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THE SMELTING OF SILVER ORE FROM HILDERSTON MINE AT LINLITHGOW, SCOTLAND

by Richard Smith and T. Kemp Meikle

SYNOPSIS
The smelting scheme for the silver ores which were taken from the Hilderston mine to the King James's mill at Linlithgow cannot be determined with any certainty from the site accounts or other contemporary reports. Nevertheless, the methods used for large scale trials, carried out in August 1608 at the Tower of London, are known in detail and are interpreted here. Also, much is known about the Hilderston and Linlithgow sites, the complex geology and some of the types of slag which have been found. Smelting schemes are proposed which are consistent with the experience of the trials in London, the smelting equipment installed at Linlithgow and the two types of ore known to have been produced.

INTRODUCTION

The mineralogy of the Hilderston deposit has recently been the subject of a paper by Meikle and is best portrayed by Atkinson's account, of 1619, relating its discovery.[1,2] The vein was found in 1606 by a local coal miner, Sandy Maund, whilst he was prospecting for coal:

> "*....and this Scotsman, by means of digging in the ground hitt upon the heavy peece of redd-mettle; no man thereabout ever saw the like. It was raced with many small strings, like unto haiers or threads. It had descended from a vaine thereof where it had engendered with sparr-stone, which in foraine provinces is called...cacilla. And he sought further...and found a peece of brownish sparr-stone, and it was mossie. He broke it with his mattocke and it was white and glittered within like unto small white copper-keese which is to be found in many common free-stones.*"

According to Atkinson, Sandy Maund travelled to the "*lead hill*" to show his find to Sir Bevis Bulmer. Atkinson himself visited the mine and sent a sample to his uncle who gave it to the Earl of Salisbury, who on April 15th 1607, in a letter to Sir Thomas Lake, referred to "*...the oure wch I receaved in the bagg I have sent it to be tryed.....*".[8]

In January 1607, Sir Thomas Hamilton, the King's Advocate and landowner took a lease for all mineral rights in the district, including those in Ballencrieff, Bathgate, the Knock of Drumcross, Tartraven, Torphichen and Hilderston.[11] In a letter from Sir Thomas to King James I, dated September 12th 1607, he complained about the attentions and personal malice shown by Sir Bevis Bulmer who had taken control of the mines and hopes that Bulmer will not have "*...left my workes waist and desert as he hes left your majesties gold mynes in Craufurdmure, efter his vnprofitable consumption of so mekill* *of your majesties money, without performance of any pairt of his great vndertaking*".[15] However, Hamilton was reported to the Privy Council as having made a profit in the region of £500 sterling per month and King James sent a commission consisting of Sir Bevis Bulmer, John Broad, George Cunningham, John Acheson, James Acheson and Edmund Doubleday to investigate.[8i] On May 8th 1608 the mine was taken over by the Crown and was put under the control of Sir Bevis Bulmer who was appointed "*..maister and surveyair of the earth werkis of the lait discouerit siluer myne.*"[8a, 11] In a series of letters to the King between September 1607 and May 1608, Hamilton somewhat nervously pleaded that he had acted in good faith throughout and that he had reserved the King's share according to law.[15] The legality of the royal seizure of the mine was questionable and Hamilton was later paid £5,000 sterling (or £60,000 Scots) in compensation. In hindsight, he did rather well from this settlement.

The mine is situated in the Lower Petershill Limestone which is cut by thin, E-W trending dykes of altered quartz dolerite and basalt. There is a N-S trending outcrop of a dolerite sill. The mineralisation consists of two distinct and separate assemblages: in the east, where the vein cuts the limestone, are galena, pyrite, chalcopyrite, sphalerite, solid hydrocarbon and quartz; in the west, and adjacent to the E-W basalt dikes and the N-S dolerite sill, are silver, nickel, and cobalt minerals with minor amounts of galena, pyrite, chalcopyrite and sphalerite.

Heddle (3) listed nine species in a vein of barite: native silver [Ag], galena [PbS], annabergite [$Ni_3(AsO_4).8H_2O$], erythrite [$Co_3(AsO_4)_2.8H_2O$], sphalerite [ZnS], nickeline [NiAs], pyrite [FeS_2],
and dolomite [$CaMg(CO_3)_2$]. Stephenson (4), further found calcite [$CaCO_3$] - the 'cacilla' found by Maund, quartz [SiO_2], chalcopyrite [$CuFeS_2$], bravoite [$(FeNi)S_2$], and a hydrocarbon (probably albertite). Meikle's work has revealed many more minerals, among the more interesting of which are: acanthite [Ag_2S], silver amalgam [Ag,Hg], cinnabar [HgS], mercury [Hg], magnetite [Fe_3O_4] and maucherite [$Ni_{11}As_8$], witherite [$BaCO_3$] and unidentified nickel arsenides [Ni_2As_2S].[1]

Meikle has pointed out the probable connection between the occurrence of mercury minerals and the hair-like deposits of native silver which characterise some of the specimens.[1] The "*redd-mettle*" found by Maund was almost certainly nickeline and this seems to have been the main species sought in ore-dressing. In the mine accounts, the ore was always referred to as "*mettle*".

THE SMELTING TRIALS AT THE TOWER OF LONDON

In December 1607, the warrant for the royal commision directed to investigate the Hilderston mines and to report on their value, mentions the loss at sea of a ship carrying ore, or samples, on its way to London.[8i] The warrant directed the commission to "*...caus to be digged oute and takin furth indifferentlie of all the sortis of ures and metallis within the said myne alsweill of the best as* *worst theirof the quantitie of ten tunne ...... which haveing collectit and inclosed in goode hogsheddes barrellis and vtheris veshells yae shall then seale all and eury one of thame with your sealls and vpon inventour of the nomber weight and quantitie yee sall cause thame to be delyuerit to our Thesaurir deputye ....*".

Soon afterwards, in January 1608, the Council directed the commisioners to go to Hilderston and take a representative sample of the ten tons of ore - about three or four stone in weight.[8j] They were to "*....cast it in ane lignott* [ingot] *ather at the saidis mynes or in his Majesteis cunyhouse* [coining house] *.... and divide the lignott in twa als equall halfis*". The commissioners were commanded to be present at the trial - one half of the ingot was to be sent to "*his heynes,*" the King, and the other half to be retained by them. We do not have the results of this trial.

Also in January 1608, the Council decreed that the "*Troy weight Inglishe*" be used for all weighing - including that of bulk ores. The experts registered their disapproval - "*Mr Edmond Doubledae and his colligis declairit that albeit they craved haverdepoix weght in respect that no ware was boght or sauld or transportit in England by the twnn bot by that weght"* - but to no avail and troy weight was used[†]. The weights of the 38 barrels sent to London were individually recorded and totalled 20,224 lbs troy.[8k]

Aitken (p.194) refers to 'Lex Mercatoria' (Part 2, Chapter 2), which describes part of the ten tons taken to London, as follows:-[9]

> "*By the King's order ten tuns of the said silver ore was brought into the tour of London, whereof one tun of 2000 lb weight was indifferently taken and calcined or grinded together, and thereunto were two tuns of lead added, commixed and afterwards molten by a continual fire and hand-blast of four men, and ther was a cake of silver remaining, weighing 17½ ounces, and the extraction out of the Lead was some four or five ounces more, so it was reported to be 22 ounces in the 100 weight of ore, but the charge was great.*
>
> "*Ther was other tryalls by William Beal with a far less quantity of Lead and roasting the oar, and by Mr Broad and Mr Russel who refined the same with the slag of Lead, others by lead ore to save the charges, and they all found above 22 ounces of silver in the 100 weight of ore. The Portugal tryall with Quicksilver found 23 or 24 ounces and some 20 lb weight being sent beyond sea, grinded, shadered, and washed, to ane expert mint master, he found upon his first tryall 42 ounces and of the others lesse, and said that the oar was easie to be wrought (but by other means) and with little charges, and that the maner to refine by quicksilver was good for poore mines of 2 or 3 ounces wher the ore had litle or no lead and that the commixture of the mine was very britle.*

> *"In August 1609, 400 barrells of the ore was brought to the tour and upon tryall by Mr Broad 29 ounces was found of ane 100 in ore and 24 lb the ton was offered for it but refused*[+]*."*

One trial, by Mr Russell at the Tower, is recorded in detail.[8b] Working by appointment of Lord Knyvett, who was the Warden of the Mint, Russell carried out the work on August 13th 1608. At this time, the construction of the washing, smelting and refining plant had already been started at Linlithgow and a considerable amount of money had been committed to the project. The text of the report is given here because of its metallurgical relevance.

> *"A Tryall made of the sylver ore within the Tower by Mr Russell at the appoyntm^{t} of the Right Ho^{ble} the Lord Knyvett in the presents of Mr Edmond Doubleday, Mr Antony Knyvett and my selfe.*

1 There was taken of the common shaddered ore such as Sir Bevis Bulmers made his tryall of . . }c pound w^{t}

2 And of leade . . . . } l pound w^{t}.

3 W^{ch} leade being first molten in the fortegle wth out y^{e} furnace the said c. pound weight of sylver ure was blowne downe through the furnace & rann out uppon the said molten leade into a mettalyne body commonly called bell metle or the stone of the myne being in weight . .} lx pound w^{t}.

4 W^{ch} leade at the first drue out in sylver according to the smale assay . } viij^{oz}

5 Out of the foresaid lx pound weight of stone passing againe through the furnace thrise by it selfe uppon the same leade was brought out more in sylver according to a smale assay . . . }viij^{ounces}

6 The aforesaid l pound weight of leade by drawing out of xvj ounces of sylver was wasted to xl pound w^{t} w^{ch} xl^{lbwt} was inriched after the rate of xlj ounces of sylver in the hundred weight of leade w^{ch} being refyned did yeld in sylver . . } xv^{oz} qs^{rs}

7 Then there was taken xxv poundw^{t} of newe leade molten in the fortegle as at the first and the test littarge & stone being molten together through the furnace and running uppon the xxv poundw^{t} of newe leade increased the leade to xlvij pound weight w^{ch} being refyned yelded in sylver . } vj^{oz} iij qs^{rs}

8 So there was produced in sylver out of this c. poundw^{t} of ure as appeareth by this ingote being xj^{oz} xvj^{dwt} fyne . . } xxij^{ounces}

9 *And there was wasted in leade in refyning and melting the c*^{d} *poundw*^{t} *of sylver ure . . . } xxv poundw*^{t}.

10 *And there is in bell metle . . . } xl poundw*^{t}.

11 *Holding in sylver at the smale assay but three quarters of an ounce at the hundred . . . } Sic.*

12 *So it appeareth that every tonn of sylver ure wilbe refyned w*th *the expence of 500 poundw*^{t} *of leade and the tonn will yeld the sylver after this rate } xxxvj*^{dwt}*viij*^{oz}

13 *W*^{ch} *is in value . . . } cxvij*^{li}*ij*^{s}*j*^{d}.

John Reynoldes"

The weights are consistent with silver being measured on the troy scale standardised in 1574 and issued subsequently in 1582 and 1588 (1lb troy; 12 oz troy; 240 dwt troy; 5760 grains). The avoirdupois scale was standardised and issued in the same years (1 lb av; 16 oz av; 256 dwt av; 7000 grains). Despite the Council decree requiring troy weight to be used for bulk weighing of ores as well as recovered silver, it is not known if this was persisted with at the trials or if commodities such as lead were recorded in troy weight. The results here are expressed below in troy ounces of silver per pound (scale unspecified) of ore as used.

The trial furnace would have been a short shaft furnace, similar to those shown in Agricola or Ercker, with an open, external forehearth, referred to in Lines 3 and 7 by the Germanic term '*fortegle*'. Lead was melted in the forehearth, usually by a jet of blast from the furnace taphole. Slag, matte and metal etc were allowed to run over the lead with occasional stirring. Mixing of the pool of lead and the furnace products would have been poor and the '*bell metle*' or '*stone*' was remelted three more times on to the same lead (Line 5).

Slag, matte (a metal sulphide phase) and speiss (a metallic phase of iron, nickel and arsenic) would then have been allowed to solidify on top of the forehearth and would then have been taken off using a fork, as shown by Agricola. The accounts for the Linlithgow smeltmill for Week 28 February 19th-26th 1609 show the purchase of "*...4 forks for lifting the cakes of bell metal off the melted lead...*".

The term '*bell metle*', as in Lines 3 and 10, appears several times in the accounts and clearly cannot refer to the accepted terminology of a Cu/Sn alloy used for bells, as there has never been any association with tin in this context. It is more probable that it was used to describe matte or speiss. Which of these two was actually formed is important to the metallurgy of the process and is discussed in more detail later.

Slags are not mentioned and this appears to be fairly common in accounts by Agricola[14], Hechstetter[6,7], etc at the time. It appears to have been common practice to remove these as they came from the furnace and solidified in the open forehearth, with no record of their weight being taken. There is an overall weight loss after the first set of lead washes of 50 lbs, which is rather too great to be explained by fume or mechanical losses, and this can be taken as an indication of the weight of slag. The loss of lead of 10 lbs will be distributed between slag, fume and '*bell metle*'.

Line 6 shows that the yield of silver from the first batch of lead used for washing was 15¼ oz out of a total 16 oz shown by assay.

The second lead wash (Line 7) included not only the '*stone*' or '*bell metle*', but also litharge from refining the first lead. It is unclear from the description if the boneash hearth (or test) of the cupellation furnace was included with the litharge (sometimes referred to as the 'test litharge') or not. The phrase "*...the test littarge and stone being molten together..*" has a somewhat different meaning if a comma is inserted: "*..the test, littarge and stone being molten together...*". Unfortunately, the subtleties of punctuation are often absent from old documents. However, this increased the recovery of lead from 25lbs to 42 lbs and yielded a further 6¾ oz of silver after refining.

Line 8 shows that the 22 oz ingot of silver was described as 11oz 16dwt fine (236 dwt) - pure silver would have been 12 oz fine (240 dwt), indicating a purity of 98.3 % Ag (ie 236/240 dwt ´ 100).

The lead loss of 25 lbs, in Line 9, appears to be a round number derived from the 75lbs of new lead used for smelting and the 47 lbs which were recovered after the second refining (ie a true loss of 28 lbs).

The '*bell metle*' weight (Line 10) is unchanged from the first smelt, despite further smelting, and contained 0.75 oz Ag per hundred, or a loss of 0.30 oz Ag. Impure silver recovered from the ore was 440 oz/ton (of 2,000 lbs), which is the 36 lb 8 oz* shown in Lines 8 or 12* . This was equivalent to 433 oz/ton of pure silver.

The silver value from Line 13 is £117 2s 1d, corresponding to a price for pure silver of $63^{7}/_{8}$d per troy ounce or £3 3s 10½d per troy lb.

Another part of the 10 ton lot of ore shipped to London was worked up by Edward Lenton (possibly a subordinate of Martin) and the silver recovery was reported by Sir Richard Martin, the Master and Worker of his Majesty's Monies in October 1608.[8c] Martin's certificate shows:

1 *Received by me Sr Richard Martin, knight, of Edward Lenton, finer conteined in one ton of Scottish ure delivered by me unto him for his Ma^{ts} use the some of ix^{lb} wt iij^{oz} xij^{dwt} xij^{qs} being better then the standard*

of xi^{g} ij^{dwt} xiij^{dwt} in every pounde weit wch maketh in standard silver ix^{lb} wt x^{o}z iiij^{dwt} x ^{qrs} at lxij^{s} per pounde wt is xxx^{l} x^{s} ix^{d} iij q^{rs}

2 Whereof for y^{e} Kinges coinage at 2^{s} 6^{p} p ^{lb} w^{t}
Rest xxiiij^{s} vij^{d}ob 1/8xxix^{li}vj^{s}ij^{d} 1/8

Edward Lenton's charges for refining one ton of ore came to £15 5s 0d and included the loss of 800 lbs of lead from one ton of ore (0.4 lbs lead per lb ore), which is a higher proportion to smelted ore than that from the trial at the Tower (0.28 lbs lead per lb ore).

There are some minor errors of writing or transcription in the above account, as given in '*Records of Mining in Scotland*', but they can be rationalised fairly simply:

The one ton trial yielded silver which was of a higher purity than the standard silver of the time which was used as the reference for pricing and which at this time was 62/- per pound. Standard silver contained only 11 oz 2 dwt 13 grains (5341 gr) of pure silver to each troy pound of 12 oz (5760 gr). The recovered silver was such that 9 lb 3 oz 12 dwt 12 gr (53580 gr) was equivalent to 9 lb 10 oz 3 dwt 10 gr (56746 gr) of standard.

The purity of standard silver was, therefore, 5341/5760 grains x 100 = 92.7%.

The weight of pure silver in the product was 56746 x 5341/5760 = 52618gr

Therefore the purity of the Scottish silver was 52618/53580 x 100 = 98.2%.

The pure silver content of the ore was 52618 grains/ton or 110 troy oz/ton

Note that this trial showed that the ore contained 110 troy oz/ton of pure recoverable silver, whereas the earlier trial at the Tower indicated 440 troy oz/ton This must have shaken the early optimism and Sir Richard Martin summarised the first ten ton trial in a report.[8d] He also urged the Council to issue two keys to control the twenty ton parcel of ore which was about to be received - one of which he would have. He also implied that he had kept good accounts which others had not. The tone of the letter was that he or an expert should take charge of the second trial. Perhaps there was some professional rivalry between Martin, who was Master of the Mint and in charge of the production of coinage, and Knyvett, who was Warden of the Mint and who had administrative responsibility. The former received payment according to output, whilst the latter received a salary.

THE TWENTY TON TRIAL

Sir Richard Martin's second report of October 1608 concerned a twenty ton parcel of ore selected from the "*100 tons brought out of Scotland*".[8e] He acknowledged their Lordships order that 3 ton lots would be distributed to six persons and that he would only receive 2 tons for trial. However, by this time difficulties were becoming apparent and he referred to his experience with the first shipment:-

> "*This being poore ure, is very chardgeable and troublesome (which is to be considered of) and especially to them that had made no tryall therefore before. For them that made no trayall afore hath remaining in them slagstone, lettage, teace, and otherwise, which is remaining to answer ye lack of silver that as it is by ye subtill assay reported to hold.*"

He went on to say that:-

> "*It is held that there is in ye Scottish ure, a substance of a matter which some call a marquisit, and other some an arsenick, and others a sulferous matter which holdeth the silver, that it cannot easily be gathered out of the same togeither, and also there is a stone called white sparr, which holdeth some smale quantity of silver, which poisoned matters if they could be destroyed, and the silver gott cleane out of ye same, it were a good and profitable service for his Majestie which is to be done by men of art & knowledg experienced in ye practice of ye same*".

This is the first time that the complexities of the mineralogy were mentioned.

Martin may never have received his two tons of ore from the twenty ton consignment because, two months after his reports, a letter from Edmond Doubleday to Lord Salisbury related the sad project when twenty tons of ore had been sent for smelting to an iron furnace in Sussex.[8f] Previous to the trial, the ore had been burned "*…for the sending away of the sulphur, arsenicke & other substances, which were over neere, and unfriendly companions to the sayde ure*". The trial started on Tuesday, December 6th, after "*….false charges of coale and iron sinder had been put into ye furnace…..*". This was a wise precaution to get slag running before putting on charge, but, "*aboute one of the clocke in the afternoone, the furnace began to clogg, & put both of us & the furnace maister & all the workemen into a greate doubt that the furnace woulde be blowne out..*". The solution was to reduce the proportion of ore to fuel and the trial proceeded. However, the trial was stopped "*…after diverse assayes made of the metalline body coming oute of the furnace by melting of the sayde ure, I see the silver of so small valewe that can be extracted from the same metalline body, that I am unwilling to have any more of the silver ure to bee moulten in this iron furnace, for fear of an unrecoverable consumption of the same silver.…*".

The embarrassment in the letters is obvious. Having told the King's Council in August that there was about 440 oz of silver to the ton of ore, the experts revised that estimate downwards to 110 oz/ton after the second set of trials and were now having to admit that they had lost well over 10 tons of ore and that very little silver had been recovered.

THE LINLITHGOW MILL CONSTRUCTION PROJECT

Meanwhile back at Linlithgow the accounts show some items of interest.[12] Between the 16th and 19th of February 1609, there was expense for "*...245 great nails for the lumheid of the Melting Mill because it is made of timber*". Although wooden chimneys were used at the end of long flues in the North Pennines lead mills in the 19th century, this was before the common use of long flues and would have been accompanied by a higher risk of fire. Nevertheless, the support construction would have been considerably less expensive than with a masonry stack and at Linlithgow the chimney of the assay furnace was also made of wood.

Between February 19th and March 4th "*....getting and carrying 2 loads of copper slag from the Silver Mill near Edinburgh to the Silver Mill near Linlithgow*" was recorded, while from the 12th to the 19th March 1609, "*eight loads of iron slag were brought from the waterside at Culross via Bo'ness in three horse loads*". Iron slags were brought at other times and it is most likely that these were used as fluxes for smelting. In a short column blast furnace it is sometimes difficult to produce a good fluid slag from mixed raw materials, particularly if they are present as large pieces. Grinding and mixing will improve the situation, but the addition of good slag from a previous smelt is particularly effective, although it adds an unproductive burden to the charge. The other possible use of iron or copper slags would be as a bedding material for furnace foundations, although cheaper alternatives such as sand would have been available nearby.

There are several references to a strange material called '*marginsat*' which was '*won*' at the Water of Devon quarry and brought '*as the Germans called for it*' via Culross and Bo'ness. This was transported in very large quantities of 10-80 loads per week. Between March 26th and April 2nd 1609, there was a payment "*For workmanship in making a great crowbar with which to break the same marginsat*", and in the following week an item "*For a creel to carry the marginsat out of the hole where it is won up to the braehead*". It was also being won at Caldronmire. The operation seems to have been significant, employing up to four pickmen and an overseer. Its ultimate destination was always described as being transported "*to the mills*", but although the Linlithgow accounts usually specified the end-use of articles or materials, this was not so in the case of '*marginsat*'. Blackband ironstone occurs at the quarry, however, and this may be the explanation. Although it may have been used for bedding furnaces (which seems unlikely when more suitable materials were available nearer to Linlithgow), it is consistent with the smelting scheme proposed later that it was used as a source of iron for the smelting process. A Scottish source would have been necessary as all the metallic iron was imported to the site from England and would have been a more precious commodity than it is today.

Week 32 (March 12th - 19th 1609) show interesting developments. The finishing touches were made to the smelting mill, a boy was sent to the mines to order metal to be brought to the mill, and wine, ale and bread was laid on for the "*...meltars and workmen at the Melting Mill, the first day they began to melt...*". At this late stage, the accounts for the same week first record "*...6 loads of clay to be mortar to the Roasting House*". This is the first time that the Roasting House was mentioned and clearly it was in a very early stage of construction. The phasing strongly suggests that roasting was only regarded as an essential part of the process at some late stage and that the project was started with no proven flowsheet.

THE SMELTING PROCESS

SMELTING AT HILDERSTON

Thomas Hamilton had presumably had been smelting at Hilderston, using a process of which we have no details. (A map of Hilderston Mine, drawn by Joseph Udny[13] and reproduced in Meikle, shows '*the old smelter house*' and a furnace.[1]) On the evidence of the difficulties which were experienced later by the experts in London and the undisputed fact that the best of the silver was near surface, it is possible that he could have used a simple smelt with lead, either in a small blast furnace, as with Russell's trial at the Tower, or in a crucible. As there was an abundance of native silver and the prospect of much more to follow, it would have been the simplest approach, but unsuitable for large scale operations with the lower grade and complex ores which were to follow. Refining may have been carried out at the King's silver refinery at Leith.[12]

SMELTING AT LINLITHGOW

The re-evaluation of the Hilderston mine by Henry Aitken[9] in 1873 and in 1896 is also described by Cadell[11], who visited the latter project. Both report the primary mineralogy to be veins of barite, calcite and dolomite with galena, nickeline [NiAs] and native silver. There were significant amounts of the secondary minerals annabergite [$Ni_3(AsO_4)_2 . 8H_2O$] and erythrite [$Co_3(AsO_4)_2 .8H_2O$]. We can also add the limestone country rock and aluminosilicates from the dolerite dyke. The reference to two types of ore by Thomas Russell in December 1608[8g] is supported by the work of Meikle[1], referred to above. Meikle's description can be summarised:-

1. *High sulphur,* low arsenic and low silver ore *('white sparre'* ore*)* - containing galena and pyrite, with smaller amounts of chalcopyrite, sphalerite, hydrocarbon and quartz. The specific gravity of pyrite is 4.9 to 5.2 and, if present with barytes (SG 4.3 to 4.6), a separation would have been practically impossible. The SG difference with calcite or typical country rock (SG 2.2 to 2.8) would render separation somewhat difficult.

2. *High arsenic*, high silver, high nickel, low sulphur ore (‘*redd mettle*’ ore) - containing silver, nickel, cobalt with minor galena, pyrite, chalcopyrite and sphalerite. Niccolite (NiAs), has a high specific gravity (SG 7.8) compared with typical country rock (SG 2.2 to 2.8) and a good separation by washing would be expected.

Ore 1 is a fairly complex sulphide ore, which would require roasting before smelting with lead. If this were not done, then the matte of copper, iron and lead sulphides would reduce the effectiveness of the collection of silver by lead. (Mattes are used today as collectors, particularly for the separation of platinum group metals.) The partial elimination of sulphur would reduce the quantity of matte and hence improve the yield of silver. The presence of matte would, however, remove copper and nickel which are significant interferences in the subsequent cupellation process.

Ore 2 is most unusual. The description of ‘*redd mettle*’ suggests that there was very little calcite or barytes vein material present and that this was principally nickel arsenide with some cobalt. Reduction would produce a speiss of nickel/arsenic alloy with cobalt. If the As content of a speiss is high, it can appear as a rather dirty metal which can occlude lead and therefore silver. However, if some iron were present, the speiss would be cleaner and a good separation from lead could be obtained. Nickel can interfere strongly with the cupellation of silver but can be removed if the speiss is allowed to cool in contact with the lead. Mr Russell’s trial in August 1608 was made “*...of the common shaddered ore such as Sr Bevis Bulmers made his tryall of...*”[8b] This sounds more like the ‘*redd mettle*’ which everyone knew to contain silver. The metallurgical performance is consistent with this and the only deviation which seems to have been made from present understanding is that they termed the speiss ‘*bell metle*’. As it would be similar to rough copper at first sight, this does not appear to be unreasonable.

The first ten tons of ore seems to have been processed without any recorded metallurgical problems, but with considerable costs, and the twenty ton trial was carried out to apply the advantages of scale. The Master of the Mint, Sir Richard Martin, in October 1608 pointed this out and also the ‘*marquisit*’, ‘*arsenicke*’ and ‘*sulferous matter*’ which would interfere with the extraction of silver into lead.[8e] He also advocated mixing the ores. According to Edmond Doubleday, writing to Lord Salisbury in December 1608, the project to try twenty tons in the Sussex iron blast furnace was originally propounded by Mr Russell, who carried out the trial in the Tower, but this may have been an attempt to pass on some of the blame for the failure.[8f] The ore was roasted to remove impurities (see above) and the account implies fairly clearly that by this time the two types had been mixed together, as there is only reference to a single type of ore at this point and no attempt was made to smelt the two types separately.

The Sussex blast furnace worked well on the iron slags which were used to warm it up, but experienced problems when on ore charges. The problems were alleviated to some extent by increasing the proportion of fuel in the charge. The simplest explanation is that they miscalculated, as although quite large amounts of slag can be rapidly melted in a blast furnace, considerably more fuel has to be used with raw charge. Further problems would have arisen from the presence of sulphides and arsenides together with zinc. These would respond well initially to the addition of more fuel but would give progressive difficulties on continued operation.

A "*metalline body*" was produced in the Sussex blast furnace trial, but Doubleday did not say if this had absorbed the lead or indeed if lead was used at all. It is not possible to say how efficiently arsenic and sulphur had been removed by roasting. Heap roasting is fairly inefficient and, although sulphur assists in the removal of arsenic, it is better if the two are present as the same mineral (eg FeAsS) and if the process is carried out in a calciner which can operate with only mildly oxidising conditions.[6] Roasting under uncontrolled conditions can lead to the formation of involatile nickel or iron arsenates and sulphates (such as those of lead and iron). Later, under the reducing conditions of a blastfurnace, the arsenates and sulphates are reduced back to arsenides and sulphides, so very little is actually achieved. The products would be slag, matte and speiss. With complex mixtures of this type, it is only too easy to tap out what appears to be a single phase of dirty slag, usually accompanied by a display of sparks as matte and speiss meet the air. Good separation requires a forehearth with sufficient holding capacity to allow the time needed for the phases to settle. If the charge contained poorly roasted sulphides and arsenides (which would absorb metals such as iron, nickel and copper), there would be a tendency for silica to absorb any lead which had been added to extract silver.

Mixing ores would probably make matters worse and there is evidence that this was the case. In December 1608, Thomas Russell wrote to Lord Salisbury, saying that he had tried a further 200 lbs of ore and "*..as being instructed by my former errors I had found out both the meanes of preparation of the two ures, and the trew furnace to work them in, to make perfect lead and by consequent a trew separation of the silver out of the ure*".[8g] This strongly suggests that two smelting routes were needed.

We do not know what these routes were but propose the following based on our understanding of the minerals present:-

Method 1 ("*White sparre ores*") - high sulphur ores were roasted, perhaps several times, such that on subsequent smelting slag and lead metal were produced together with some matte. The iron silicate slags, which were known to have been imported to Linlithgow from copper and iron production, would assist with the removal of gangue constituents and would minimise absorption of lead or silver into slag. Some silver would have been lost in matte, but the amount would have been small and the process would have been conceptually similar to that used by the Germans for smelting complex copper/lead ores from the English Lake District.[6]

Method 2 ("*Red mettle ores*") - low sulphur ores were smelted directly after careful dressing to remove calcite and barytes. A speiss of nickel/cobalt/ copper/iron and arsenic would result, together with lead metal. Small quantities of sulphur would be soluble in the speiss and the addition of iron or copper slags would act as a supplementary source of iron to assist the formation of a clean speiss as well as helping to remove non-metallic vein materials and fuel ashes. As with Method 1, losses of silver to speiss would be small and could easily be minimised by the use of large quantities of lead.

Thomas Russell also claimed that he had found "*..the trew furnace to work them in.*". What aspects of furnace design would be critical to the process or was this a piece of bluff? Given that the short blast furnace was about the only option available and would certainly have done the job, his opportunities for furnace development were limited. Anything to improve phase separation would have been welcome and raising the tuyere some distance above the hearth would have allowed a pool of slag and speiss to separate before tapping intermittently. An external forehearth with open top would have been almost *de rigeure* to German or English smelters at the time and there is no reason to propose an alternative. The open forehearth would permit removal of slags, speiss or matte as they solidified, if they were clean. The purchase of "*...4 forks for lifting the cakes of bell metal off the melted lead...*", referred to above, strongly supports this view.

SLAGS FOUND AT THE LINLITHGOW SITE

Meikle has distinguished two types of slag from the Linlithgow site and has arranged for examinations on single specimens by scanning electron microscope (SEM) and x-ray diffraction (XRD).[5] A more extended range has been examined by one of us using an optical microscope, and detailed examinations by SEM are in progress.[10] The types found were:-[5]

Black/brown (*tan*) *Slag* – This is light to dark-brown in colour, dense and tough in texture, displaying inherent elongated crystallisation and relatively large cavities with free-standing, near cubic and elongated spear shaped crystals of the same colour grown into these cavities. These were identified by XRD as probable gehlenite with some wollastonite, with SEM partial analysis confirming the presence of both Ca and Si. Another dark crystalline slag appeared to be mainly diopside and wollastonite. Small barytes crystals were noted occurring sparsely on the bulk sample, but there were no metallic residues. This slag type is very similar to tan-coloured slags found at Hilderston by Meikle.[5]

Light Grey Slag - This slag is mostly of light weight, comprising much open layering and varying in colour from almost white to a dark bluish-grey colour where freshly fractured. Cleavage surfaces and cavities are commonly coated with white material, either granular, fibrous or in small hexagonal plates, and less commonly by translucent, deep to pale orange pseudo-hexagonal or pseudo-trigonal crystals (< 3mm), accompanied frequently by tiny thin golden-yellow plates. Infrequently this slag also contains small spheres (< 10mm) of metallic iron or matte residues.

Although other materials have been found, the Linlithgow site has been very much disturbed by later activity and more recently by motorway construction. There is no guarantee that either type of slag has come from the seventeenth century silver process or has a metallurgical origin. The grey slag is visually similar to fused ash from a coal-fired boiler and may have come from the coal ashes produced by cupellation or possibly lime burning.

Authors' Note: In carrying out the research for this paper, particular care has been taken to distinguish between old and new style dates. In England, the year began on March 25th until September 14th 1752 when it was changed to January 1st. The change to new style dates in Scotland was made in 1600 following a proclamation by King James VI dated Haliruidhous, December 17th 1599. Scottish documents of this period have, therefore, used new style dates while English documents have used the old style. Items of correspondence between the two countries seem to have followed the local usage, with no deference shown to persons of higher status. All dates quoted here have been corrected to the new style and fortunately this has been necessary in only a few cases.

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8f. Edmond Doubleday on 20 ton trial, 11/12/1608; PRO., Dom. Jac. I., xxxviii, 23, 1608.

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+ This overview of the first ten tons of ore gives some indication of the several ways in which it was consumed. The reference to 400 barrels of ore is equivalent to about 100 tons if packed in hogsheads. Martin's account of October 1608 refers to 100 tons "*brought out of Scotland*" of which 20 tons was selected for trial in an iron blast furnace in late 1608 and is described here. The date of August 1609 appears to be erroneous as this ore was shipped in 1608.

* Note the error in the original or transcript of dwt for lb.

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