritime Museum, was the first among contemporary horologists to make glass springs. It was after visiting Betts to see his springs that former British Horological Institute president, Anthony Randall began his remarkable researches, for which Betts provided the initial glass and pyrex materials. More recently the author of this paper has had the privilege of working with Rory McEvoy, formerly Curator of Horology at Greenwich, and now Lecturer in Horology at Birmingham City University, to make glass springs. However, Randall's researches are exceptional in that he successfully fitted the springs to a chronometer, to extraordinarily beautiful results, and has now been rating his glass spring chronometers for some years. Betts's springs were sadly broken or given away to private collections, the author's own attempts are rudimentary at best, and excepting the exquisite and virtuoso researches of Anthony Randall,⁸ only a handful of operable springs exist in collections worldwide.

Two of Dent's helical springs are held by the British Museum, London; one, 1958,1006.3009, apparently a demonstration piece never incorporated into a mechanism, (Figure 1), the other, 1958,1006.3394, still fitted to the glass balance disc with which it was extensively trialled (Figure 2). In addition, the British Museum also hold a flat spiral of glass with mercury balance by the ingenious Glasgow clockmaker, James Scrymgeour, (1958,1006.3073), developed independently but predating the Dent springs by six years, (Figure 3). There remains a prototype balance spring in the Musée international d'horlogerie, Switzerland, never fitted to a mechanism, which, though lacking documentation, is thought likely to be the product of Professor Adrien Jacquerod's mid-twentieth century researches for the Laboratoire Suisse de Recherches Horlogères in Neuchâtel, Switzerland.⁹ The Conservatoire National des Arts et Métiers (CNAM), Paris, hold a 'spiral en cristal' among the spare parts for a marine chronometer carrying the dial inscription "BREGUET NEVEU N-4982 ET CIE". The CNAM catalogue records this glass spring as thought to have been made in the final decades of Breguet family management (1850–1870), Museum no. 50315-0000-.¹⁰ However, research by Jonathan Betts in the Breguet manufacturing archives shows that No.4982 was made in the mid 1830s. While that specific entry is undated, the following chronometer, Breguet No.4983, is of the same general type (Horloge Marine, 1 barillet, petit modele), and was sold in 1832. There is no reference to the balance spring of 4982. There remains, then, some ambiguity as to the date of the Breguet glass spring. Finally, a Dent exhibition two-day chronometer, numbered 1771, and made around 1842, with glass balance and glass balance spring, was auctioned by Messr. E. Dent & Co. to the Time Museum, Rockford in November

⁸ Anthony Randall, Glass Balance Springs 1, *Horological Journal*, (June 2000), 192-5; Glass Balance Springs 2, *Horological Journal*, (July 2000), 237-40; Making and Testing Glass Balance Springs, *Horological Journal*, (February 2009), 56-60; Spiraux de verre, *Horlogerie ancienne* n°71, (2012), 35-48.

⁹ Email communication, Jean-Michel Piguet, Conservateur adjoint, Musée international d'horlogerie, Switzerland, 21 July 2016. See also Randall, *Horological Journal*, (June 2000), pp.193, 194-5.

¹⁰ Email communication, Mathilde Bertrand, Centre de documentation, CNAM, 23 November 2017. This information corresponds with the CNAM catalogue, accessed March 2018: http://phototheque.arts-et-metiers.net/?idPageWeb=95&popUp_infosPhoto=1&infosIdPhoto=23393&interfaceParent=tableLumineuse&PHPSESSID=4e201324982ed83694ec689e16ce7a64

of 1972. Anthony Randall's 1992 catalogue of the Time Museum collection describes the piece as made especially for exhibition, very finely finished and without motion work, hands or a dial. It uses a brass full plate movement with removable barrel bridge a high one-piece balance cock and diamond endstone. The glass helical balance spring is fitted to a glass balance disc with bi-metallic vertical strips for compensation. This accompanies an Earnshaw spring detent escapement and fusee with Harrison's maintaining power. The timepiece is mounted with the balance spring displayed in a brass bowl, mounted on a velvet base, with an ivory plaque inscribed *Dent's glass spring chronometer*, and a dial plate of diameter 87mm.¹¹ From The Time Museum, 1771 passed to The Museum of Science and Industry, Chicago, and is now in private hands following sale by Sotheby's, New York, in 2004, for \$30,000.¹²

This article is the product of research undertaken with the generous support of the Antiquarian Horological Society Education Fund. It is concerned with the specialist history of Dent's glass chronometer components, and what the first technical analysis of the British Museum springs may offer to historical understanding and future horological research. A paper presented by the author in July 2017 at the Antiquarian Horological Society London Lecture Series,¹³ considered technical details of the construction and development of Dent's glass springs, and showed how, through these specifics, state standards, and the glass excise, the career of Dent's glass springs was directly linked with some of the most significant events in nineteenth century British history – not least the commutation of tithes, the regulation of the Factory Acts, and the repeal of the Corn Laws.¹⁴ The paper offered here focuses instead on the data and technical analysis of specialist horological interest. The initial project proposal was to bring substantial un-researched archival material on the springs in the Royal Observatory papers held by Cambridge University Library, and Dent family papers held in Guildhall, London, together with the existing Dent glass springs held by the British Museum. Crucially, this study, undertaken on behalf of the Antiquarian Horological Society, developed into a collaboration with the British Museum. The result has been two firsts - not only the first in-depth archival research on the manufacture, trial and application of Dent's glass chronometer components, but also the first technical analysis, undertaken at the British Museum Research Laboratory.

From magnetism, to elasticity and heat

In March 1833 Arnold and Dent wrote to the *Nautical Magazine* to notify the editor, hydrographic officer Alexander Bridport Becher, of their experiments at the Royal Observatory to ascertain to what extent magnetism affects the rates of chronometers. From these researches, the precision chronometer makers concluded that 'it is to the composition of the balance, and the balance-spring, that we must look for the

¹¹ Anthony Randall, *The Time Museum Catalogue of Chronometers*, (Rockford: The Time Museum, 1992), p.127.

¹² Email communication, Patricia H. Atwood, Accredited Senior Appraiser at the American Society of Appraisers, 25 July 2016.

¹³ The report of which appeared in *Antiquarian Horology*, Dec 2017, pp.569-7.

¹⁴ The formal write up of the London Lecture Series presentation is now in press with open access journal, *History of Science*.

improvement of the chronometer'.¹⁵ In April, after a passing mention of the magnetic experiments, the firm announced that it was their conclusion as to the significance of the material composition of the balance and balance-spring, rather than the problem of local magnetic attraction itself, that had prompted them to inquire just how far glass might be substituted for metallic substance.¹⁶ The following month of May, Arnold and Dent set out their magnetic researches with a clear demarcation between the two lines of research, stating

the discovery of the use of glass for a spring... did not take place till after the [magnetic] experiments... were nearly completed. We could not therefore connect the trial for the glass spring with those experiments.¹⁷

While others, such as the Reverend George Fisher, developed a special preoccupation with glass to overcome the problem of local magnetic attraction,¹⁸ the emphasis for the chronometer maker, Dent, was on the problem of losing rate at extreme temperatures, and on the quality of elasticity. As is now well understood, the material of the balance spring affects going rate. Soft springs, made of materials like gold or unhardened steel, lose their elasticity over time, causing a gradual losing rate in the longer term. By the 1830s chronometer makers 'almost universally' used springs of hardened and tempered steel to avoid just this.¹⁹ However, the solution itself introduced a further problem: following manufacture and adjustment hardened steel springs show an accelerating rate. Such acceleration could, in turn, be reduced by using hardened tempered steel of a couple of years' use, so the tension in the structure of the metal had been worked out. This was the state of knowledge when Dent first published his April 1833 notice of the glass spring researches. The article made an important contribution, previously unmarked in print: even the best chronometers, with springs of properly hardened and tempered steel, when exposed to extremes in temperature, would lose at the maximum and minimum.²⁰ In the course of this paper we find the first principle of Dent's glass balance-spring was the homogeneous arrangement of particles out of which the glass was composed, and the implications of this for the behaviour of the spring over time and temperature change.

Figure 4: Daily rate of glass spring chronometer No. 790 on board H.M. Ship Fairy and at The Royal Observatory 29 May 1834 - 15 Oct 1836.²¹ Anthony Randall's research has shown what Dent believed, that over a long period, some ten years continuous running, the severe acceleration exhibited by glass springs subsides, and the rates achieved can be excellent without breaking or showing any signs of

¹⁵ John Roger Arnold & Edward John Dent, Magnetic Influence on Chronometers, *The Nautical Magazine*, (March 1833), 161-2, p.162.

¹⁶ Arnold & Dent, *The Nautical Magazine*, (April 1833), p.222.

¹⁷ John Roger Arnold & Edward John Dent, Magnetic Experiments on Chronometers, *The Nautical Magazine*, (May 1833), 262-276, p.268.

¹⁸ George Fisher, Navigational workbook: collected observations and workings, 1825-1852, Board of Longitude, National Maritime Museum, FIS/23/41.

¹⁹ Arnold & Dent, *The Nautical Magazine*, (April 1833), p.223.

²⁰ Arnold & Dent, *The Nautical Magazine*, (April 1833), p.222-5.

²¹ John Roger Arnold & Edward John Dent, On the Application of Glass, as a Substitute for Metal Balance Springs in Chronometers, *The Nautical Magazine and Naval Chronicle*, (December 1836), 705-717, pp.714-6.

fatigue.²² However, in Dent's words, documented in 1837 by the American electro-magnetist, Joseph Henry, the long period required for glass to take up 'permanent elasticity' meant 'good capital would be locked up in their [Arnold & Dent's] manufactory.'²³

Figure 5: Daily rate of glass spring chronometer No. 616 at The Royal Observatory Greenwich, 12 October 1833 – 17 Oct 1836.²⁴ Readers may be interested to compare these graphs (Figures 4 and 5) with the pyrex spring daily rates published by Anthony Randall.²⁵

By March of 1836, the glass-spring chronometer No 616 had been rated at the Royal Observatory, (Figure 4), and No. 790 on board H.M. Ship *Fairy* under Captain Hewett and at the Royal Observatory (Figure 5) for three years. Dent applied to Hydrographer to the Admiralty, Francis Beaufort, for the continuation of the rates; who, in turn, wrote to Airy noting

As far as they have gone these experiments have been highly interesting showing the gradual change of structure which has taken place in the glass during the period that elapsed between the spring being put in motion and its arriving at the maximum of change. This may be ascribed to the species of glass Mr Dent employed and I want him to try different species of both Crown and Flint.²⁶

The Glass Tax divided the glass industry into five different sectors, flint, crown, plate, broad, and bottle. This system discriminated in particular between common bottle glass, with a low rate of tax, and other glass subject to higher rates. Flint glass, made of silica and a significant proportion of lead, was one of the more heavily taxed, over four times the rate imposed on common bottle. The manufacture of this high lead glass was subject to constant surveillance by excise officers and suffered from the most lengthy and complex systems of weighing, re-weighing, watching, and gauging, of all the types of glass defined by the excise.²⁷ As what follows will show, Dent had already trialed and was in fact now using both Crown and Flint glass, though in different capacities and under different names. Beaufort's desire that Dent should use

²² Email communication, Anthony Randall, 18 April 2018.

²³ Nathan Reingold, (ed), *The papers of Joseph Henry, Volume 3: 'January 1836-December 1837, The Princeton Years'*, City of Washington: Smithsonian Institution Press, (1979), p.237.

²⁴ Arnold & Dent, *The Nautical Magazine*, (December 1836), pp.712-4.

²⁵ Randall, *Horological Journal*, (February 2009), p.59.

²⁶ Francis Beaufort to George Biddell Airy, 2 March 1836, CUL, RGO, 6, 585.

²⁷ Commissioners of the Excise, *Thirteenth report of the commissioners of inquiry into the excise establishment and into management and collection of the excise revenue throughout the United Kingdom: Glass*, (London: William Clowes and Sons, 1835), pp.1-22; David Brewster, 'Some Account of the Late M. Guinand, and of the Important Discovery Made by Him in the Manufacture of Flint Glass for Large Telescopes.' *Edinburgh Journal of Science*, 2, (1825), 348–354, p.348; and 'Memoir of the Life of M. Le Chevalier Fraunhofer, the Celebrated Improver of the Achromatic Telescope and Member of the Academy of Sciences at Munich.' *Edinburgh Journal of Science* 7, (1827), 1–11, pp.10–11. Quotation reprinted in David Brewster, 'The Decline of Science in England and the Patent Laws.' *Quarterly Review* 43, (1830), 305–342.

different species of Crown and Flint, reframed the research Dent had already been carrying out since 1833, in the formal terminology of the fiscal regulation of glass manufacture.

In his first April 1833 announcement Dent expressed acute concern at the high proportion of lead necessary for the manufacture of his glass springs. The advantage of lead to the glass industry was that it acted as a flux, lowering the working-temperature.²⁸ Further, the high refractive index of lead glass made for a product of such distinctive brilliance it had long been the foundation of both luxury and optical glass-making industry in Britain. In the early 1830s the latter of these two was in the throes of a crisis. Unable to compete with European optical glass, a Joint Committee of the Royal Society and the Board of Longitude for the Improvement of Glass for Optical Purposes had been appointed in April 1824 to rectify the situation, with celebrated chemist Michael Faraday as principal researcher.²⁹ When in 1833 Dent stated that ‘nothing demands the attention of the chemist more than the production of glass which shall, if possible, be entirely free from lead’, he made a direct reference to Faraday’s researches on behalf of the Committee, one of the most vocal lobbies for the repeal of the glass tax.³⁰

Technical analysis

The explicit emphasis, by Dent, and by his government patrons, on the specific composition of the glass, highlighted the importance of undertaking technical analysis of the British Museum glass springs, in order to compare their composition to databases for contemporary glass, and to better interpret the existing primary material on Dent’s researches. In May through June 2017 the springs were analysed in the British Museum Research Laboratory. Non-destructive imaging and compositional analysis was carried out using a combination of variable pressure – scanning electron microscopy – energy dispersive X-ray spectrometry (VP-SEM-EDX) and X-ray fluorescence (XRF).

The two British Museum helical glass balance-springs made by Dent, (1958,1006.3009, and 1958,1006.3394), the Scrymgeour flat spiral, (1958,1006.3073), and the glass balance disc of 1958,1006.3394 were analysed to provide a useful comparison. The springs were not cleaned prior to analysis and dirt could be seen on their surfaces. Ideally analysis would be carried out on clean and flat samples. For this reason, while we can have confidence in the conclusions drawn from the results of this study, all compositional data presented should be considered only semi-quantitative. Because of the constraints of VP-SEM-EDX chamber it was

²⁸ Myles Jackson, *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics*, (Massachusetts Institute of Technology, 2000), p.101.

²⁹ Jackson, *Spectrum of Belief*, (2000), pp. 143-70.

³⁰ Commissioners of the Excise, *Thirteenth report...* (1835), pp.1-22. David Brewster, ‘Some Account of the Late M. Guinand, and of the Important Discovery Made by Him in the Manufacture of Flint Glass for Large Telescopes.’ *Edinburgh Journal of Science*, 2, (1825), 348–354, p.348; and ‘Memoir of the Life of M. Le Chevalier Fraunhofer, the Celebrated Improver of the Achromatic Telescope and Member of the Academy of Sciences at Munich.’ *Edinburgh Journal of Science* 7, (1827), 1–11, pp.10–11.

only possible to analyse the two Dent springs 1958,1006.3009, and 1958,1006.3394 using this technique. All parts (spring 1958,1006.3009, spring and balance disc 1958,1006.3394, and the Scrymgeour flat spiral 1958,1006.3073) were analysed using XRF.

VP-SEM-EDX compositional analysis and backscattered electron (BSE) imaging was carried out using a Hitachi S3700N VP-SEM-EDX, with the SEM in variable pressure mode (40Pa) with 20kV accelerating voltage. Compositional analysis was carried out at 10mm working distance using Oxford instruments Aztec EDX quantification software. Corning Museum of Glass standards A and C were analysed under the same conditions and the employed methodology gave results with errors of less than 20% for major elements and 30% for minor elements when compared with published values. During analysis it was noted that spring 1958,1006.3009 was particularly dirty and was found to have potassium chloride salts on its surface, which hinder accurate compositional analysis of the glass (see Figures 6-9). Multiple small areas on 1958,1006.3009 were analysed in an attempt to avoid the salt crystals and other dirt. The eight results for potash (K_2O) and chlorine (Cl) for this spring were then plotted on a scatter plot and the trend-line found. The Y-intercept (6.6 wt% K_2O) was used as an estimate of the correct value for K_2O (i.e. a value of 0 wt% Cl in the glass was assumed) and the results for this spring normalised using this value (see Table 1). Larger areas were analysed on 1958,1006.3394, as there was less visible dirt. The XRF results corroborate that 1958,1006.3009 contains more potassium than 1958,1006.3394.

For the XRF analysis, unprepared surfaces of the springs 1958,1006.3009, 1958,1006.3394 and 1958,1006.3073, as well as the glass balance disc of 1958,1006.3394 were analysed using a Bruker ARTAX spectrometer under the following operating conditions: helium atmosphere, 50 kV, 0.5mA current, 0.65 mm diameter collimator and 200 seconds counting time.

Table 1: Semi-quantitative VP-SEM-EDX results for the two glass springs and data from Dungworth³¹ and Dungworth and Brain³².

The glass of the two Dent springs, 1958,1006.3009 and 1958,1006.3394, was found to be compositionally very similar, but not identical (Table 1). The three main components found in these two springs were silica, potash and lead oxide. They are produced of a type of glass known as ‘Flint Glass’ or ‘Lead Crystal’. The composition is very different from standard window glass in use during their period of manufacture. Dungworth³³ found the majority of window glass of the 1830s to be of two compositional types ‘Kelp Glass’ and ‘Synthetic Soda’ (Table 1) and neither of these compositional types match the glass of these springs. It has not been possible to find a published analysis of a contemporary lead glass that is similar to these springs. The closest published parallel is Lead Crystal Group 4 (labelled as ‘Flint Glass’ in

³¹ David Dungworth, ‘Historic Window Glass. The use of chemical analysis to date manufacture’ *Journal of Architectural Conservation* 18 (2012), 7-25, p. 13.

³² David Dungworth and Colin Brain, C ‘Late 17th-century crystal glass: an analytical investigation’. *Journal of Glass Studies* 51 (2009), 111-137, p. 125.

³³ Dungworth *Journal of Architectural Conservation*, (2012), p. 13.

Table 1), which dates to 1685-1720.³⁴ This glass has the same three major components but higher potash and lower silica levels. From the small number of components in these glasses it appears that the raw materials used to produce the glass of the springs were very pure (Table 1). Litharge (lead oxide), potassium nitrate (saltpetre) and silica (probably in the form of crushed flint), are the most likely raw materials to have been used.³⁵

The methodology employed for XRF analysis in this project does not permit the detection of sodium, aluminium or magnesium, so it was not possible to state whether these components were present or not in the glasses which were only analysed using this technique. All three springs (1958,1006.3394, 1958,1006.3009 and 1958,1006.3073), and the balance disc (1958,1006.3394) were analysed using surface XRF. Spring 1958,1006.3073 is extremely thin and so the results for XRF analysis are based on a very small volume of glass. However, it is possible to state that the glass of this spring is of a significantly different composition to the springs of 1958,1006.3394 and 1958,1006.3009. The glass of spring 1958,1006.3073 contains significant levels of silica (SiO₂), lime (CaO) and potash (K₂O), and no lead. It also contains particularly high strontium levels, which, assuming there also a significant level of sodium present, suggest that it may have been produced using a seaweed-based alkali source ('Kelp Glass', see Table 1). The balance disc of 1958,1006.3394 is produced from 'Kelp Glass', which is compositionally similar to 1958,1006.3073.

Figure 6: Low magnification BSE images of the two springs (a. 1958,1006.3394 b. 1958,1006.3009). Andrew Meek, copyright Trustees of the British Museum.

Figure 7: BSE images showing surface features of the glass springs (a. 1958,1006.3394 b. 1958,1006.3009). Andrew Meek, copyright Trustees of the British Museum.

Figure 8: High magnification BSE images of the surfaces of the springs showing horizontal striations (a. 1958,1006.3394; b. 1958,1006.3009). Andrew Meek, copyright Trustees of the British Museum.

Figure 9: BSE images showing the broken ends of spring threads (a. 1958,1006.3394; b. 1958,1006.3009). Andrew Meek, copyright Trustees of the British Museum.

The threads of spring 1958,1006.3009 are thinner than those of 1958,1006.3394, c.400µm and c.700µm respectively (see Figures 6 and 7). The striations on the threads suggest they were drawn (Figures 7 and 8). They are much more clearly visible on 1958,1006.3394, but can be seen on both springs. Initial analysis suggests that the glass threads were drawn and then wound around a former and flattened onto it changing their shape (see Figure 9). 1958,1006.3394 is more flattened than 1958,1006.3009. It is clear that both springs share similarities in their production

³⁴ Dungworth *Journal of Architectural Conservation*, (2012), p. 13.

³⁵ Dungworth and Brain, *Journal of Glass Studies*, (2009), p. 129.

processes. However, while the overall process is the same the end products are significantly different from one another.

The lead glass question

To summarise the compositional data set out in the previous section, Scrymgeour's flat spiral, 1958,1006.3073, was made from common window glass with a distinctive kelp base. By contrast, the two Dent springs, 1958,1006.3394 and 1958,1006.3009, used a high proportion of lead and extremely pure synthetic materials, giving further weight to Dent's statement that the firm had 'manufactured [their] own glass springs'.³⁶ While the glass of the springs may have been made by Dent himself, the balance of 1958,1006.3394 was different again, compositionally very similar to the kelp-based window glass of the Scrymgeour flat spiral, 1958,1006.3073, and as such more likely to be commercially available glass brought in, rather than made in the workshop.

The high lead content of the Dent springs prompts certain questions. We know Dent expressed acute concern at the amount of lead he considered indispensable to the construction of the springs, and that he called upon the chemist to make absolute priority 'the production of glass which shall, if possible, be entirely free from lead', in a direct reference to Michael Faraday's work on behalf of the Joint Committee on optical glass. At the same time, however, we know that Dent had access to glass without any trace of lead, such as that used in the balance of 1958,1006.3394, and was encouraged to test different species of glass.³⁷ We know that exquisite glass springs were made without lead, using common window glass, such as Scrymgeour's flat spiral, 1958,1006.3073; and, from the documented rates, that lead glass springs also suffered from a gaining rate (Figures 4 and 5), such as Randall found to be the case, in his virtuoso researches using Pyrex.³⁸ Finally, while still minimal in comparison to metals, lead glass has a significantly greater coefficient of thermal expansion than glass made without lead. Why then the lead glass? Using the information provided by the technical analysis, it is now possible to return to the primary documentary evidence, to understand Dent's emphasis on high lead content for the springs.

In light of the technical analysis, it is clear Dent's focus was not just material, but on what he took to be the particulate composition. To the effect where 'the best chronometers [rated] at the two extremes of temperature [exhibit] that both at the maximum and minimum the rate will be a losing one', Dent argued 'we can only attribute[,] the want of affinity existing between the metallic particles which compose the balance spring.'³⁹ In setting out the challenge faced by the scientific chronometer maker to the improvement of the balance, Dent stressed that '[o]ne great desideratum is, that the balance should be formed of a homogeneous substance; but the difficulty with gold is this, that it requires more alloy, and in this state its liability to break is

³⁶ John Roger Arnold & Edward John Dent, 'Experimental Chronometers', *Nautical Magazine*, (July 1833), 417-8, 417.

³⁷ Francis Beaufort to George Biddell Airy, 2 March 1836, CUL, RGO, 6, 585.

³⁸ Randall, *Horological Journal*, (June 2000); *Horological Journal*, (July 2000); *Horological Journal*, (February 2009); *Horlogerie ancienne* (2012).

³⁹ Arnold & Dent, *The Nautical Magazine*, (April 1833), p.224.

very great.⁴⁰ The statement is significant. Gold springs required *more* alloy, not any alloy at all, while fracture in metals notoriously followed the line of a change in particular crystal structure.⁴¹ Homogeneity did not equate to purity, rather all materials were to one degree or another, a mixture. The concern was best summarised by Dent himself, in the July issue of the *Nautical Magazine* that same year:

The errors to which chronometers are generally liable, arise, in many cases from the uncertainty in the construction of the balance-spring, with respect to its being homogeneous, and to this we attach the utmost importance in making chronometers... we are therefore of opinion, that the relative proportion of the component particles of the glass to each other, in order to form the balance-spring, is a point well worthy the investigation of scientific men, and it is, moreover, one on which we should be most thankful for information.

For Dent, one of the principal challenges of the scientific chronometer maker was to ensure as much as possible the even distribution of constituent particles in the balance spring.

In section 1 it was noted that Beaufort wrote to Airy in March of 1836 regarding Dent's request for the continuation of the glass-spring chronometer rates at the Royal Observatory.⁴² Two months on Beaufort presented Dent's report and three years' ratings to the Royal Society. In the manuscript of this paper, Dent noted it was evident '[t]hat there exist physical defects beyond the perfect mechanical production of the balance spring...

however exquisite in Workmanship it may appear, and however complete its power to maintain a perfect figure, when in different degrees of tension, may be; Yet the imperfect distribution of its component parts may render it quite inapplicable to the purpose of correct performance. In support of this, it may be briefly stated that a spring having no visible defect when removed from a Chronometer for its irregularity, and replaced by another without any other alteration being made, the Chronometer will assume a different character from its former one, with respect to performance; thus showing that to the homogenous arrangement of the particles forming the Spring more is to be attributed than to its manipulation.⁴³

Not only was the particular composition of the glass pivotal to Dent's researches but also the dynamic arrangement of these constituent particles.

Lead, it was noted in section 1, acted as a flux in the manufacture of glass. The addition of lead facilitated an even melt and distribution of constituent materials.

⁴⁰ Arnold & Dent, *The Nautical Magazine*, (April 1833)p.224.

⁴¹ Cyril Stanley Smith, Introduction, *Réaumur's Memoir's on Iron and Steel*, Chicago: University of Chicago Press, (1956), p.xxix; Cyril Stanley Smith, *A History Of Metallography: the development of ideas on the structure of metals before 1890*, Chicago: University of Chicago Press, (1960), p.160; René Antoine Ferchault de Réaumur, [translated by Anneliese Grünhaldt Sisco], *Réaumur's Memoirs on Steel and Iron: a translation from the original printed in 1722*, Chicago: University of Chicago Press, (1956), p.199.

⁴² Francis Beaufort to George Biddell Airy, 2 March 1836, CUL, RGO, 6, 585.

⁴³ A Paper on the application of Glass as a Substitute for Metal Balance Springs in Chronometers By Messrs Arnold and Dent – Communicated by Francis Beaufort, received 5 May, read 12 May 1836, Royal Society, AP 20 7 & 8.

Dent's conception of elasticity was centred on the cohesion of particles. The conceit that underpinned the construction of his high lead springs was that a perfectly homogeneous distribution of particles would produce perfectly orderly thermal and elastic behaviour. Dent's concern for the homogeneous distribution of particles was also the concern of the Joint Committee into optical glass, whose overwhelming obsession was the production of large blanks of perfectly clear, homogenous glass.⁴⁴ It was for this reason that Dent chose to articulate his problem by setting it in the framework of Faraday's researches on behalf of the Joint Committee.

Rate gain and the glass balance disc.

This section shows Dent's glass balance-spring chronometers sustained the interest of the wider scientific community for a period of nearly two decades, despite the problem, also found by Randall using Pyrex,⁴⁵ that glass springs appear to continue gaining rate for much longer than hardened steel.⁴⁶ However, the most significant impact of Dent's glass researches, not just for his own chronometrical science but also the system of trials at the Royal Observatory, came not from the glass spring but rather the glass balance disc. Once again, structure and material composition identified by the British Museum's technical analysis provide crucial information.

Through the 1830s and 1840s Dent's glass balance-spring mechanisms were exhibited across the country: first, in the Royal Institution, London, June 1833,⁴⁷ and February 1834;⁴⁸ then Edinburgh, at the fourth meeting of the British Association for the Advancement of Science, September 1834.⁴⁹ London, at the Royal Society in 1836,⁵⁰ Royal Institution, April 1837;⁵¹ Newcastle, for the eighth British Association meeting in 1838,⁵² and Plymouth, for the eleventh, in 1841, where Dent communicated the continuous ratings of the glass springs since 1833.⁵³ The springs were intended for display at the United Services Institution in the early 1840s, and as models for the lectures of Cambridge astronomer Richard Sheepshanks at the Institution.⁵⁴ In June 1842, through his working relationship with Wilhelm Struve of the Russian Observatory, Dent was asked to exhibit the glass mechanism to the Emperor of

⁴⁴ Jackson, *Spectrum of Belief*, (2000), pp. 143-70.

⁴⁵ Randall, *Horological Journal*, (February 2009).

⁴⁶ Randall's ratings of nearly two decades now seem to suggest the rate gain may finally be slowing.

⁴⁷ Institution Of Civil Engineers, *The Athenaeum*, 295, (June 1833), pp. 403-404.

⁴⁸ Royal Institution, *The Athenaeum*, 330, (Feb 1834), p.145.

⁴⁹ Fourth Meeting Of The British Association For The Advancement Of Science, *The Athenaeum*, 360, (September 1834), 694-699, p.696.

⁵⁰ Royal Society, *The Athenaeum*, 458, (1836), 554-555.

⁵¹ Reingold, *The papers of Joseph Henry*, (1979), pp. 237, 241-3.

⁵² Eighth Meeting Of The British Association For The Advancement Of Science, *The Athenaeum*, 566, (1838), 619-637.

⁵³ Eleventh Meeting Of The British Association For The Advancement Of Science, *The Athenaeum*, (722), (August 1841) 668-679.

⁵⁴ Though it is unclear whether this exhibition took place, and Sheepshanks was irritated by not having the springs for his lectures. Dent letter out book, Dent to Lewis Hippolytus Joseph Tonna, 1839; and Dent to the Council of the United Services Institution, 16 January 1840, Guildhall MS 18010.

Russia;⁵⁵ within a year he was appointed chronometer maker to the Emperor by special warrant. On 14 February 1845, while Dent applied for the commission to manufacture the Great Clock at Westminster, Big Ben, Prime Minister Sir Robert Peel made his address to the House of Commons, on the subject of the repeal of glass duty, holding out one of Dent's glass springs to the assembled audience, as an example of the kind of extraordinary innovation that would proliferate should the glass tax be repealed.⁵⁶ In 1851, a Dent Marine chronometer with glass balance-spring, glass balance, and compensated, for temperature, by means of platinum and silver, was displayed in Class X at the Great Exhibition. The official catalogue noted that the glass balance-spring had been tried at the Royal Observatory, and on board H.M. surveying ship, *Fairy* and referred the visitor to the official rates, published in 1834.⁵⁷ Arnold and Dent's covering letter to these results claimed that 'the glass chronometer... stands, as regards its performance, surpassed by nine only out of the twenty-eight deposited' in the public trials. Though this claim had been amended a few issues later, to 'surpassed by thirteen out of the twenty-eight first deposited',⁵⁸ the readers of the *Catalogue* were not directed to the correction. The international jury for the Horological Instruments exhibited, which included Baron Pierre-Armand Séguier, mechanist and member of the Académie des Sciences, and Swiss physicist Professor Jean-Daniel Colladon, as well as London lawyers Edmund Becket Denison and E.J. Lawrence, were impressed and drew attention to Dent's glass-spring chronometer, in the hope of inducing further research.⁵⁹

On 7 April 1837, after his lecture at the Royal Institution, Dent exhibited his glass springs to American electro-magnetist, Joseph Henry, and took the opportunity to further set out some of his thoughts on glass and elasticity, now exactly four years on from the first announcement. Henry recorded the episode in his diary, noting,

[Mr Dent] finds that glass and all substances used for springs of a solid kind decrease in elasticity [with a rise in temperature] on two accounts. 1st by an increase of length and 2^{ndly} by a decrease of elasticity from the separation of the particles. The latter effect produces the greatest amount of decrease of elasticity as was shewn by gradually shortening a hair spring in proportion as the heat was increased from 32° to 100° by the quantity due to the expansion. The decrease of time as shewn by the watch in an hour would in this way give the diminution of elasticity due to the molecular change.⁶⁰

⁵⁵ , Dent, to Struve Dent letter out book, 15 June 1842, Guildhall MS 18010

⁵⁶ *Sir Robert Peel's Financial Statement, Delivered in the House of Commons on 14 February 1845, New Tariff: Tables of New Duties of Customs*, London: James Gilbert, 49 Paternoster Row (1845).

⁵⁷ Class X. Philosophical, Musical, Horological and Surgical Instruments, *Great Exhibition: Official, Descriptive and Illustrated Catalogue*. London, (1851), p.401.

⁵⁸ John Roger Arnold & Edward John Dent, Chronometers with Glass Balance-Springs, *The Nautical Magazine*, (July 1834), 420-422, p.422; John Roger Arnold & Edward John Dent, Glass Balance Spring in Chronometers, *The Nautical Magazine*, (July 1834), p.611.

⁵⁹ E.B. Denison, Baron Armand Segurier, Professor Daniel Colladon, E.J. Lawrence, *Reports by the Juries on the subjects in the thirty classes into which the exhibition was divided*, London, (1852), pp.336-7.

⁶⁰ Reingold, *The papers of Joseph Henry*, (1979), pp. 237, 241-3.

The current state of knowledge in horological science understands the relationship between temperature and rate to be much more complex. As the temperature rises, the force delivered by a spring reduces linearly with increasing length, but at the same time increases linearly with its height, and increases as a cube law, to the power of eight, with its thickness. The complexities of these material relations prohibit any attempt to determine the effect of molecular changes in the way Henry describes of Dent. Nonetheless, the diary entry corroborates Dent's particulate theory of elasticity, according to which an entirely even distribution of particles would guarantee orderly elastic action. The final sentence, which describes the correlation between loss of rate and of elasticity, is especially telling. The previous year, Beaufort had already expressed great interest in the glass springs' capacity to show gradual changes in structure through use.⁶¹ For Dent and his patrons, observations of the glass balance-spring offered a highly precise way of measuring dynamic state change in the material property of elasticity over time.

Henry also noted the use of a glass balance disc, introduced by Dent sometime before July of 1833 and after the first successful application of a glass balance-spring to a chronometer in April that year, because the compensation required was so small it was found to be impossible to achieve with a metal balance disc.⁶² Henry described the balance disc as follows

... made of glass and is compensated by two small slips of compound metal brass and platina placed perpendicular to the plain of the balance. By an increase of temperature the spaces [ie pieces] of metal are bent outwards or inwards and consequently the rotatory motion altered. These pieces of metal are adjusted by cutting off small pieces until the watch does not vary for any change of temperature.⁶³

For Dent '[i]ndependent of the lamina, [the glass disc] is a solid body' with the anticipated advantage 'that it will be in no way affected by centrifugal force, and, under all circumstances, that it will always preserve the same figure.'⁶⁴ The observation was important. Centrifugal force acting on the balance rims of a conventional compensation balance while it is oscillating can greatly affect the rate of a chronometer. Although the phenomenon was understood by a few late eighteenth and early nineteenth century makers, Jonathan Betts notes that it was not until 1887, and Victor Kullberg's paper on 'Centrifugal Force and Isochronism',⁶⁵ that it was considered in print.⁶⁶

Table 2. Francis Baily, On the Mercurial Compensation Pendulum, Read May 9 and June 13 1823, table transcribed from *Memoirs of the Royal Astronomical Society*, Vol. I, Part II, (London: Baldwin, Cradock and Joy, Paternoster Row, 1825), 381-420, p.416 and errata.

⁶¹ Francis Beaufort to George Biddell Airy, 2 March 1836, CUL, RGO, 6, 585.

⁶² Arnold & Dent, (July 1833), pp.417-8, 417.

⁶³ Reingold, *The papers of Joseph Henry*, (1979), pp. 237, 241-3.

⁶⁴ Arnold & Dent, (July 1833), pp.417-8, 417.

⁶⁵ Victor Kullberg, Centrifugal Force and Isochronism, *Horological Journal*, Vol. 30, September 1887, pp.6-7.

⁶⁶ Betts, *Marine Chronometers at Greenwich*, (2017), p.63.

Our technical analysis revealed that the balance-disc was of a different composition to the spring, containing no lead and corresponding to a common kelp-based window glass. This corroborates the understanding that lead was incorporated into the glass of the spring to engineer the homogenous distribution of particles, with the concern of the springs elastic behaviour, given the glass disc was expected to preserve its figure. In Dent's correspondence with Airy, he notes '...I refer for all the dilatations to Mr Baily's table', (Table 2).⁶⁷ From this statement we know that the chronometer maker took his measures of thermal behaviour from astronomer and stockbroker Francis Baily's table, published in his 1823 work on the mercurial compensation pendulum, and showing the linear expansion of various substances for one degree of Fahrenheit's thermometer.⁶⁸ Dent's reference to Baily's table reveals the choice of a common kelp-based window glass for the balance to be as specific and significant as the choice of lead glass for the spring. In Baily's table, kelp glass, with no lead, was defined using head of the Ordnance Survey, William Roy's 1785 results, which famously built on the thermal researches of civil engineer John Smeaton to calibrate the chains used to measure the base line of the Ordnance Survey of Britain.⁶⁹ In this way the particular composition of Dent's glass balance-disc brought his glass researches into correspondence with the highest standard of precision survey work and the most celebrated example of the substitution of metal with glass. This calibration, and the authority of the chain of reference, from Baily to Roy and Smeaton, would play a crucial role in the development of nineteenth century precision chronometry.

In early February 1842, Dent wrote to Airy proposing an improved solution to temperature compensation; which he termed 'secondary continuous compensation' that would move the ordinary compensation weights on a change of temperature, in a direction nearly concentric with the centre of motion and so minimise variations in the isochronism of the system.⁷⁰ The development of effective compensation was complicated by the marked difference between the effects of temperature change on the inertia of the balance and the tension of the spring. In his 1838 *Pendulum Researches and Improvements*, Dent claimed that,

[I]n 1833, at the meeting of [the British] Association in Cambridge, he was the first who publicly resolved the effect of variable temperature upon the balance springs of chronometers into two distinct portions: viz the one, so long

⁶⁷ Edward Dent to George Biddell Airy, 21 February 1843, CUL, RGO 6, 585.

⁶⁸ Francis Baily, On the Mercurial Compensation Pendulum, Read May 9 and June 13 1823, *Memoirs of the Royal Astronomical Society*, Vol 1, Part II, (London: Baldwin, Cradock and Joy, Paternoster Row, 1825), table: Linear Expansion of various substances for one degree of Fahrenheit's Thermometer, 381-420, p.416.

⁶⁹ John Smeaton, Description of a New Pyrometer with a Table of Experiments Made Therewith, By Mr J Smeaton, F.R.S, *Philosophical Transactions*, 48, (1753-1754), 598-613, Tables I and II; Anita McConnell, *Jesse Ramsden (1735-1800) London's leading scientific instrument maker*, (Ashgate, 2007), pp.194-200; Jim Bennett, Plates from Royal Society Publications: illustrating William Roy's baseline on Hounslow Heath, *Notes and Records of the Royal Society*, 60, (2006), 225-30.

⁷⁰ Edward Dent to George Biddell Airy, 5 February and 12 February 1842, CUL, RGO 6, 585

known, which produces the variation of length; and *another, that had hitherto escaped attention, which affects the elasticity of the spring.*⁷¹

Though Dent's analysis of the relation between length of the spring and the force delivered is specious by the standards of modern horological science, nonetheless his use of the glass disc did indeed remove the complication of the changing moment of inertia, a significant advance in Dent's experimental chronometrical science.⁷² However, in the late 1830s, the authority of Dent's claim, that the variable could be successfully removed through material substitution, depended on the authority of the assumption that any expansion in the glass was negligible and so could be safely ignored.⁷³ It depended on the specific kelp-based window glass of the balance, and the chain of reference leading back to Roy's national survey and the researches of Smeaton.

Glass and temperature to calibrate the Greenwich Time Service

Dent was far from the only maker to develop improved compensation. In the Royal Greenwich Observatory archives held by the Cambridge University Library, the volume 'Claims for Chronometer Improvements' is devoted exclusively to the competition among pre-eminent makers such as Eiffe, Molyneux, Parkinson, Frodsham, and Dent, for an improved mechanism of temperature compensation.⁷⁴ In the decade covered by the volume, 1834-1844 the competition became increasingly heated. This decade of competing temperature compensation claims directly followed Dent's first announcement in the *Nautical Magazine* in 1833 and the introduction of the glass balance-spring chronometers to be rated at the Observatory that same year. Further, 1833 saw the installation of the time ball at the Royal Observatory, the mechanical dissemination of Greenwich Time, a concern that more than ever before made salient the local specificity of time measurement. In 1836, Airy succeeded John Pond as Astronomer Royal, and the Premium Trials which had taken place annually since 1822, were terminated. Shortly after his appointment Airy wrote to Beaufort asking for information as to 'whether it has ever been usual to use extreme temperatures (I mean from sharp frost to the heat of a warm room)' to trial chronometers 'and whether there would be any objection to doing so again'.⁷⁵ Beaufort's reply followed promptly the next day,

I am not aware that, in any instance, artificial temperatures have been applied to any Chronometers that were on trial for the Admiralty - as the whole annual term would expose them to a change of 50° or 60° - But I think it extremely proper that in certain cases they should be submitted to the more rigorous trial of being exposed more abruptly to changes of temperature between 20° and 85° of Fahrenheit.⁷⁶

With Beaufort's approval, Airy began trialing Eiffe's temperature compensation (Eiffe 3 and 4), against two chronometers (Earnshaw 543 and 819). First, out of doors

⁷¹ Edward John Dent, *Pendulum Researches and Improvements*, London, (September 1838), p.4, copy in CUL, RGO 6, 585.

⁷² Edward John Dent to George Biddell Airy, 5 February 1842, CUL, RGO 6, 585.

⁷³ Edward John Dent to George Biddell Airy, 5 February 1842, CUL, RGO 6, 585.

⁷⁴ 'Claims for Chronometer Improvements', 1834-44, CUL, RGO, 6 587.

⁷⁵ George Biddell Airy to Francis Beaufort, 23 December 1835, CUL, RGO 6, 587.

⁷⁶ Francis Beaufort to George Biddell Airy, 24 December 1835, CUL, RGO 6, 587.

between 27 February and 26 March, ‘screened by a double board from the rays of the sun’ with a mean temperature that ‘probably did not differ much from 44° Fahrenheit. Following this, ‘from March 26 to May 21, the chronometers were kept in the usual place in the chronometer room, the mean temperature probably differed little from 55°’. Finally ‘from May 21 to June 25 the chronometers were placed before a fire in the chronometer room, the mean temperature was probably near 70°.’⁷⁷ These experimental set ups and temperature estimates were crude compared to the researches conducted in 1833 and 1834 by Dent, and presented by Beaufort to the Royal Society in May of 1836. A significant proportion of the manuscript paper read by Beaufort was devoted to describing the method of preserving a stable temperature of 12° Fahrenheit for 12 hours even during the summer months. While the Observatory made rudimentary experiments that estimated artificial temperatures ranging from 44° to 70° Fahrenheit, Dent’s glass springs underwent precision observations through extremes from 12° to 100° Fahrenheit.⁷⁸

In April 1836, while preparing the report of their various experiments on the glass springs, Dent wrote to Beaufort pointing out that the official rate of the glass spring chronometer No. 616 supplied by the Observatory since 12 October 1833 ‘does not contain the thermometer’, and further soliciting the hydrographer’s help in obtaining the missing measures.⁷⁹ Beaufort wrote directly to Airy’s First Assistant at the Observatory, Robert Main, noting his anxiety to have a full statement of the performance of the springs.⁸⁰ Main’s reply took a few days, and was incomplete when it came, prompting Beaufort to repeat his request on 3 May.⁸¹ Main responded the next day,

Dear Sir,

I find on inquiry that it was formerly not usual to register the temperatures in the Chronometer room except during the Annual public trials. The months in question fall between consecutive trials. I have directed strict search to be made but no record of the temp can be found. Perhaps the accompanying temp registered from the circle room thermometer may be of some service to Mr Dent...⁸²

This realisation, prompted by Dent’s glass researches, took place at a pivotal moment, with the apparent termination of the Premium Trials. Far from their cessation, the ‘termination’ that same year saw the public spectacle of the Premium Trials formally institutionalised in the working of the Observatory under Airy’s management. From the moment of Dent’s request, all trials would take place alongside constant temperature observations. Further, and with explicit reference to the glass spring chronometer trials, it was decreed that,

⁷⁷ George Biddell Airy to Charles Wood, 29 June 1836, CUL, RGO 6, 587.

⁷⁸ A Paper on the application of Glass as a Substitute for Metal Balance Springs in Chronometers By Messrs Arnold and Dent – Communicated by Francis Beaufort, received 5 May, read 12 May 1836, Royal Society, AP 20 7 & 8.

⁷⁹ Edward John Dent to Francis Beaufort, 23 April 1836, CUL, RGO 6, 585.

⁸⁰ Francis Beaufort to Robert Main, 23 April 1836, CUL, RGO 6, 585.

⁸¹ Robert Main to Francis Beaufort, 26 April 1836; Francis Beaufort to Robert Main, 3 May 1836, CUL, RGO 6, 585.

⁸² Robert Main to Francis Beaufort, 4 May 1836, CUL, RGO 6, 585.

...in the beginning of 1843 and at all subsequent trials, [chronometers] will be rated at the discretion of the Astronomer Royal through a variety of temperatures, from the lowest that can be obtained without artificial means, up to that of 100° Fahrenheit.⁸³

The same year, 1843, saw the newly established Liverpool Observatory pioneer the first design and use of dedicated chronometer ovens for testing chronometers through a range of temperatures, a system later copied by Airy for the Greenwich Observatory in 1850. Public pressure for a Liverpool Observatory had grown through the 1830s, but only met with success late in 1841, following the involvement of the British Association, one of the principle audiences for Dent's glass springs research. Robert W. Smith has described in this journal how the appointed director, astronomer John Hartnup, had three central tasks 1) to determine the longitude of Liverpool with as much accuracy as possible; 2) to give accurate time to the port; 3) to test and rate chronometers.⁸⁴ 1843, the year of Hartnup's appointment, saw the publication of Dent's 1842 determination of the difference in longitude between Greenwich and Liverpool,⁸⁵ cementing the chronometer maker's role in the foundation of the Liverpool Observatory. It was in these foundational years that Hartnup became focused on the problem of middle temperature error and the changing elasticity of the balance spring with temperature, a preoccupation that would ultimately give rise to the famous Hartnup balance.⁸⁶ Under Hartnup's pioneering chronometrical thermometry, Liverpool Observatory became a model establishment in the extension of the national time service, such that, in 1866, Airy noted 'in regard to regulated clocks, the best instances in the world are those of Liverpool and Glasgow.'⁸⁷ Through Dent's intimate engagement with questions of temperature and elasticity, questions he was brought to in the study of the molecular composition of different species of glass, he developed the local specificity of time as a local specificity of temperature. The exemplary regulation of the Liverpool Observatory, that gave accurate time to the port, came not just from the accurate determination of the longitude of Liverpool, or the close communication with Greenwich, but specifically from the temperature-focused testing and rating of chronometers.

Conclusion

The research presented here began with the great expectations of government scientific administrators, apparently unfulfilled. Yet in the course of a mixed methods study, combining technical analysis with archival research, the specific glass of the balance spring and disc were found to play a critical role in Dent's identification of Middle Temperature Error, and, in the second quarter of the nineteenth century, the

⁸³ Hydrographic Office, 26 November 1841, *Notice to Chronometer Makers*, CUL RGO 6 574.

⁸⁴ Robert W. Smith, The Hartnup Balance, *Antiquarian Horology*, 14, 01, (March 1983), 39-45.

⁸⁵ William Lassell, Account of an Observation of the Solar Eclipse of the 7th July, 1842, made at Starfield Observatory; together with an Account of some Chronometrical Experiments to determine the Longitude of that Observatory, *Memoirs of the Royal Astronomical Society*, (1843), 91-6.

⁸⁶ Smith, *Antiquarian Horology*, (March 1983), 39-45.

⁸⁷ George Biddell Airy to D. Stoney, 1 Jan 1866, CUL RGO, 6, 616.

authority of his analysis. This identification and analysis not only shaped the innovative designs and extraordinary precision of Dent himself, one of the nineteenth century's greatest clock-makers, but also influenced horological culture and practice more generally. Perhaps most significantly of all, this culture change had important implications for the extension of the national time system, where local time was analysed as a function of local temperature. Analysis of innovation has often focused on design, without attending to the significance of materials. Yet one of John Harrison's greatest legacies might be said to be the exquisite compensation he achieved through close attention to the combination of specific material properties, notably in his bimetallic strip. In this sense, Dent's glass research was a continuation of Harrison's ground breaking work. The implications of the specific composition of Dent's glass have been unmarked until now, but their importance suggests a line for future research: to forget the catalogues of standardised materials we now rely on and consider instead the exquisite detail of the particulate composition of component parts in these technological masterpieces. Such a focus brings practice to the fore, but truly situated in the wider culture of the day.