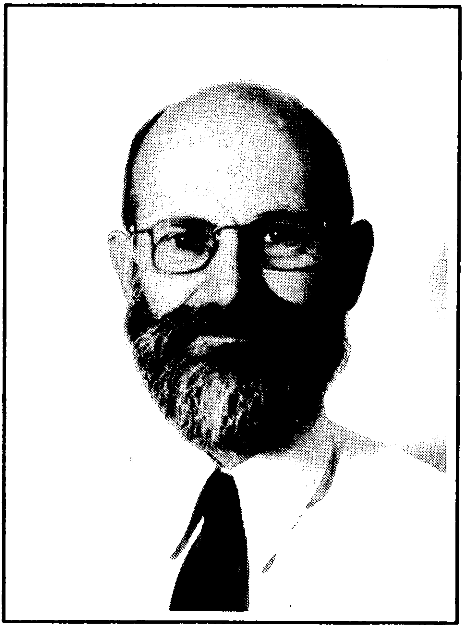


THE ONE BEST WAY : INSTRUMENTS FOR MEASUREMENT AND CONTROL

Stuart Bennett

When I first began to write about the history of control engineering — as a Research Assistant preparing material for the inaugural lecture of my Professor — much of the engineering history I read was written by engineers, for engineers, and like most of the more general history of technology, it was internalist in approach. It was an account of inventions and of the struggles and eventual triumph of inventors; there was also the assumption that technical progress followed from scientific discovery. There were some dissenting voices : Lewis Mumford, in a series of books, took a broader view; as did the physicist J.D. Bernal who, in writing from a Marxist perspective, attempted to relate scientific and technical change to economic and social conditions.[1] It was refreshing to read Bernal arguing that the scientific discoveries of the 19th century owed much to the mechanicians and practical men of the 18th century.

Over the past 25 years the genre has been transformed : the history of technology has been incorporated into the mainstream of economic, social and labour history. Economic historians such as David Landes and Nathan Rosenberg have explored deeply industrial change and the complex relationships between technology and economic and legal structures. Alfred D. Chandler Jr. in his book *The Visible Hand* drew attention to the important changes in the organisation of industrial companies which occurred during the latter part of the 19th century and the early part of this century; in particular to the development of a managerial bureaucracy with its need for measurement, and calculations of performance and efficiency.[2] Thomas P. Hughes has shown that technical change needs to be viewed as part of the development of socio-technical systems.[3] The work of the labour process historians, and in particular Harry Braverman and David Noble, has focused attention on the issue of who is in charge, managers or workers.[4] More recently both sociologists and historians have argued that technology is a social construct and that technological change cannot be understood outside its social context.[5]

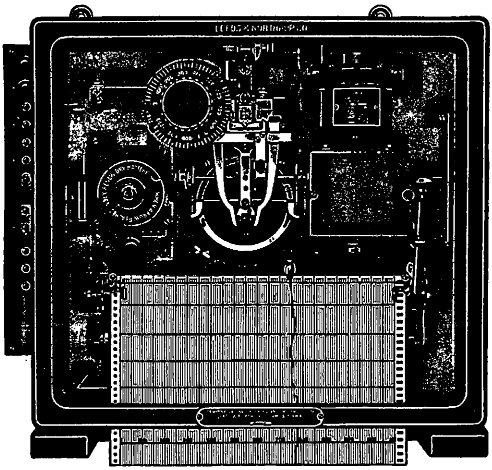
There is also a growing interest in studying the history of smaller scale enterprises and networks of independent producers.[6] As well as in the history of the enabling technologies such as the telegraph and telephone. My particular interest is in an enabling technology — measuring, recording and controlling instruments — and their introduction into industry.[7] The scientific triumphs of the nineteenth century physicists combined with changes in business structures together produced a thirst for quantification and standards. This in turn led to the movement of measuring instruments — indicators, recorders and eventually automatic controllers — from the scientific laboratory to the factory; and also to extensive changes in the record keeping within businesses.[8]

I am going to tell the story of one instrument : the Leeds & Northrup recorder which was designed and developed by Morris E Leeds between 1908 and 1912. Morris E Leeds was born, in 1869, into a Quaker family. He developed a fascination for nature, became an expert botanist and ornithologist, tried his hand at teaching but eventually decided on a career in business. Through family connections he joined the James W Queen Company of Philadelphia, then the largest American instrument firm; during 1892-93 he studied at the University of Berlin and took the opportunity to visit the leading European instrument makers. He continued to work for the Queen company until 1899 when he left to form his own company - the Morris E Leeds Company. In 1903 he took as a partner the physicist Edwin Northrup and the company was renamed as the Leeds & Northrup Company.

The Leeds recorder (see figure 1) is designed to produce on paper a record of small changes in electromotive force (emf) produced by a measurement sensor, for example, from a thermocouple or from the

LEEDS & NORTHRUP COMPANY

PRICE LIST



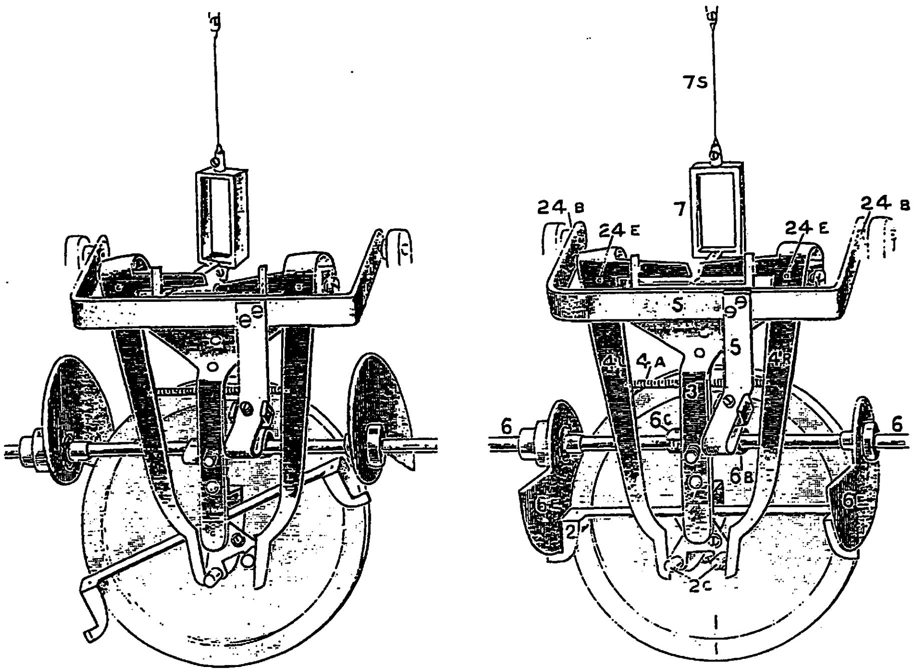
No. 8571-h Potentiometer Recording Controller with front setting device

POTENTIOMETER RECORDING
CONTROLLERS

Fig. 1 : Leeds & Northrup Recorder (reproduced from Leeds & Northrup Catalogue No. 84 1920).

imbalance in a Wheatsone bridge circuit. The emf is converted into a mechanical movement by the use of a galvanometer and this movement is recorded over a period of time as a trace on paper. The technical problems are (i) how to get a visible mark on the paper without disturbing the galvanometer movement and hence distorting the measurement; and (ii) how to get a record on a rectangular grid rather than a curved grid - the galvanometer arm swings in an arc. The essence of the device is a servomechanism, that is a position following system which both amplifies the movement of the galvanometer arm and also follows its movement precisely. To do this, Morris Leeds designed a system in which, periodically (typically at 1 minute intervals), the galvanometer needle was clamped and then mechanical feelers were used to sense its position. The principle is illustrated in figure 2. The spring loaded feelers are pressed against the needle, the larger the deflection of the needle from

CONSTRUCTION AND OPERATION OF THE RECORDER MECHANISM



MECHANISM UNBALANCED
Fig. 1.

MECHANISM BALANCED
Fig. 2.

Fig. 2 : Detail of the recorder balancing mechanism (reproduced from Leeds & Northrup Catalogue No. 85 1914).

the null position, indicated by the centre of the feeler arms, the greater the tilt in the follow-up mechanism. When the needle is unclamped the cam (6E on figure 2) corrects the tilt and in so doing moves a pen across the recording paper. The first recorders used clockwork drives for the chart and the follow-up mechanism, however, by the time the recorder was released for general sale the clockwork drives had been replaced by single electric motor whose speed was controlled by a mechanical governor.

Neither the periodic clamping of the needle, nor the use of a follow-up servomechanisms were new; both were use in the Callendar recorder (see figure 3) being sold by the Cambridge Scientific Instrument Company (it was marketed by the Taylor Instrument Companies in the USA). The Callendar recorder used electrical contacts and on-off control for the follow-up mechanism : a key feature of the Leeds recorder was that the follow-up movement was made proportional to the error. Furthermore the Leeds instrument was designed for industrial use rather than scientific use and was made robust.

Recorders were sold to the Packard Motor Company, who had approached the Leeds & Northrup Company in 1909 for advice and assistance with overcoming the problem of the lack of trained heat treaters, and to the Midvale Steel Company where they were used in the heat treatment room. A Leeds & Northrup employee, William J Wrighton, when visiting the works noticed that the traces obtained clearly showed the recalescence point of the carbon steel being treated (see figure 4). The recalescence point, also referred to as the critical point, is the point at which a phase change takes place in carbon steels. Investigations by Henry Clifton Sorby and others during the 1880s on the effects of heating and quenching of carbon steels, that is steels containing between 0.6 % and 1.4 % carbon, had shown that the hardness, and hence the ability of steel to retain a sharp edge, was dependent on the grain structure and crystalline form of the ferrous-carbon mixture. Heating and cooling changed the grain structure, for example, rapid cooling (quenching) preserved the grain structure that had been formed at the high temperature.

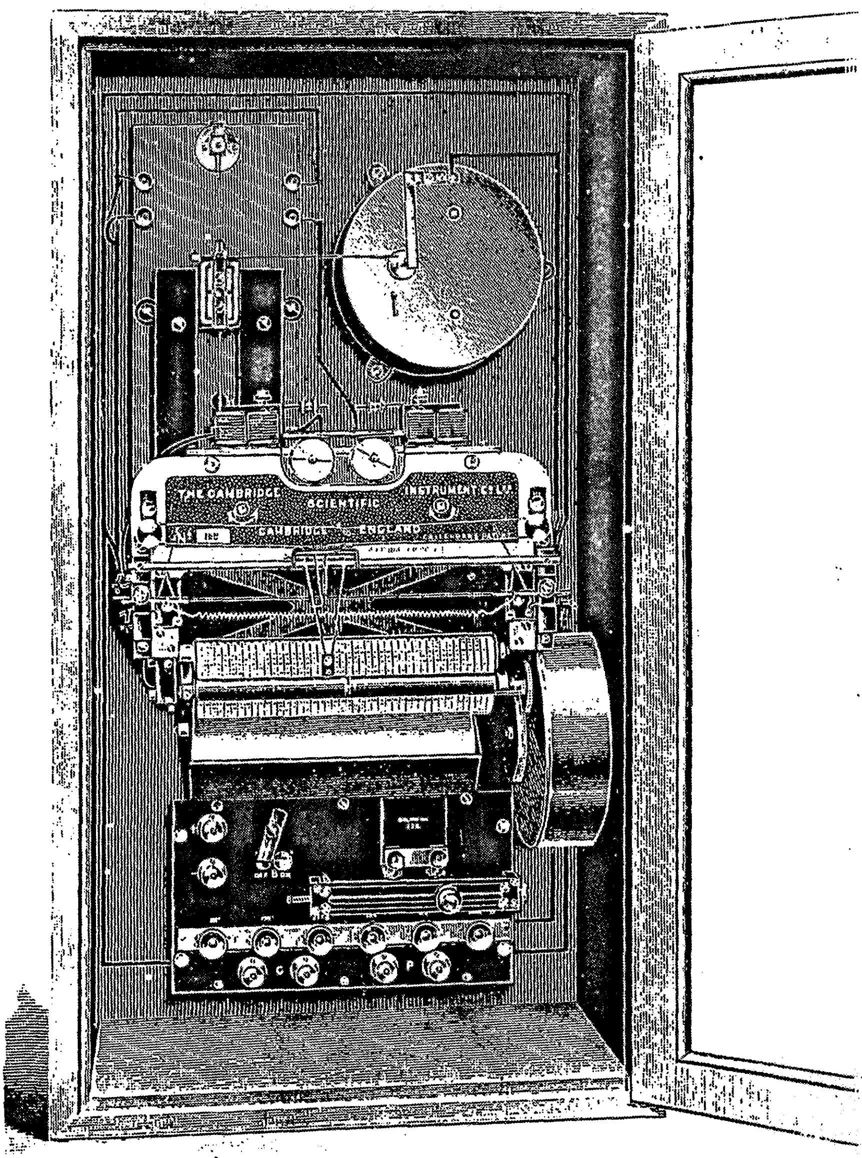


Fig. 3 : Callendar Recorder (reproduced from the Cambridge Scientific Instrument Company Catalogue 1906).

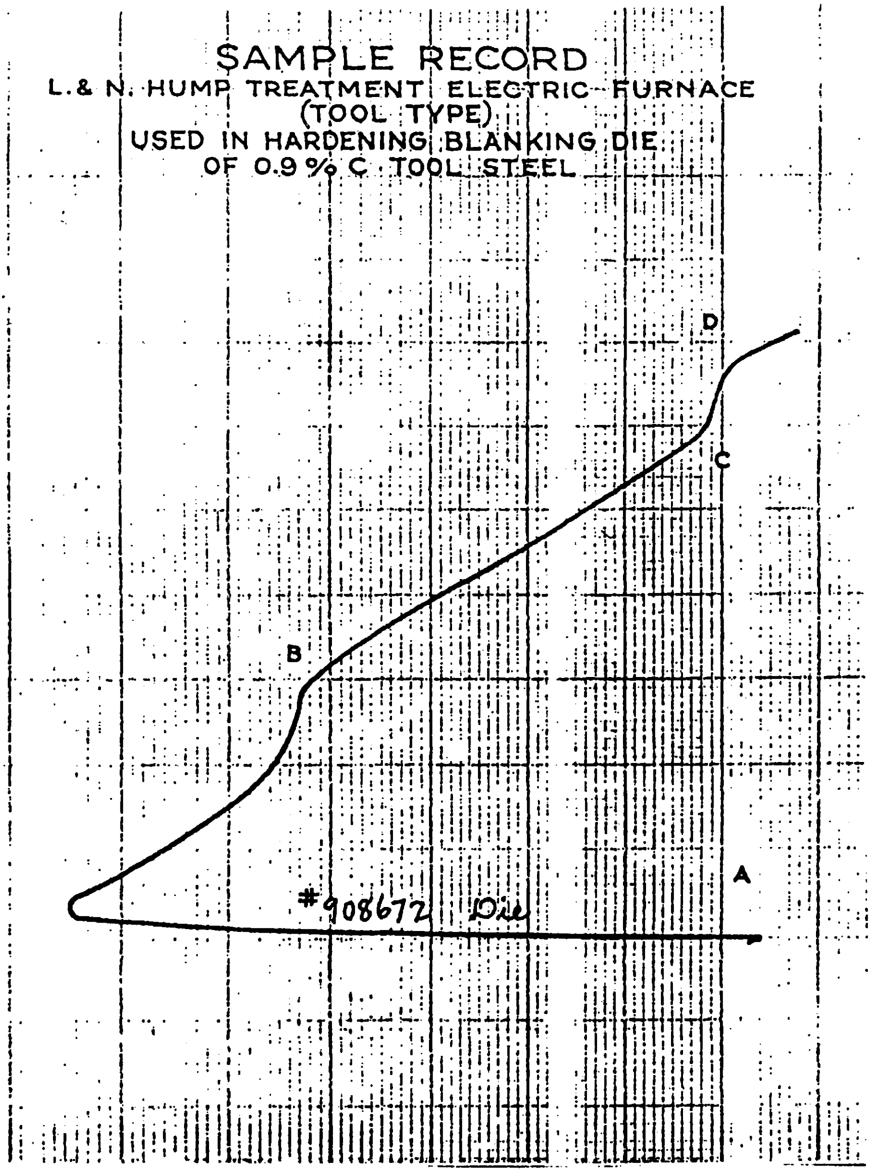


Fig. 4 : Recalescence Curves (reproduced from Leeds & Northrup Catalogue No. 84 1920).

In the hardening of components such as gears, and in the preparation of steel for the edge tools, the steel has to be heated to just above the critical temperature. Unfortunately this temperature varies with the composition of the steel and hence the furnace temperature, in the absence of accurate knowledge of the composition, was not an adequate guide. During the phase change heat is absorbed and hence the temperature does not rise so that by observing the rate of rise of temperature the critical point can be determined without knowledge of the composition.[9] This is what Wrighton had noticed. He filed a patent application, in 1915, for a method of heat treatment in "which the temperature...need not be known or determined". The patent was assigned to the Leeds & Northrup Company and was granted on June 20, 1916.[10] The method was promoted as the "Hump" method of heat treatment and the company began to manufacture electric furnaces for heat treating steel components. The furnaces were equipped with the Leeds recorder and also could be fitted automatic temperature control systems (the purpose of these was to prevent overheating and hence "burning" of the steel).

The Leeds recorder was sold in large numbers, for not only were the fitted to the furnaces manufactured by Leeds & Northrup but also to furnaces sold by other manufacturers (any company fitting a Leeds recorder was granted a right to use the hump method without payment of a royalty). The mechanical recorder was eventually superseded in 1931 by an electronic version, the "Micromax".

This is the story as told in the official company history *Precision, People and Progress*, written by William Vogel and published in 1949.[11] It is a traditional story of invention and discovery, of technological progress and of the transfer of scientific knowledge to industry. The Leeds recorder can be seen as a simple straightforward technical improvement of the Callendar recorder. A similar account is found in P. H. Syndenham's book *Measuring Instruments : tools of knowledge and control.*[12]

But this story leaves many unanswered questions. Why did the Packard Motor Company approach a *scientific instrument* maker for help with an industrial problem ? Why was the recorder built in two forms : the multi-point recorder and the single point curve tracing recorder ? Why did a scientific instrument manufacturer change to become a major industrial instrument manufacturer (and furnace manufacturer) ?. Surely not on the basis of a chance discovery ? Vogel tells us that Morris Leeds did not do anything without considerable thought and thorough preparation. Why did companies buy expensive recorders (in 1912 a simple indicator was sold for around $30, a Leeds recorder cost between $250 and $430) ? Why did some firms install recorders on the shop floor where they could be seen and used by workers, while others installed them in the superintendent's office and in central control rooms ?

Let me tell the story in another way. When Edwin Northrup joined the Morris E Leeds Company in 1903 there was already considerable interest in pyrometers for measuring the high temperatures found in metal production and working applications. Journals such as *American Machinist*, a publication intended for skilled artisans and small factory owners, and the *Engineering Magazine*, whose intended readership was managers and supervisors, carried articles in 1900 and 1901 on the industrial use of pyrometers. They also carried reports of experiments on heat treatment being carried out by Frederick Winslow Taylor and Maunsel White at the Bethlehem Steel Company in which accurate temperature measurements were being made by using a pyrometer. Taylor's famous paper on the "Art of cutting metals" was published in 1906, and the 1906 catalogue of the Cambridge Scientific Instrument Company carried illustrations of the use of pyrometers for heat treating. In 1907 the William H Bristol Company announced its base metal thermocouple together with a chart recorder and these were widely advertised and reported in trade papers. According to Bristol's 1907 catalogue, Bristol Electric Pyrometers (see figure 5) were already in use in over 300 companies including 14 Automobile Manufacturers (one of which was the Packard Motor company). In 1909 the American Gas Furnace Company was selling a furnace with automatic temperature control and in 1910 the Hoskins Manufacturing Company of Detroit was offering a "Recalescent outfit", which comprised a small electric furnace and a temperature indicator.

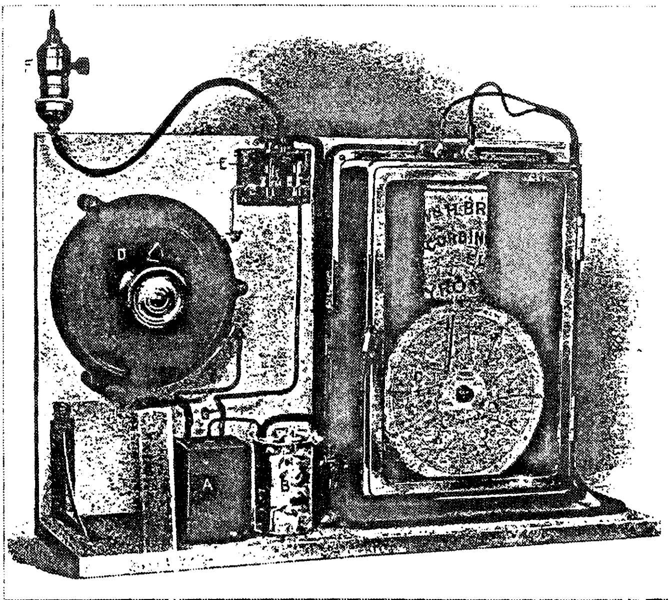


Fig. 5 : Bristol Company Electric Furnace and Recording Pyrometer (reproduced from the *Engineering Magazine*, 1909).

Judging by a paper published in 1908 in the *Transactions of the American Institute of Chemical Engineers* Edwin Northrup was clearly aware of the industrial use of electric resistance pyrometers, and he had a detailed understanding of problems associated with their introduction into an industrial environment. He observed that a pyrometer system can easily provide "a workman at the furnace, and a superintendent in the office" with simultaneous readings of temperature. He refers to the availability of a recorder, which from his description would appear to be the Callendar recorder, and he emphasises the importance of such devices in obtaining "unbiased evidence".[13]

The content of this paper suggests reasons why the Packard Motor company might have asked Leeds & Northrup for assistance. However, firms such as the William H Bristol Company, the Hoskins Manufacturing Company, Edward Brown, and Taylor Instruments all had experience in this area and had developed appropriate instruments so there is still some mystery as to why Leeds & Northrup were asked to help. There is one possible connection, Frederick Taylor was friendly with F.F. Beall of the Packard Motor Company and, given that around 1909 Morris Leeds seems to have also become involved with work at the Midvale Steel Company, there may be some connection. Taylor's approach to the question of shop management — in his 1903 paper he argued that "all possible brain work should be removed from the shop"; that management should determine, by careful observation and recording, followed by scientific analysis, the "one best way" of carrying out a task; and that artisans should obey management's orders — was likely to have appealed to Morris Leeds. As would the comments of James M Dodge who, in 1906, described the Taylor system as "simply an honest, intelligent effort to arrive at the absolute control in every department, to let tabulated and unimpeachable fact take place of individual opinion"[14] Leeds, although he believed in looking after the welfare of his workers, was anti-union, and believed that it was the duty of the workers to obey managers.[15]

The system installed at the premises of the Packard Motor Company reflected this view of the relationship between management and workers (see figure 6). A small electric test furnace, equipped with a curve tracing recorder, was used to determine the critical temperature. The main furnaces were fitted with thermocouples and the signals from these were recorded on multi-point Leeds recorders placed in a separate room. The supervisor in the control room set the desired furnace temperature and each furnace was equipped with a set of lights and a temperature error indicator which showed the difference between the set temperature and the measured temperature. The furnace operator did not have any indication to the actual temperature.[16]

This system is similar to that used by the Standard Tool Company of Cleveland, Ohio which was described by E F Lake in an article in *American Machinist* of 1908. The heat treatment furnaces were housed in a special building with window apertures designed to maintain constant ambient light conditions and hence assist the operator in estimating the temperature of the components being treated by observing their colour.

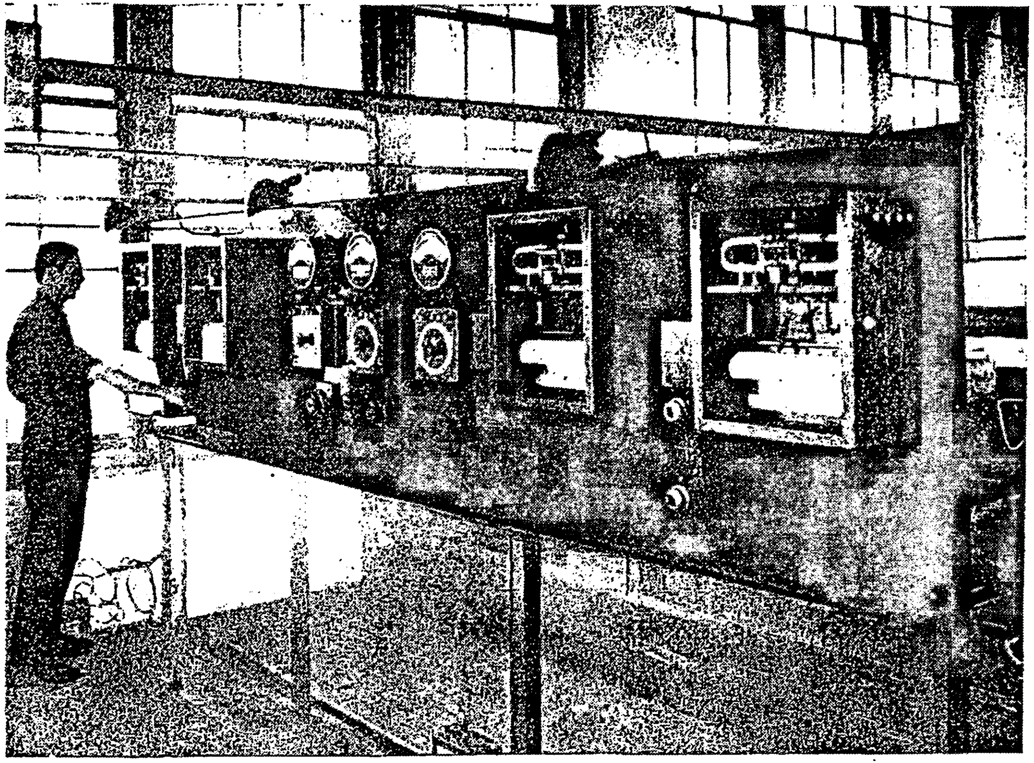


Fig. 6 : Leeds & Northrup Heat Treatment Control System - Packard Motor Company (reproduced from *Factory*, 1915).

However, the operator did not judge temperature by colour alone; each furnace was equipped with a thermocouple and a supervisor in a central control room periodically read the temperature of the furnace, if the temperature corresponded to that on the job sheet then no action was taken, if the temperature was too high or too low this was signalled to the operator by a temperature indicator attached to the furnace. This system was devised to "aid the operators in their work", for as Lake explained "intelligent judgement of the operators cannot be ignored" and they made the final decision that the treatment was complete.[17]

The earliest published reports of the Packard system that I have been able to find are those which appeared 1915. However, in the Leeds & Northrup Company records there is a reference, in the Experimental Committee minutes dated 25 March 1912, to project X-79 "Experimental Recalescence Recorder" and to recalescence curves obtained for samples of steel for Packard. On 18 November 1912 this file is reported as closed and the comment is made that the recorder is now a practical device for determining critical points. At a further meeting at the end of November 1912, project X-230 "Recalescence furnace of a type to be marketed" was reported as being completed. This was a laboratory scale furnace which was installed at the Packard Motor Company and was used for determining the temperature at which different components reached the critical point.[18]

There is no reference to the Packard system in the 1914 recorder catalogue, the illustrations are of installations at the Midvale Steel works : perhaps the Packard Company did not want any publicity. This catalogue is interesting in that it draws attention to the recorders being placed were workmen can see them. The publication of Frederick Taylor's views in book form in 1911 and the congressional hearings on "The Taylor and other systems of shop management" held during 1912 had fuelled the debate about "shop management" and, in particular, who was to exercise control on the shop floor - the artisan or the manager. Measuring instruments were one source of contention - should artisans on the shop floor be provided with instruments to help them perform their job better or should the managers and superintendents use the instruments ? Many saw in the recorder a means of control "because mechanical recorders eliminate the personal equation, they give an important measure of control." Both because it provided information for managers but also because "one of the most valuable features of such devices is the moral effect on the workmen".[19] Advertisements and catalogue descriptions were not always so blatant as this but they still go over the message. By 1914 there began to be references, in advertisements, to scientific management "modern methods of scientific management have settled beyond all question that he use of Recording Instruments is indispensable in order to secure the highest efficiency and economy of results" ran one such advert from the Bristol Company in 1914.[20]

The minutes of the meeting of the Experimental Committee for November 1912 report a decision to commence project X-270 "Develop an electric furnace for hardening and annealing", this project went well at first and in June of 1914 it was reported as being complete with the design being turned over to the engineering department to prepare for production. One of the first furnaces built was used by Leeds & Northrup themselves and another one seems to have been supplied to the Midvale Steel Company. The furnaces did not work as expected and in a paper given at a meeting of the American Society for Testing Materials in June 1915 Leeds reported on experiments carried out by Radclyffe Furness and A H Miller of Midvale Steel and William Wrighton of Leeds & Northrup. They found wide temperature variations in the oven, problems of different rates of heating with different sized specimens and observed the large quantity of heat absorbed during transformation.[21] It is presumably as a result of this work that Wrighton filed the patent application for the Hump method.

During the period between 1915 and 1920 the Leeds & Northrup Company changed from being a scientific instrument manufacturer and supplier to become industrial instrument manufacture. It was also during this period that the influence of Morris Leeds declined; a crucial point in this change was the formation, in 1918, of Executive Committee comprising Leeds, C Reed Cary the sales director, C S Redding, Chief Engineer and I. B. Smith who was responsible for development. Morris

Leeds remained as President of the company and chaired the Executive Committee but from 1920 onwards he devoted most of his energy and time to personnel matters.

During 1918 and 1919 the Executive Committee devoted a lot of time to developing a strategy for the Company. They were aware of the company's dependence on the recorder, (just how dependent did not become clear until the end of 1919 when they reviewed the performance over the eight years and discovered that 50% of the total income had come from recorder sales and that the profits from the recorder — around $48,000 — were greater than the total net profits for the period of $42,000).

The recorder was an excellent product and was superior to all its rivals. As long as they could convince a customer of the need for a recorder they could sell it at a premium price and make a good profit on the sale. But how could they convince a customer to expend $250 to $400 on a recorder instead of $30 to $40 on a simple indicator, or $75 on a Hoskins Manufacturing Company recorder ? The Hump patent offered a means of persuading customers to buy a recorder but it added significantly to the cost of a furnace — typical furnace prices were between $430 and $1010 depending on size. They were also aware from reports from their sales staff that the Hump patent was going to be difficult to defend against infringements. How could they detect and prove that a user, who installed another company' s recorder on a heat treatment furnace, was using the Hump method ? They also had to make a decision about the electric furnace development; they had already made a significant investment in the furnace but there were still major problems to be overcome. Sometime during 1918 they decided to continue with this product. This decision was to have far reaching consequences, it took almost 10 years and an expenditure of $100,000 to get a satisfactory electric furnace, and during the down turn in the business cycle, which occurred in 1921, the committed expenditure on the furnace almost bankrupted the Company.

Having made the decision the Executive committee, in January

1919, considered a report from I. B. Smith on a strategy for selling the heat treatment furnaces. He proposed directing sales effort at managers but noted that if they adopted this approach "then we have opposed to us a class that is as a rule not intelligent, but prejudiced and very jealous of anyone or anything lessening their importance in the eye of management".[22]

The outcome of this change in strategy can be seen in 1920 catalogue for the Hump method in which it is claimed that "all heat-treating operations can be brought under the complete and certain control of one man, who is guided by the unequivocal indications of instruments." This was a significant change, for the whole essence of the hump method was to aid the operator. The 1923 edition of the catalogue put the position even more clearly :

> "By installing temperature measuring instruments of the indicating type a physical effect of temperature is substituted for the workman's guess, but quality is still dependent upon the care and accuracy with which he adjusts valves, etc. The next step is to put in an autographic recorder to keep a record of the results of his efforts and to guide him in applying his manipulative skill. It is manifest that each of these steps makes possible the employment of less trained or lower grade labor in obtaining a given result, but the next step, the use of automatic temperature control, eliminates labor almost entirely, in so far a continuous regulation is concerned."

The support for fully automatic control given at the end of this paragraph is a reflection of the declining influence of Morris Leeds. The 1918 catalogue had argued that for accurate temperature control a curve drawing recorder need to "be used by the man who operates the furnace" for in "furnace control, the direction in which the temperature is changing is a factor of equal importance with the temperature at any instant." Leeds had for many years opposed attaching automatic control units to the recorder because he argued that the then available technology — on-off control — could not provide adequate control and that a human operator would provide more precise control of temperature.

What do the stories of the Leeds recorder tell us ? It seems to me that the recorder was developed to meet a management desire for records rather than to meet a specific technical need, the Callendar recorder or even manual recording of results would have provided the information necessary to set the temperature of the furnace. The recorder was part of a system of heat treatment, which was itself part of a manufacturing system. The technology adopted was determined by the chosen system of manufacturing.

Turning to the Hump method : although the evidence is not entirely clear, I think that prior to the experiments carried out in 1915 at the Midvale Steel Company Leeds & Northrup had viewed the curve drawing recorder as a "scientific instrument for use in the testing laboratory, so that although they must have observed the recalescent points in the heating curve many times they had not connected these with the production process". The tests at Midvale were being carried out on a Leeds & Northrup furnace intended for production use and when the temperature records showed the recalescent break point Wrighton realised that the curve drawing recorder could be used for production purposes.

By 1919 the Leeds & Northrup Company faced a difficult choice : Taylorism and the Scientific Management movement insisted that there was "one best way" but the company had two heat treatment systems which, in scientific management terms, were diametrically opposed. One, setting the furnace to a precise, predetermined temperature gave the management direct control, all an operator had to do was obey (experience during the 1920s showed that is was not as simply as this but that is another story). The other, the Hump method called on the operator to exercise judgement : for when batches were heated in a production furnace the critical point was not as clearly delineated as in a laboratory test of a single specimen. There was, of course, a strong financial pressure for Leeds & Northrup to favour the latter approach for it would increase the sales of the highly profitable recorder.

Illustrations given in the catalogues produced by Leeds & Northrup show that their customers made various choices : some adopted the Hump method and put a recorder alongside each furnace, others continued with multi-point recorders and a central control room, and yet others adapted the Hump method for use with a central control room and signalling systems. There was no consensus on the "one best way". The proponents of Scientific Management will of course argue that examining the detail of each application will show one best way — it is difficult to deploy historical evidence to dispute such a claim, we cannot interview the people involved and the written accounts are open to many interpretations. However, turning to our own times, we find in a recent book by Robert J Thomas some parallels. Thomas, a professor of organization theory at MIT and a member of the Leaders in Manufacturing program, made a detailed study of technical change that occurred during the 1980s in four different manufacturing sectors. He argues that form which technological change takes depends on the power structures within the organisation. The group holding the "power" to make the decision will rationalise its decision using any convenient argument : technological necessity, strategic choice, employment stability, but the outcome is determined when the particular group wins the power to make the decision.[23]

Technology does not dictate how it should be used, or if it should be used at all, we as a society, through the moral values we hold and the political decisions we take, choose. There is not one best, technologically determined, way.

Acknowledgements

Thanks to the generous support of the Hagley Museum & Library, Wilmington, Delaware and to a travel grant from the Royal Society of London I was able to consult the Leeds & Northrup papers held in the archives of the Hagley Library.

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1. Lewis Mumford, *Technics and Civilization,* Routledge & Kegan Paul, London, 1934; J. D. Bernal. *Science in History, Watts & co. 1954.*

2. David S. Landes, *The Unbound Prometheus,* (Cambridge University Press), 1969, Nathan Rosenberg, Perspectives on Technology, Cambridge : Cambridge University Press, 1976, Alfred D Chandler, Jr., *The Visible Hand : The Managerial Revolution in American Business.* (Cambridge, MA: Belknap Press, 1977).

3. Thomas P. Hughes, *Networks of Power : Electrification in Western Society 1880-1930,* (Baltimore, MD: Johns Hopkins Press, 1983).

4. Harry Braverman, *Labour and Monoply Capital : the degradation of work in the twentieth century,* New York, 1974; David Noble, *America by Design,* New York: A.A. Knopf, 1977 and *Forces of Production : A Social History of Industrial Automation,* New York : Alfred A Knopf, 1984.

5. See for example Wiebe E Bijker, Thomas P. Hughes and Trevor Pinch, *The Social Construction of Technological Systems,* MIT Press, 1987; and the work of Donald MacKenzie, for example *Inventing Accuracy : A historical Sociology of Nuclear Missile Guidance,* MIT Press, Cambridge, MA., 1990.

6. See for example Philip Scranton, "Manufacturing Diversity : Production Systems, Markets, and an American consumer Society, 1870-1930", *Technology & Culture,* **35**(3) (1994) : 476-505.

7. See for example, Stuart Bennett, A history of Control Engineering : 1930-1955, Peter Peregrinus, 1993, "The development of process control instruments 1900-1940", *Transactions of the Newcomen Society,* **63** (1992) : 133-164, and "'The Industrial

Instrument - Master of Industry, Servant of Management' : Automatic Control in the Process Industries, 1900-1940" *Technology & Culture,* 32(1) (1991) : 69-81.

8. The professions were not immune from these changes, for example, .see Deborah J Coon, "Standardizing the subject : experimental psychologists, introspections, and the quest for a technoscientific ideal", *Technology & Culture,* 34(3) (1993) : 757-783. For a discussion of the systematisation of businesses see JoAnne Yates, *Control through Communication : the rise of system in American management.* (Baltimore : Johns Hopkins, 1989).

9. This was first noticed by F. Osmond, in 1887, who observed that as steel cooled the rate of cooling was slowed down at certain points and that these breaks were associated with phase changes in the steel. He also found similar breaks when steel was heated.

10. US Patent 1, 188, 128, June 20 1916.

11. William P Vogel, Jr., *Precision, People and Progress,* (Philadelphia, 1949).

12. P.H. Sydenham, *Measuring Instruments : tools of knowledge and control,* (Stevenage, Peter Peregrinus, 1979).

13. Edwin F Northrup, "Modern electrical resistance pyrometry", *Trans. American Institute of Chemical Engineers,* 1 (1908) : 116-129.

14. James M dodge, "A history of the introduction of a system of shop management", *Transactions of the American Society of Mechanical Engineers,* 27 (1905-6) : 724.

15. See D. M. Nelson, "Precision, People & Progress, The business Career of Morris E Leeds 1869-1952, *Leeds & Northrup Journal,*

4 (1968) : 23-27.

16. The accounts of the Packard installation given in *Automobile*, **32** (March 11, 1915) : 460-1 and in *American Machinist*, **42(10)** (March 11, 1915) : 413-7 disagree on the location of the control panel.

17. E.F. Lake, "A new design for hardening rooms", *American Machinist*, **31(2**, (1908) : 327-331.

18. All references to the Leeds & Northrup Experimental Committee and Executive Committee are to the Company Records held as AC 1110 in the Archives Section Hagley Museum and Library, Wilmington, Delaware.

19. "Automatic Assistant Managers", *Factory*, **XIV** (4) (April 1904) : 290.

20. This was one of series which appeared in the *Engineering Magazine* during 1914.

21. Morris E Leeds, "Some neglected phenomena in the heat treatment of steel", *Proc. 18th Annual meeting of the American Society for Testing Materials*, **XV** (June 1915) : 6-22.

22. I.B. Smith, Meeting of executive committee, Jan 30, 1919, Leeds & Northrup, Executive Committee vol. 1, AC1110 Reel 1, Hagley Museum and Library.

23. Robert J Thomas, *What Machines Can't Do : Politics and Technology in the Industrial Enterprise*, University of California Press, 1984.