PROBLEMS

The Effect of Technical Change in the British Copper Industry Between the Sixteenth and the Eighteenth Centuries *

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The general history of the copper industry in the United Kingdom during this period is familiar.[1] It began in the sixteenth century with the import of the highly developed continental system of smelting, which turned out to be only marginally competitive under English conditions and petered out in the 1630s. By the end of the seventeenth century the adaptation of the reverberatory furnace for copper placed the industry in a stronger position, and it became, for much of the eighteenth century, the first copper producer in the world. On the whole, this success has hitherto been attributed to the use of coal which, in this new furnace, replaced the expensive wood-based fuel of the old process.

Copper has always been so important that discussions of its history have tended to overlook the other minerals widely found associated with it. For

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[1] H. HAMILTON, *The English Brass and Copper Industries to 1800*, (London, 1967); Rhys Jenkins, "Copper Smelting in England: Revival at the End of the Seventeenth Century", *Newcomen Society Transact.*, XXIV (1943-4 & 1944-5), 73-80; M.B. DONALD, *Elizabethan Copper*, (henceforth Donald, *Copper*) (London, 1955); J.R. HARRIS, *The Copper King*, (Liverpool, 1964); JOAN DAY, *Bristol Brass*, (Newton Abbot, 1973); J.A. ROBEY & L. PORTER, *The Copper and Lead Mines of Ecton Hills, Staffordshire*, (Leek, 1972); T.R. HORNSHAW, *Copper Mining in Middleton Tyas*, (Northallerton, 1975); R.F. TYLECOTE, *A History of Metallurgy*, (London, 1976), pp. 69, 128-30.

both miner and smelter, on the other hand, their return was often compounded of all the useable minerals found together. Sweden may have been the most prominent exception, where copper was either the sole, or at least the vastly predominant mineral occurring in the major deposits. In the United Kingdom copper was mostly found associated with other metals, such as lead or tin; in Central Europe major sources held significant proportions of silver, which may have dominated profits until the middle of the sixteenth century.[2] If any copper was produced in England before the 1560s, this left no traces in the records; by then, some interest in introducing the modern industry had become apparent.[3] The stimulus for the successful enterprise came from the German group engaged in the English re-coinage of 1560-1; two of its members were related to Daniel Hoechstetter the elder, whom they promoted as an expert for the discovery and production of copper.[4] Daniel had been trained upon the lead, silver and copper mines of the Rauris and Gastein valleys in the Austrian Tyrol;[5] this may explain his choice of a Cumbrian site, not far from the known silver mines around Alston, with a promising silver content in Cumbrian lead mines and, at first, in Goldscape copper ores.[6] All this would help to explain why Daniel and his craftsmen came to construct their new works to smelt silverbearing copper. That included provision for the sophisticated seiger process, designed to extract the optimal proportion of silver from copper ores, by utilising the greater attraction of molten lead as against molten copper for the silver contained in their mixture. It required a lengthy series of roastings and smeltings, which treated comparatively small quantities of partly smelted copper in their later stages, and produced very

[2] E. Westermann, *Das Eislebener Garkupfer und seine Bedeutung für den europäischen Kupfermarkt 1460-1560*, (Köln/Wien, 1971), and "Die Bedeutung des Thüringer Saigerhandels für den mitteleuropäischen Handel an der Wende vom 15. zum 16. Jahrhundert', *Jahrbuch für die Geschichte Mittel- und Ostdeutschlands*, XXI (1972), 68-70; H. Kellenbenz, "Europäisches Kupfer, Ende 15. bis Mitte 17. Jahrhundert', in H. Kellenbenz (ed.), *Schwerpunkte der Kupferproduktion und des Kupferhandels in Europa, 1500-1650*, (henceforth *Schwerpunkte*) (Köln/Wien, 1977), p. 348.

[3] Donald, *Copper*, p. 96.

[4] Dr. W. Hoechstetter and Walter Hoechstetter, *Stammtafel der Hoechstetter*, (München, 1976), pp. 3, 56, shows two Ullstätt ladies as Daniel Hoechstetter's great aunt and cousin: Daniel Ullstätt was one of the organisers of the re-coinage and went to Keswick at the start of the new Cumbrian copper industry, as did Hans Loner, the husband of one of Daniel Hoechstetter's cousins - *op. cit.*, p. 57; British Library, Lansdowne MSS, V, No. 47, fo. 151-2.

[5] F. Gruber and K.H. Ludwig, *Salzburger Bergbaugeschichte*, (Salzburg - München, 1982), p. 22, supplemented by information kindly supplied by Dr. Gruber and Dr. Friedrich Blendinger.

[6] G. Hammersley, (ed.), *Daniel Hechstetter the younger: Memorabilia and Letters, 1600-1639* (henceforth *Hechstetter*), (Stuttgart, 1988), Introduction, pp. 30-7, 50-1.

pure copper as well as silver.[7] The process was laborious and therefore expensive; in Cumbria, costs were exaggerated by the need to attract and finance highly skilled manpower from far away, and by a fairly extravagant scale of planning and building. This was developed at a time when the copper mines of Central Europe were becoming deeper and more difficult to exploit, but only briefly before first Swedish and then Japanese copper began to offer increasingly severe competition.[8]

In 1563 that could not have been anticipated. Daniel the elder, in any case, possessed much of the prospector's optimism. Backed by an established group of Augsburg financiers and respectable English shareholders, he engaged in the expensive recruitment of almost 150 highly qualified Tyrolese and South-German workers, and constructed almost two dozen buildings in his first ten years, from sheds for the storage of turf, roofed stampmills, and a brewery, to a substantial three-storied smelting house, a not much smaller house for himself and his growing patrician family, as well as forges and workshops. All this was intended to deal with the product of something like ten mines, haphazardly distributed over an area of about thirteen miles north to south and seven miles east to west, from Caldbeck Fells to Borrowdale and from Fornside south of Keswick to Gatesgarth north of Buttermere. Mining, however, was soon confined to Goldscope above Newlands, Caldbeck Fells and Borrowdale; these continued to produce reasonable quantities of copper until the 1590s, while their silver content soon declined to virtual insignificance; silver production did not revive until the second decade of the seventeenth century.[9]

Some of the seeming extravagances of Daniel the elder may have been due to his need to adapt techniques to an unfamiliar variety of copper ores and to locally available fuels. He discussed both his difficulties and his significant variations in the orthodox sequence of operations with unidentified Austrian or German experts.[10] By about 1570, a mere three years after the start of operations, they had begun to employ turf and coal for the earlier stages of copper smelting, confining the need for the more expensive chopped wood and

[7] E. Egg, "Das Schmelzbuch des Hans Stöckl. Die Schmelztechnik in den Tiroler Hüttenwerken um 1550", *Der Anschnitt*, XV, Sonderheft 2 (1963), 3-34, provides some details of and accounts for earlier methods; L. Suhling, *Der Seigerhüttenprozess. Die Technologie des Kupferseigerns nach dem früben metallurgischen Schrifttum*, (Stuttgart, 1976), gives the best possible account of the process, though tending to fill gaps in earlier accounts from later works. For both these references I am [cf. MS p. 2] obliged to Prof. Hildebrandt.

[8] K. Kumlien, "Staat, Kupfererzeugung und Kupferausfuhr in Schweden 1500-1650", and K. Glamann, "Japanese Copper on the European Market in the 17th Century", both in *Schwerpunkte*, pp. 241 ff, 280 ff.

[9] Donald, *Copper*, p. 217; *Hechstetter*, p. 171.

[10] *Hechstetter*, pp. 152-4, 132-7.

charcoal to the final processes of smelting and refining, which needed only one ninth of the total weight of fuel employed.[11] Local experience may have suggested the possible utility of such fuels; cheap turf was available all around him, but his coal came from Bolton in Cumbria, about twelve miles north across country. Presumably the new fuel could not have been employed without some adaptation of methods and furnaces. The distance of many Cumbrian woods across hills and moors, and the rights of common frequently claimed over them, may have suggested experiments with more accessible fuels quite apart from the costs: in the sixteenth and seventeenth centuries, Cumberland still contained substantial areas of woodland. In any case, fuel prices did not dominate the costs of copper smelting: they may have accounted for between a quarter and a third of the total.[12] For all that the son, Daniel the younger, further reduced fuel costs in about 1620, when he discovered that coke, which cost less to carry from mine to smelter, could safely replace coal in the preliminary stages of smeltings;[13] for sophisticated metallurgy, so early a replacement of wood-based by other fuels was a notable innovation.

Copper smelting had been developed to a high level of sophistication in central Europe during the sixteenth century: mining techniques though improved to some extent, remained fairly primitive. Here too the Hoechstetters introduced some of the most highly developed methods in a combination which may have been unparalleled in contemporary Britain. They built the first British railway inside Goldscope mine, on one of the continental patterns.[14] Soon after the turn of the century, Daniel and Emanuel Hechstetter, the sons and successors, built a lengthy leat to conduct water over a large waterwheel there installed underground, to drive what may been suction pumps, all probably on a very much larger scale than anything known in Britain before then.[15] Waterdriven bellows, forge hammers and stampmills had all been familiar for some time; their concentration in one site at Brigham, on the river Greta above Keswick, with the complexity of dams, sluices and channels involved, may have been unusual, if not unique. As for the inlet tube driven through a shoulder of rock to feed the leat for all these works, that too may have been new for Britain, although presumably requiring no more than unusual manual skill and perseverance from the workers drilling it.[16]

The detailed running accounts, in which two generations of Hoechstetters probably recorded all their income and expenditure during approximately 53 years of independent operations, have not survived. Before 1600 there remain

[11] G. Hammersley, "The Rise and Decline of the early English Copper Industry, ca. 1550-1660", in *Schwerpunkte*, p. 25.

[12] *Ibid.*

[13] *Hechstetter*, pp. 162-4.

[14] M.J.T. Lewis, *Early Wooden Railways*, (London, 1974, p.b.), pp. 16-7.

[16] Donald, *Copper*, illustration facing p. 169. The tube remains plainly visible today; it is unmarked.

the detailed but indiscriminate accounts provided for the Augsburg principals until 1574, and the calculations with which the managers attempted to justify the enterprise to the crown and to creditors or potential investors.[17] Data contained in the two sets of manuscripts compiled by Daniel Hechstetter the younger between about 1600 and 1633 should be preferable, because they appear to represent attempts by the managers to clarify and identify particular aspects of operations.[18] They are probably as honest as one could hope to find, but neither comprehensive nor totally reliable: most of them hint at optimism, and all were compiled for specific purposes, not for comparison; often they tend to omit details which the compiler may have regarded as constant, or as wholly familiar. There are altogether five useable accounts drawn up between about 1600 and 1621.[19] These agree that the expenses of providing ore at the smelter accounted for half the costs of making copper, disregarding money spent on exploration or drainage. One of the three sets of accounts, itemising the costs of fuel, deals only with turf, charcoal and wood, without coal. That shows ore as responsible for 59 per cent of the total costs, fuel for fifteen per cent, skilled labour in roasting, smelting and refining for about 25 per cent, and unskilled labour for fetching and carrying something like one and half per cent.[20] A rather shorter account of about 1601, where coal is used as well, has costs of ore at 62 per cent; its fuel costs of 34 per cent may be rather too high, as they include the labour for roasting, and less than five per cent are left for equipment and other labour.[21] A summary of 1615, which impresses as fairly reliable, allocates 49 per cent of the costs to ore, 32 per cent to fuel, 17 per cent to skilled and unskilled wages, and just over two per cent to a variety of other materials: it does not seem altogether inconsistent with the data for 1601.[22] Only one of the accounts clearly sets out the money spent on the different fuels, with a proviso that it allowed for rather more turf than needed for that year. This shows that well over half had been spent on turf, between a third and a quarter on coal, and more or less the same proportion on charcoal and wood.[23] The other two accounts detail the costs of fuel less precisely, but indicate a much smaller proportion of money spent on wood-based fuel, at well under 10 per cent of the total fuel costs.[24]

[17] W.G. Collingwood (ed.), *Elizabethan Keswick, Cumberland and Westmorland Antiquarian and Archaeological Society*, Tract ser., VIII (1912); Donald, *Copper, passim.*

[18] MSS of the Duke of Northumberland at Alnwick Castle, Y II 6, Y II 7, as in *Hechstetter*, pp. 79-350.

[19] *Hechstetter*, pp. 122-4, undated, but perhaps between 1598 and 1605; pp. 114-7, ca. 1600-2; pp. 90-1, 1602 and 1619; pp. 82-3, 1615; pp. 186-7, 1621.

[20] *Hechstetter*, pp. 122-4.

[21] *Hechstetter*, pp. 114-7.

[22] *Hechstetter*, pp. 82-4.

[23] *Ibid.*

[24] *Hechstetter*, pp. 114-7, 122-4.

The reliability of the total costs of smelting indicated by these accounts is sometimes difficult to assess. Thus the account for the smelting of Coniston ores in about 1600 does not indicate the final yield of copper from its 100 kibles of ore: it must have been less than the eighteen and a quarter hundredweight of black copper and thin copperstone before their final roasting and refining. If this ore had yielded something like a hundredweight from eight kibles, widely assumed elsewhere in these records, that would imply an improbable loss of a third in weight during the last two stages of smelting, and set the total costs of the process at the high figure of £3.2.2. per hundredweight. Assuming a final yield of about fifteen hundredweight of copper, one from seven kibles of ore, a plausible assumption, gives costs of about £2.11.10. per hundredweight.[25] If this could be regarded as an acceptable guess, costs of £2.15.1. in 1601 or 1602 would indicate an increase of about six per cent, and of £4.10.9. in 1615 on of seventy-five per cent from that.[26] While these figures look fairly reasonable, the accounts group and set them out in different ways, making straightforward comparisons between them difficult. All the same, they suggest fairly strongly that this was exceeded by the increase in the cost of labour. Even if the price of fuel trebled between 1600 and 1615, or increased by two thirds between 1602 and 1615, it did not account for as much as a third of the total costs of smelting, while wood and charcoal were responsible for less than eight per cent of them.[27] The cost of woodbased fuel certainly continued to increase during the seventeenth century, subject to specific local conditions: it remains improbable that this should, at any time, have made it into the factor which dominated the costs of smelting copper.

The first Cumbrian copper industry was abandoned for good in 1636; it was really finished by 1633.[28] So far as Daniel Hechstetter's papers suggest any explanation for this, they indicate his inability to discover new promising sources of ore. That may have been the result of the declining competence of owners and miners or, less probably, of the difficulty of exploiting other veins economically under prevailing technical conditions and at ruling prices. Certainly their costs of mining and smelting had always left their returns closer to the margin than was desirable or even bearable in the long run. In the

[25] *Hechstetter*, pp. 122-4.

[26] *Hechstetter*, pp. 114-7.

[27] In 1600, depending on the final yield assumed, fuel costs lay between 6s 2d and 7s 7d per hundredweight of copper, in 1601 these were 18s 5d and in 1615 £1. 9. 3d. (rounded off to the nearest penny). Prices and quantities were about 6d per load for over 13,000 loads of turf, 3s 9d per sack for 640 sacks of charcoal, £30 for 480 cords of wood, and £150 for 4,500 horse loads — ca. 450 tons — of coal (*Hechstetter*, pp. 88-9, 112-3, 114, 162-4).

[28] Cumbria County Record office, Carlisle, Leconfield MSS, D/Lec/81; D.R. HAINSWORTH (ed.), *Commercial Papers of Sir Christopher Lowther 1611-1644*, *Publications of the Surtees Society*, CLXXXIX (1977), 27-8.

end, British copper during the first three quarters of the seventeenth century could not compete successfully with the Swedish product which, incidentally, relied on more primitive smelting methods. That would appear to be demonstrated by the fate of Ecton Hill, on the borders of Staffordshire and Derbyshire, and potentially a major source of high grade copper. It was more or less successfully exploited between 1659 and possibly the early 1670s, to peter out in a similar kind of failure.[29] Interest in the Coniston mines revived after 1686, perhaps partly as a result of the decline of the Swedish industry; Goldscope was re-opened only a little later in the 1690s, when Coniston began to be re-worked.[30] A few other attempts to mine copper ores, or even to smelt copper on a small scale, may well have escaped notice: copper was just valuable enough to hold out a hope of profit for even minor operations.

Towards the end of the 1680s attempts began to adapt the reverberatory furnace to the smelting of copper with coal-based fuel, which introduced the real and lasting revival of the British copper industry.[31] It has been widely assumed that this new method demonstrated its absolute superiority over the older and more laborious process almost immediately. No working accounts, however, have survived to demonstrate this, and much of the expert, though clearly not totally impartial evidence provided by Swedish observers contradicts it.[32] They seem to make an exception only for Upper Redbrook Copper works, where they indicate that copper was finished in a 'breast' furnace using charcoal, which was said to produce reasonably pure copper.[33] Overall there remains a strong impression that the copper smelted around Bristol during the first twenty years or so employing the new process retained too high a proportion of impurities to serve as the proper raw material either for fine brass making or for some of the more delicate end products.[34]

Unfortunately no accounts have survived to illuminate the operations of copper works in the United Kingdom during the eighteenth century, perhaps

[29] J.A. ROBEY, "The Ecton copper mines in the seventeenth century', *Bulletin of the Peak District Mines Historical Society,* IV (1969), 145-55. It is conceivable that mining problems were among the reasons.

[30] Cumbria County Record Office, Kendal, Fleming/Rydal MSS, Nos. 2769, 2613, 3003, 3219; & WD/RY, Box 21, 20 May 1692; W.T. SHAW, *Mining in the Lake Counties,* (Clapham, Yorks, 1970), p. 10.

[31] DAY, *Bristol Brass,* pp. 26-7.

[32] Liverpool University Library, Archive Department, RHYS JENKINS PAPERS on Copper Mining, MS 7.1, Thomas Cletscher's relation, (21), pp. 7-11, Kahlmeter's report, (21)-(26), and *passim.* I am obliged to Liverpool University Library for the loan of their microfilm of these MSS.

[33] RHYS JENKINS PAPERS, MS 7.1. (21)-(26), Kahlmeter, pp. 52-5.

[34] This is the general impression suggested by the works referred to in Note 2. above. It seems to be confirmed by the careful study of the British copper industry during this period in Dr. J. MORTON's thesis for the Ph. D., University of Birmingham, 1985.

because it did not involve enough of the landed interest, which might have preserved such material in its archives, or because enterprises changed hands too frequently to allow for survival of mere accounts. What summary statements and estimates remain were all compiled for some specific purpose, rather than as part of normal running activities; the few surviving accounts cover so wide a range, that mere mining and smelting of copper cannot be singled out satisfactorily. What the evidence does make clear is a significantly wide difference in the quality of the ores and in the prices and quality of coal, which makes it virtually impossible to identify the general effect of the reverberatory furnace upon costs.

The only hope for any kind of comparison with the Hechstetter accounts is offered by the set of annual reckonings compiled for the Witerock Company of Swansea during the 1750s and 1760s, especially as these too appear to have been intended mainly for internal use. These works had been established about 1720;[35] in 1737 they were operated by Thomas Coster, Joseph and Samuel Percival and Henry Barne; after Coster's death in 1740 they were called Joseph Percival & Copper company.[36] The reckonings appear in a notebook containing a mixture of memorabilia;[37] its pertinent pages are headed "The Annual State of Whiterock in regard to Smelting from the 30 June 1749 to the 30th of June 1750", and this continues line by line with annual headings until 1765-6; the line for each year occupies two facing pages.[38] Vertical columns in the table indicate the weight of copper ore smelted, of copper made, and of coal used, wages and salaries paid, and the cost of coal per ton of copper. The table appears to be a copy: wages have been omitted after 1759, and so have the costs of coal per ton of copper and the amounts of coal used per ton of ore and per ton of copper after 1762-3.

The data suggest both variations in the qualities of the ores and of the coal, unless these resulted from significant differences in the workers' skill or in other conditions. Thus the amount of ore used to produce a ton of copper varied from 5t 17cwt to 8t $5^1/_2$cwt, averaging 7t 7cwt 43 1b; in only eleven of the seventeen years did quantities lie between 10cwt plus or minus of the average. The quantities of coal used varied to a similar extent, but independently of the ores, from 3 wey $20^3/_4$ carts (at 28 carts to the wey) to 5 wey $9^1/_2$ carts per ton of copper, with the average at 4 wey 17 carts; in only ten years did the quantities lie within half a wey of the average. The price of the ore does not appear; coal seems to have beem bought on long running contracts and remained at ninepence a cart for seven years, while for the other seven it only

[35] A. Raistrick. *Quakers in Science and Industry*, (Newton Abbot, 1968), p. 213.

[36] Day, *Bristol Brass*, p. 68, where the date of the works' foundation is given as 1737. Neither this, nor Raistrick (N. 35, above) give the source for their dating.

[37] Bristol Archives Office, No. 12171 (1).

[38] *Ibid.*, pp. [14-9] [numbered by me].

once dropped by a little more than just over two per cent or two tenths of a penny below that.

These are notable variations in costs and quantities, but they remain insignificant when compared with costs at Keswick. The coal required to smelt a ton of copper in the 1750s cost at most £5.6.2d and on average £4.13.0$^{3}/_{4}$d, while the lowest stated fuel costs 150 years before had been £6.5.0. per ton, almost 18 per cent higher; the £29.5.5d of 1615 was almost six times as much.[39] That difference may well be exaggerated by accidental factors, rather than relative efficiency. It is difficult to establish the modern equivalent of the wey; by the end of the eighteenth century a Swansea wey of 24 carts could vary between nine and eleven tons;[40] how was that related to the wey of 28 carts, by which Lord Mansell sold his coal in 1755-6?[41] If Whiterock employed between 40 and 41 tons of coal to smelt a ton of copper, it paid less for that than Keswick had been paying for its 20$^{1}/_{2}$ tons, to say nothing of its £15 worth of turf and its £6.17.3$^{1}/_{2}$d for wood and charcoal. Whiterock may have used only about a third of the total weight of fuel needed at Keswick, and it paid disproportionately less for it. These data clearly bear out the normal explanation for the concentration of the copper industry in South Wales with its cheap coal, regardless of the greater efficiency of the new process.

All the same, costs in South Wales and the Bristol region were not at all uniform. At Mellincrythan near Neath, for instance, between £7.17.6d and £8.15.0d went on coal per ton of copper,[42] while an attempt to demonstrate excessive expenditure on fuel at Redbrook on the Wye claimed that there they had to spend £12.10.0d.[43] Of course even this represented a substantial saving on fuel costs at Keswick. Nevertheless, comparisons between the two techniques are made more difficult by the differences in other expenses involved. In Keswick a ton of copper needed about thirteen tons of ore, costing £44.1.2d.[44] Redbrook or Neath needed no more than ten tons of ore, presumably of a higher grade, which cost about £60 by the time it reached the works from Cornwall; with the high costs alleged for Redbrook, its £12.10.0s for coal left less than £6.10.0s per ton for wages, buying and selling agents and rent. Wages, agents and rent at Keswick were almost fourfold

[39] *Hechstetter*, pp. 122-4 (ca. 1600); *Hechstetter*, pp. 82-4 (1615).

[40] M.V. Symons, *Coal mining in the Llanelli area*, I (Llanelli, 1979), pp. 325-7.

[41] Bristol Archives Office, No. 12171, p. [2].

[42] University College of Swanesea Library, Morris MSS, box called "Miscellaneous", account headed "The charge of making a ton of Copper when the ore produces one in ten", and another headed «Suppose a Q't of Oare yielding about one in Ten were to be sent... to be made into Coppar at Melincrythan".

[43] Morris MSS, 'Miscellaneous', p. of accounts headed "At Redbrook", relating to the making of 7 and 8 tons of copper.

[44] *Hechstetter*, pp. 82-4.

that, at £24.14.3d.[45] It does not become at all clear how far the differences in costs merely reflect the greater isolation of Cumbria, and the need to continue paying imported craftsmen and their successors at levels appropriate to their status and their displacement, rather than the difference in efficiency between the processes. It may well be that mining wages in Devon and Cornwall were depressed, and that larger numbers competed for employment by the Costers, Champions, and Freemans in Gloucestershire and South Wales. Of course the new process may also have needed a smaller proportion of highly qualifed workers to produce its copper.

It would be useful to be able to compare the costs of investements required in each period, but this becomes even more problematic than the comparison of working costs. Daniel Hoechstetter the elder certainly spent too optimistically: by his death in 1581 he had gone through more than £50,000 and left the enterprise virtually bankrupt. That may have been the result of a variety of misfortunes and misjudgments after 1568; between 1564 and 1568 he spent £18,512, still substantial, but without much evidence of unwonted extravagance.[46] Just over £3,000 or 16 per cent was the cost of buildings, not only for the works, but some substantial dwellings for workers and for himself and his family. Well over £7,000 or 39 per cent went on mines and on exploration for them, with nearly £6,000 of it on the two most productive mines in Borrowdale and around Newlands. Over £1,300 or seven per cent went on peat and charcoal, four and a half per cent on furniture, wine, drapery and petty cash, with the remainder spent on travel and a large proportion of unclassifiable items. That only leaves a general impression of excessive but not unjustifiable expenditure.

If these are only approximate figures, they yet seem rather more illuminating than indications of the costs of works built in the eighteenth century. At Middleton Tyas in North Yorkshire the "smelt mill" was set up for almost £108, largely using local materials and local labour.[47] The account mentions only one furnace, without specifying any of the subsidiary equipment normally required to prepare the ore and to refine the metal. The ore was apparently of an exceptionally high grade, with over 60 per cent of copper:[48] even so, the itemised equipment seems too simple. At any rate, the inventory compiled for Mellincrythan copper works leaves quite a different impression.[49] It should be fairly reliable, as it was explicitly accepted by the

[45] *Hechstetter*, pp. 82-5. The figures here used exclude two items from the account, £ 13 a year for timber and £ 100 for interest on borrowed capital.

[46] Collingwood, *Elizabethan Keswick*, p. 4.

[47] Hornshaw, *Middleton Tyas*, p. 52.

[48] *Op. cit.*, p. 33.

[49] University College of Swansea, Library, MSS miscellaneous, in cardboard box: "Inventory of Mellincrythan works in the Parish of Neath on occasion of Lease by Herbert Mack to Thomas Coster of Bristol, merchant on 2 December 1732". The

two experts concerned with the transaction, Sir Herbert Mackworth, the owner, and Thomas Coster, the prospective tenant. It has two weaknesses for comparability: the buildings are omitted, and much of the equipment is valued in a rather defective state. Thus it includes items like "5 copper furnaces, One faulty, And the rest $^1/_2$ worn but valued with the 82 grate bars to 83 [pounds]". The store of Stourbridge bricks, presumably for use in the furnaces, is valued at 35 shillings per ton; it would be useful to know how many of them were needed for one furnace. Anyway, the worn and damaged equipment for this works is valued at almost £483, more than fourfold the cost of setting up Middleton Tyas smelter from scratch. Of course Mellincrythan had 15 furnaces against Middleton Tyas's one: would it have cost something like £1,500 to build it from scratch? Was it greater routine in construction which accounted for building costs of £70 per smelting and £50 per calcining furnace at Denby in Derbyshire between 20 and 30 years later?[50] Or were costs simply lower between Neath and Middleton Tyas? If the total defective but workable equipment at Mellincrythan was valued at £483, what might have been bought from Denby after its closure in 1769 by the Duke of Devonshire's agents for £329?[51]

It remains difficult to assess the precise status of another item which, on the face of it, contains some information about the value of copper works in the eighteenth century. This consists of the articles of an agreement concluded in 1720 between the Company of the Copper Miners of England, Thomas Chambers junior, who was its governor, John Essington, James Bradley and Case Billingsley, all giving addresses in either London or Wandsworth.[52] It concerns the reorganisation and re-financing of the company, which had been established on 3 August 1691, when it had issued 700 shares. Now it had been decided to issue another 20,300 shares, allegedly to improve its general operations, and to enable it to buy up mines, land and property in England. While the resulting transactions give an appearance of complexity, they seem superficially straightforward. Chambers held the lease of Lower Redbrook Copper Works from the Society for 33 years at £100 a year and had a interest in some Cornish copper mines; the other three had, for £9,400, bought the lease of the "Copper Mill at Wimbledon" for 31 years as from 1 July 1691 at a rent of £42 p.a. All four had now agreed to assign their works to the Society; at £5 per share, Essington, Bradley and Billingsley are to buy 5,000 of these each, and Chambers 4,300, while the Society could

works may have been built as early as 1698: "The Mackworth Undertakings at Neath (from MSS of Mr Glen Taylor)', [no author given], *Neath Antiquarian Society Transactions*, 2nd ser., VII 1937-1939, (Neath, 1939), 69-70.

[50] Robey & Porter, *Ecton Hill*, p. 67.

[51] *Op. cit.*, p. 70.

[52] British Library, Add MS 6654/Pluto CLXXXIV D, Derbyshire Collection, Mineralia Mus. Brit. ex Legato A Wolley Arm., 207-17.

dispose of the remaining 1,000 shares, as it wished. From the total of £96,500 cash paid by them, Chambers was to receive £17,000 for Lower Redbrook, £4,500 less than he paid for his shares, while the other three were to be repaid their £9,400 for Wimbledon, leaving £65,600 of theirs invested in the Society. Of the remainder, Chambers was to have another £10,000 for distribution to the holders of the first issue of shares, of which he himself held 203, the deputy governor 40, and everyone else named a smaller number. That, of course, left Chambers's net cash investment at below £1,700.

Despite the peculiar features of parts of the transaction, the values given to the two copper works leases may bear some realistic relationship to their proper valuation. Chambers and his deputy governor held fewer than half of the 524 old shares listed (it is, of course, impossible to guess at the effects of the 176 remaining shares omitted from the list); Essington, Bradley and Billingsley do not appear among the original shareholders. This kind of relationship might plausibly have modified the degree of skullduggery involved. It is not clear whose property Wimbledon had been before the set of transactions here outlined, but its purchase price may have been raised by its proximity to London; it seems probable that the relationship between its rent of £42 yearly and that of Lower Redbrook at £ 100 may correspond more nearly to their respective size and capacities. Wimbledon may have been mainly intended to smelt or refine imported ores (perhaps mostly from Barbary), while Redbrook worked up, first Devonian and then, increasingly, Cornish ores. Very crudely assessed, the figures may suggest a capital cost of a copper works in the early eighteenth century two or three times as large as that of the Cumbrian works in the late sixteenth century; output of copper may have been quadrupled for the later works, though quality had almost certainly deteriorated.

Although these are all slighly speculative suggestions, they do tend to confirm in the end that the reverberatory furnace made copper more economically. What is more difficult to estimate are the speed and impact of technical change upon its operation during the eighteenth century. For this it appears that only literary sources are available, and they provide at best no more than a crude guide to timing. The early, mainly Swedish, reports agree that English copper at the beginning of the eighteenth century remained inferior in quality to that made by established methods in Sweden and on the Continent: it retained too much sulphur and other impurities.[53] By the middle of the eighteenth century, Angerstein describes English works without elaborating on their failings: presumably they had by then learned how to make pure copper competitively.[54] By the end of the century a German expert regarded the produce of the English reverberatory furnace as of very

[53] cf. Notes 32-33, p. 64, above.

[54] Rhys Jenkins Papers, MS 7.1. (22), "Journal of Angerstein's journey through England, 1753, 54, 55", pp. 5-7, 16-28.

high quality and suggested, that German copper smelting would improve, if they were to adopt this method.[55]

Again the costs of building and equipping the new style of works appear only rarely in any sources. It was perhaps in the 1730s when furnaces were first lined with Stourbridge bricks instead of local materials:[56] whatever their comparative costs of production, carrying these to Bristol or South Wales must have made them more expensive. Willian Champion installed a Newcomen engine at Warmley in 1750 to recycle the water employed to drive his furnaces and engines: it cost £2,000 to build, used £300 worth of coal in a year, and, of course, involved frequent and quite expensive repairs.[57] Presumably the increase in total costs was justified, either by having to meet growing demand, or by permitting more regular working.

The attempt to discover the costs of copper mining presents a different set of problems. Most mining accounts deal with wages and other running costs, and only rarely refer to equipment, to say nothing of such items as repairs to pumps or fodder for horses. In any case the level of expenditure on equipment depends almost entirely on the specific conditions in a particular mine: Ecton managed to clear a depth of 150 yards below the river just before 1769 with a common horse gin and rag and chain pumps, supplemented by an ingenious waterwheel below ground; it paid, because its ores were rich.[58] Mona and Parys mines in Anglesea produced a much lower grade of ore, so accessible that picks, shovels and carts were almost the sole equipment required, enabling their copper to undercut virtually every other mine in the country.[59]

By the middle of the eighteenth century, of the other hand, most mines, certainly in Cornwall, were forced to rely upon forms of steam pump to keep the water down: here the employment of the latest technology indubitably added to cost.[60] High-powered technology is not a universal requirement of successful large-scale mining; the rich copper/silver mine in the Falkenstein near Schwaz, by the Inn in the western Tyrol, could in the sixteenth century afford to employ hundreds of labourers to drain its depths, until they were eventually replaced by a sophisticated and expensive set of water-driven pumps, which could perform the work more cheaply.[61] Or there were the

[55] A.G.L. LENTEN, *Briefe über die Insel Anglesea vorzüglich über das dasige Kupfer Bergwerk...*, (Leipzig, 1800), pp. 110-2, and *passim*.

[56] as N. 49, p. 9, above.

[57] DAY, *Bristol Brass*, pp. 80-1.

[58] ROBEY & PORTER, *Ecton Hill*, pp. 21, 24, 28-9.

[59] HARRIS, *Copper King*, pp. 158, 160.

[60] A.K. HAMILTON JENKIN, *The Cornish Miner*, (London, 1962), pp. 99-100; J.S. ALLEN, "The Introduction of the Newcomen Engine from 1700-1733", *Trans. Newcomen Soc.*, XLII (1969-70), 169-87.

[61] O. PICKL, "Kupfererzeugung und Kupferhandel in den Ostalpen", in *Schwerpunkte*, pp. 126-7.

great Swedish mines from which mere manual labour could produce vast quantities of ore so cheaply, that their output could domninate the copper-markets of northern Europe for the first three quarters of the seventeenth century.[62]

Mines do not go on for ever. The Falkenstein, it is true, lasted for centuries; apparently it still continues to produce at least some silver. Swedish mines deteriorated after about a century. Anglesea dominated British copper mining for about a generation and then declined; Ecton Hill could enrich the Duke of Devonshire and employ quite a large workforce, bur could never hope to supply more than a small portion of British demand after the middle of the eighteenth cenntury, and petered out before the middle of the nineteenth.

For mining, unlike copper smelting, a large number of accounts have survived. I cannot claim to have seen all of them; as a rule, only a very small proportion of them include any reference to immobile equipment, such as pumping or lifting devices. These were needed in most Cornish or Devon mines after the first quarter of the eighteenth century, when copper was often found some way down old tin mines, and was sometimes mixed with tin ore.[63] It may be reasonable to regard Trevenson mine in 1742 as a fair sample of general Cornish conditions, at least for the smaller or medium-sized mines: it produced about £600 worth of copper ore in two years and two months.[64] For this it apparently required by then two water-powered pumps with a lengthy conduit or launders at a cost of £35, two water wheeled engines with bobs and sweeps at £65, 55 fathoms of 'large bore wooden pumps' and ten fathoms of small bore at £32.10s, and engine house and wheelpits together at £17.10s, a total of £150. In addition there were three whims at £13.4s, and houses costing £11.6s plus various minor bits of equipment, altogether a total of £193.2s, which did not include the value of the iron and brass cylinders belonging to the engines.[65] This was a small mine compared to Dolcoath which, for 45 months, produced an average of more than £5,600 worth of ore annually[66]; no description of its equipment has been found, but there is no obvious reason to assume that a larger mine could be operated more cheaply than a small one. Cook's Kitchen, for instance, employed two wheels of 42 and 48 foot diameter, as well as a massive 54 foot wheel underground to pump from 80 fathoms below the 30 fathom adit,[67] which presum-

[62] H. Kellenbenz, "The Organization of Industrial Production", in E.E. Rich and C.H. Wilson (eds.), *The Cambridge Economic History of Europe*, V, (Cambridge, 1977), pp. 494-5.

[63] D.B. Barton, *A History of Copper Mining in Cornwall and Devon*, (Truro, 1961), pp. 20, 27; Hamilton Jenkin, *Cornish Miner*, as N. 60, above.

[64] Cornwall Co.R.O., DDJ 1807/16, August 1743.

[65] Cornwall Co.R.O., DDJ 1807/12, 15 November 1742.

[66] Cornwall Co.R.O., DDJ 1807/23 (sheet 2), September 1740 - May 1744.

[67] Barton, *Coppermining*, p. 19.

ably meant rather higher expenditure on installation and maintenance than at Trevenson.

It is conceivable that, at least for the larger and more productive mines, such costs may be regarded as relatively insignificant, despite the additional expense of repairs and replacement for fairly fragile equipment. When it comes to the installation and operation of Newcomen engines after about 1720, costs were bound to affect prices and profits significantly, and by 1730 between four and six Cornish mines were employing these.[68] Their costs of construction clearly varied enormously, from £200 plus to £2,000 plus, depending not only on site and local conditions but also on available materials.[69] To that must be added the frequent and often expensive repairs, to say nothing of the moderate royalty to the inventor and the significant costs of fuel, which of course varied with the size and efficiency of engines, but also with their distance from the mines, between something like £300 and £1,000 a year for those not draining coal mines.[70]

To acquire and establish a Watt engine also involved expenditure which was anything but standardised; figures quoted vary almost as widely as for the Newcomen engine, between £600 and £2,000.[71] As it required parts far more accurately made and machined than did the Newcomen engine, it seems plausible that the new, and much more efficient engine should have been significantly more expensive to acquire and build.[72] It did use far less coal, but Boulton and Watt charged their royalty as the cost of a third of the fuel saved, which meant for Poldice at the end of the eighteenth century £1,500 a year for two engines, and for Consolidated £2,500 for five: allegedly this added about thirty shillings to the costs of a ton of copper.[73]

The layout of the most productive mine at Ecton was, for Great Britain, unique: a deep, almost vertical shaft with, at least for some time, only minor

[68] J.S. ALLEN, "The Introduction of the Newcomen Engine from 1717 to 1733", *Transact, Newcomen Soc.*, XLII (1969-70), 173-81.

[69] J. FAREY, *A Treatise on the Steam Engine*, (1827; reprt. Newton Abbot, 1971), pp. 229-30, 232; A.E. MUSSON & E. ROBINSON, "The Early Growth of Steam Power", *Econ. Hist. Review*, 2nd ser., XI (1959), 424, 428 & *passim.*, J.R. HARRIS, "The Employment of Steam Power in the Eighteenth Century", *History*, LII (1967), pp. 139, 145; A. RAISTRICK, *Dynasty of Ironfounders*, (London, 1953), p. 150, and "The Steam Engine on Tyneside, 1715-1778", *Trans. Newc. Soc.*, (1936-7), XVII (1938), 133, 143, 146.

[70] HAMILTON JENKIN, *Cornish Miner*, pp. 161, 118 N. 67; L. WILLIES, "Technological Development in Derbyshire Lead Mining 1700-1880", *Bull. of the Peak District Mines Hist. Soc.*, VII (1979), 140-1.

[71] ROBEY & PORTER, *Ecton*, p. 32: Hornshaw, *Middleton*, p. 114.

[72] A.E. MUSSON and E. ROBINSON, "The Early Growth of Steam Power" *Ec. Hist. Rev.*, 2nd ser., XI (1959), 424, quoting James Watt jun., who was presumably not concerned to exaggerate the difference in price.

[73] BARTON, *Copper Mining*, p. 31.

drainage problems. Thus equipment like boards and plank, iron hoops, nails and ropes was almost all it required in 1769 when these accounted for between a tenth and a seventh of total expenditure on mining.[74] After 1774 this was to be supplemented by the "Deep Adit" which was to give direct access to the dressing floors in the Manifold Valley,[75] while by 1783 a waterpowered pump had been installed underground.[76] All that reflected the greatly increased scale of operations, with an approximately tenfold growth in expenditure since 1769, due mainly to the greater depth of the work. About a quarter of all expenditure listed went on materials and transport; the latter probably included the carriage of ores to the smelter at Whiston as well as the wider disposal of both ores and copper, and the transport of coal between mines and smelter. Indeed, more than a tenth of the expenditure in both the selected sample periods went on costs at the Whiston smelter.[77] Then again the ingenious pumping engine, for which surviving accounts are apparently not complete, though they do include the pumping equipment, cost at least £650,[78] not unlike the Newcome engine, but of course without the cost of fuel and probably with fewer and less expensive repairs. In any case, with a weekly return from ore of well over £3,000, Ecton and Whiston could well tolerate a weekly expenditure of £300 to £400. On the other hand it soon became clear that, with output rising to a peak by 1786, even more power was needed to pump out water and to raise ore. By 1787 James Watt had designed an 8 HP engine for Ecton, to help drain its unparalleled depth and to raise some of its ore. That cost at least £750,[79] and it used coal, which was presumably supplied from the ducal mines at some expense, undoubtedly increased by the need to haul the regular supply up a steepsided hill. Again the ropes employed with the engine were not cheap either, and they had to be replaced at fairly frequent intervals, at a cost which rose steadily from the initial £100.[80] In addition there were the usual running expenses, with repairs to boiler, moving parts and so forth, as well as the minor item of extended expert supervision by the engineer at 18s per week, which continued at least until July 1791.[81]

Finally there is the example of Middleton Tyas in North Yorkshire, today

[74] County R.O., Stafford, D 3060/1, accounts for Ecton Mines for 7 weeks to 13 Jan., 6 weeks to 24 June, & 7 weeks to 12 Aug. 1769.

[75] Robey & Porter, *Ecton*, p. 27.

[76] *Op. cit.*, pp. 27-8.

[77] County R.O., Stafford, MF 57, Accounts for Ecton Mines for 7 weeks to 8 Feb., and for 7 weeks to 9 Aug. 1783.

[78] Robey & Porter, *Ecton*, pp. 29, 30.

[79] *Op. cit.*, p. 32.

[80] Robey & Porter, *Ecton*, p. 34.

[81] *Ibid.* and Duke of Devonshire's MSS at Chatsworth, "Ecton & Whiston MSS" in unnumbered box, "Ecton & Whiston Reckining 7 Weekes ending 30th July 1791", 3rd written on p.: "Jno Varley work of the steam Engine - 6.6.0".

so unlike a former mining district, that only small traces remain to reveal its past. The mines were worked between about 1740 and the 1780s and produced some very rich ores. In 1744 just over $24^1/_2$ tons of ore could return a profit of over 100 per cent on all expenses, including the building and operation of a new smelter. More than three quarters of the expenditure on mining and associated trades in that year went on cutting and ore getting; about £27 of the total of £179 was spent on the manager, the smith, timber, pitprops, shovels, and other equipment.[82] By 1752 the mines had been sunk far enough to need pumping equipment, and the two horse gins set up were apparently powerful and elaborate enough to make them relatively expensive.[83] Two years later they had been supplemented by a Newcomen engine at a cost of £2,000, for which fuel supplies represented a major problem.[84] For the time being, the returns from mining were ample enough to compensate for this extraordinary expense, which certainly did not produce the ores more cheaply; the engine was in fact abandoned within about ten years,[85] perhaps because the distance which its coal had to be carried made it too expensive to operate after all. Typical of the proverbial optimism of mining entrepreneurs, when the ore output at the mine had begun to decline in 1775, the owners bought yet another steam engine, this time from the Carron Company for less than £950;[86] four or five years later the mines were given up as virtually exhausted.

There is, of course, a general problem associated with the expense for all mining equipment: it only increases as lower levels begin to be exploited, but may reach a peak as the mine approaches exhaustion, or the limits of profitable exploitation. Thus, when output at Ecton had dropped to about half from its peak, the costs of maintaining its engine in the 1790s began to absorb a more substantial part of the income; by the 1840s attempts to recover the mine had begun to cost more than the ore produced.[87] A similar experience ended the exploitation of Middleton Tyas, which had lasted for barely fifty years by the 1790s.[88] It is therefore difficult to assess the general profitability of mining at a particular site, when significant investment may unpredictably lead to great or moderate success or end in total failure. That consideration does not affect the general suggestion: technical ingenuity was applied to facilitate what would have been difficult or impossible without it, at a cost

[82] North Yorkshire C.R.O., Northallerton, ZAW 115, "The Copper mine at Middleton to the Adventurers therein Dr; 1744", supplemented by what appears to be virtually a standard price for copper ore at £28.10s. per ton, shown as the same for 1746 and 1750 in ZAW 117, the account for 1750.

[83] Hornshaw, *Middleton Tyas*, pp. 85-7.

[84] *Op. cit.*, pp. 90-4.

[85] *Op. cit.*, p. 110.

[86] *Op. cit.*, p. 114.

[87] Robey & Porter, *Ecton*, pp. 47-8.

[88] Hornshaw, *Middleton Tyas*, pp. 114-6.

which tended to reflect the level of ingenuity required. That is not a general and inflexible rule: Watt engines saved significantly on fuel, even if they were more expensive to construct than Newcomen engines.

I would be rash to claim conclusive results for this attempt to compare the costs and profits of copper mining and smelting over such a lengthy period of time. If one might say that, by the second half of the eighteenth century, Cornish copper ore cost upwards of seven pounds per ton,[89] while copper was sold at £80 to £100 a ton,[90] can one reasonably compare this with the £4 to £4.10s per ton of ore which went to produce copper sold for about £115 in the first half of the seventeenth century?[91] Quite obviously as the value of money had tended to decline during that century and a half, the reverbaratory furnace was making copper more cheaply, confirming the standard assumption. No doubt this is, at least to a small extent, explained by the lower cost of coal compared to charcoal, although it may be necessary to judge the differences in costs of fuel cautiously, as these depended significantly on mine and quality employed. It is more difficult to explain the relatively small increase in the cost of copper ore, despite significantly greater investment in machinery. The obvious answer to this problem might lie in the pressure on wages and standards of living, resulting from the growth in population during the eighteenth century: an aspect of the 'immiseration' of the workers? This would disregard the very special status and conditions of the Tyrolese and German craftsmen, who made up the principal labour force of the Hoechstetters — but that may not explain the whole difference in wages and rewards. In any event, the pressure on mining costs became evident, first in the menace presented to Cornwall and Devon by Williams's Anglesea enterprise, and then by the growth in copper imports, to supplement the increasingly expensive British ores.

If it is clear that the reverberatory furnace offered a superior method for the smelting of copper, its employment of coal as fuel does little, if anything, to account for that. A proper explanation of this superiority may require more comprehensive technical insight than I can claim to posses. For an amateur, it is only possible to point to the greater technical 'elegance' which is implied by the replacement of several stages of manhandling by a single continuous set of operations, and to the greater quantities, which the reverberatory furnace could handle. Again, if copper ores were produced at little more cost with the employment of more intricate and demonstrably more expensive machinery, there must be other factors involved than the indubitably greater efficiency of Newcomen or Watt pumps. Greater efficiency and effectiveness in operations do not always make things cheaper: if a Canadian com-

[89] B.R. Mitchell & Phyllis Deane, *Abstract of British Historical Statistics*, cambridge, 1962), p. 156.

[90] Hamilton, *Brass and Copper*, p. 366.

[91] *Hechstetter*, pp. 83, 85, 87, 90, and *passim*.

pany sought to investigate Caldbeck Fells as a potential source of copper in the 1960s, it did so primarily because copper had become vastly more expensive, not because modern methods had made it cheaper to mine and smelt.[91]

In the end, it may have been the increasing utilisation of copper, rather than its more efficient production, which created the British copper industry of the eighteenth century. No doubt that demand was assisted by the relative stability in its price; it remains an open question, whether some greater increase in costs would have seriously delayed or slowed down its growth.

[92] CUMBRIA C.R.O., Carlisle, Leconfield MSS, D/Lec/81, the printed prospectus of Coniston Copper Mines Ltd., a Canadian company.