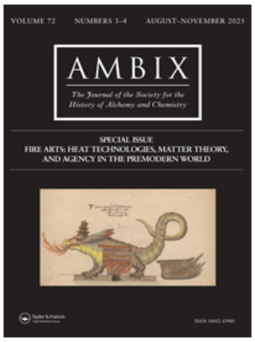

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Fire Management in Practice: Building and Managing Charcoal-Fired Assay Furnaces as Experimental Reconstructions

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This article describes a programme of experimental reconstruction, involving the building and firing of a series of charcoal-fired assay furnaces, and the findings generated by this activity. The furnace builds drew from designs described and illustrated in nineteenth-century technical manuals for assayers and two sixteenth-century texts: *De Re Metallica* by Georgius Agricola and *A Treatise on Ores and Assaying* by Lazarus Ercker. Comparing the resulting "chimeric" structures' performance generated insights into how such solid-fuel assay furnaces behaved in practice, what roles specific structural elements described in different primary sources played in their overall function, and the fire management skills needed to operate them. Consequently, it was possible to identify how the designs materialised technological choices that prioritised either responsiveness or long-term operation. The experimental reconstructions also led to a reappraisal of the nature and wider relevance of a selection of the primary sources used in the project.

"As such regulation of the fire cannot be very well described and such knowledge can be acquired only through great practice, there is not much I can do." (Lazarus Ercker, 1574).[1]

[1] Lazarus Ercker, *Lazarus Ercker's Treatise on Ores and Assaying*, trans. Anneliese Grünhaldt Sisco and Cyril Stanley Smith (Chicago, IL: University of Chicago Press, 1951), 51.

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Introduction

The following paper describes a programme of experimental charcoal-fired furnace construction and testing, undertaken to develop the author's knowledge of how to conduct cupellations using such furnaces and to understand the technological choices inherent in historical designs. The furnace design drew from sixteenth-, nineteenth-, and early twentieth-century sources as well as past and concurrent experiences of ceramic kiln construction. It is helpful to consider the series of test furnaces as structural chimeras, both in terms of their appearance and their function. From a history of alchemy and chemistry perspective, their primary value lies in what they demonstrate about the behaviour of charcoal-fired furnaces in general, and in the insights they offer regarding the function and efficiency of specific elements of the designs from different historical periods.

The reasons behind this non-conventional approach to experimental reconstruction are complex. They include material limitations, transport and workshop logistics and availability, the overall cost of assembling a functioning test furnace, the requirement to ensure a furnace is safe to operate, and the need to quickly test iterative structural revisions.

The furnaces described in the referenced texts were used to conduct fire assays. A fire assay consists of two main processes: "cupellation" (where gold and silver are separated from base metals using a thick-walled, porous vessel called a "cupel" to produce a precious metal alloy) and "parting" (where the silver component of this alloy is digested by nitric acid, leaving isolated gold). Measurement of the results of each stage provides a quantitative result first for the overall precious metal content (i.e. silver + gold) and second for the moiety of gold.[2] Unprocessed metallic ores can also be tested by fire assay once a preliminary stage, called "scorification," has been undertaken. Scorification breaks down the simpler metallic compounds in the ore and concentrates the metal components as a separate mass from the slag ("scoria"). Scorification can be undertaken in a refractory crucible or in a small, shallow refractory bowl called a "scorifier." Fire assay using the mineral acid parting process was adopted in Europe during the late medieval period (once knowledge of mineral acids had developed) and was widely practised across the continent until the twenty-first century, when the X-ray fluorescence (XRF) method of analysis became accepted as a legal standard for assaying and was widely adopted as a less destructive and less polluting alternative.[3] But fire assay is still used for individual tests, especially in contexts where XRF results may be compromised by a complex or unknown elemental composition of the sample being assayed.

[2] International Standards Organisation, *ISO 11426:2021 Jewellery and Precious Metals – Determination of Gold – Cupellation Method (Fire Assay)* (ISO, 2021).

[3] International Standards Organisation, *ISO 23345:2021(E) Jewellery and Precious Metals – Non Destructive Precious Metal Fineness Confirmation by ED-XRF* (ISO, 2021).

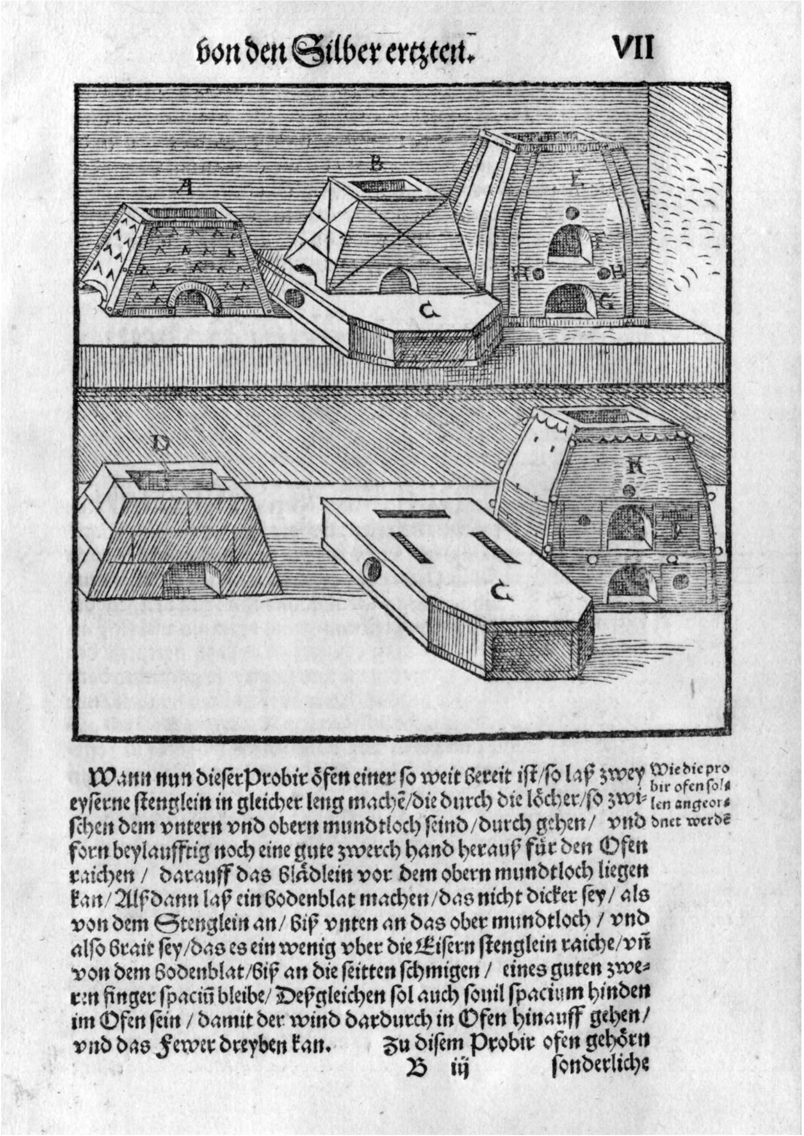
Ever since my first experience of fire assaying as a trainee assayer at the Birmingham Assay Office in 2008, I have wanted to engage with the process at a more visceral level than twenty-first century assaying conventions and furnaces allow. As part of my PhD research on the social and physical circulation of gold, I tracked down a nineteenth-century assay furnace in museum storage. Viewing this massive construction of riveted wrought iron and brick gave me some intimation of how different an undertaking cupellation would have been two hundred years ago. Conducting ethnographic research on different crafts as embodied practice and identity-building performative activities further sharpened my interest. I became increasingly intrigued about what managing a solid-fuel assay furnace would really entail. I was also interested to find out how using such a furnace would affect participants' perceptions and understandings of the fire assay as a form of material transmutation as well as a method of analysis.

Library research provided another perspective. Reading translations of the sixteenth-century texts written by Georgius Agricola (1494–1555) and Lazarus Ercker (ca.1530–1594) sparked an interest in sixteenth-century assay furnaces as artefacts in their own right.[4] But the odd-looking line-up of furnaces illustrated in Ercker's *Treatise* (Figure 1) were hard to reconcile with any other furnaces or kilns I had seen or used. Despite the obvious expertise of the author, my pre-existing practical knowledge of furnace and kiln construction and fire management led me to doubt that these strange objects would be able to reach and maintain the temperatures needed for successful assays.

I also started to collect more recent books that describe the fire assay process using solid fuels in comprehensive detail. Many of these, published in the later nineteenth and early twentieth century, were written as educational textbooks for technical college students. They not only comprehensively covered the subject of fire assaying but also included chapters on building furnaces and sourcing the necessary materials and equipment. Their explanations of constructing furnaces that used coal, charcoal, wood, gas, or oil helpfully included the principles behind the designs. Some of this information, I surmised, could be employed to construct a viable test furnace which would run on charcoal, the same fuel as used by assayers across Europe in the sixteenth century. This would give me the practical experience of running a charcoal-fired cupellation, which would enable me to interrogate the sixteenth-century texts from a new perspective.

The decision to start the exploration using nineteenth-century designs rather than by attempting to create a facsimile of a sixteenth-century furnace was based on logistic practicalities. Sixteenth-century furnaces were created to be a single block of material, so revising the structure even slightly would entail a whole new build. In addition, as the design consisted entirely of bespoke elements, the cost of creating even one furnace would be exceptionally high and demand the engagement of a

[4] Georgius Agricola, *De Re Metallica*, trans. Herbert Clark Hoover and Lou Henry Hoover (New York: Dover Publications, 1950), 219–241; Ercker, *Treatise on Ores and Assaying*.


von den Silber ertzten. VII

A B C D E H G K

Wann nun dieſer Probir öfen einer ſo weit bereit iſt/ſo laß zwey eyſerne ſtenglein in gleicher leng machẽ/die durch die löcher/ſo zwi-ſchen dem vntern vnd obern mundtloch ſeind/durch gehen/ vnd forn beylauffig noch eine gute zwerch hand herauß für den Ofen raichen / darauff das blädlein vor dem obern mundtloch liegen kan/Alßdann laß ein Bodenblat machen/das nicht dicker ſey/ als von dem Stenglein an/ biß vnten an das ober mundtloch / vnd alſo brait ſey/das es ein wenig vber die Eiſern ſtenglein raiche/vñ von dem Bodenblat/biß an die ſeitten ſchmigen / eines guten zwe-ren finger ſpaciũ bleibe/ Deßgleichen ſol auch ſovil ſpacium hinden im Ofen ſein / damit der wind dardurch in Ofen hinauff gehen/ vnd das Fewer dreyben kan. Zu diſem Probir ofen gehörn

Wie die probir ofen ſollen angeordnet werdẽ

B iij ſonderliche

FIGURE 1 Various Types of Assay Furnaces (A) the assay furnace built for the old assayers of strong sheet iron (B) the Nuremburg assay furnace (C) the Nuremburg furnace base (D) an assay furnace hastily built of brick (E) an assay furnace of potter's clay bound with iron bands (K) an iron assay furnace built of sheet iron as used in armour, in Lazarus Ercker: *Beschreibung: Allerfürnemsten Mineralischen Erzt, vnnd Berckwercksarten* (*Treatise on Ores and Assaying*), 7r. Courtesy of Bayerische Staatsbibliothek/ Münicher Digitalisierungszentrum.

range of specialist craftworkers. In contrast, the modular nature of the nineteenth-century designs facilitated quick revisions with little practical effort and minimal financial outlay. Purchasing the industrially-made elements was also relatively inexpensive.

From late 2023 to 2025 I built four test furnaces. The first, built in Kent, UK, closely followed a basic nineteenth-century design. Subsequent iterations, two built in Texas and a final one in Kent (see Appendix), incorporated features culled from the sixteenth-century descriptions, introduced to determine the effects they had on efficiency and operation.

This article covers the practice of building, firing, and refining the test furnaces, an experience which helped me identify the function and effectiveness of specific elements found (or missing) in sixteenth-century furnace designs. This led to some wider reflections on the sixteenth-century texts. The writing of this article has generated further results. First, it led me to consider the specific capabilities of the furnaces described in the nineteenth – and early twentieth-century books. Second, it prompted me to reflect on these technical manuals as artefacts in their own right. Initially treated as background reference, they have since become increasingly interesting as material representations of technological standardisation.

The methodology bears some relation to experimental reconstruction as described by science and technology studies authors (including the past contributions to *Ambix* mentioned below), but I am the first to admit it does not neatly align with some of their precepts. I leave the reader to decide whether this deviance is a methodological innovation, a regretful error, or outright heresy. Building on the results to date, perhaps in another three or four years, it will be possible to build a close reconstruction of the iron-cased frit furnace described by Ercker, but I would be the first to admit this is still some way off (and may never be realised). An incidental result of the work undertaken to date has been a heightened understanding of how difficult constructing any functioning furnace from scratch is in practice. What this article does offer are new insights into how the furnaces described by Agricola and Ercker functioned, drawn from the practical observations of each of the test furnaces in operation. It also considers how the forms of the assay furnaces from the two eras reflect the historical context of assaying during those periods.

Comparing experimental reconstruction to other academic approaches

While experimental reconstruction has a marginal position in the general body of historical research, it has a more established role within science and technology studies.[5] Historians of science have adopted material culture methodologies to explore recorded scientific or alchemical experiments and processes and to reflect on and re-evaluate the theories these practical activities engendered.[6]

5 Leonie Hannan and Sarah Longair, *History through Material Culture* (Manchester: Manchester University Press, 2017).

6 For examples see Hasok Chang, *Inventing Temperature: Measurement and Scientific Progress* (Oxford: Oxford University Press, 2004); Hasok Chang, *Is Water H_2O? Evidence, Realism and Pluralism* (Dordrecht: Springer, 2012); Marianna Marchini, Massimo Gandolfi, Lucia Maini, Lucia Raggetti, and Matteo Martelli, "Exploring

In terms of thermal processing and analysis, a key moment in the promotion of reconstruction as a viable methodology was the publication of the *Ambix* 2016 special issue edited by Hjalmar Fors, Lawrence Principe, and Otto Sibum, in which the editors proposed an iterative framework for this type of investigation and presented examples of its application.[7] This method has since been successfully adopted in subsequent programmes of research.[8] While the current project has employed a similarly iterative structure, sequentially moving between the practical experiments and texts, there is a key difference. In the current paper, the primary focus is on the furnace as a mutable artefact in which a specific process takes place, rather than on the analytical chemical process (i.e. cupellation) *per se*.

It is worthwhile reflecting on the close relationship between experimental reconstruction in science and technology studies and similar practical approaches practised by other disciplines. Archaeologists have developed new insights into the practices of alchemy and early chemistry through a focus on the extant material culture of laboratories.[9] Within anthropology, *participant-observation* is a canonical approach that frequently involves replicating practical activities demonstrated by respondents in the field. The intention of such ethnographic exercises is to develop a nuanced understanding of the activity in question as a social practice and an identity-constructing performance.[10] One finds similar reflexivity in autoethnographic research that focuses on craft practices.[11] In these contexts the technical information derived from respondents can be taken as a type of fixed social fact.[12] In such anthropological research it is the interpretation of these social facts, rather than attempts to determine any inherent veracity, that becomes the key research issue.

Important common features of all these approaches are (1) an acute reflexivity with regards to the practical activity in question and (2) a robust connection between the practical activity and wider research, connected to an academic

6 *Continued*
the Ancient Chemistry of Mercury," *PNAS* 119 (2022): https://www.pnas.org/doi/10.1073/pnas.2123171119 (accessed 8 Oct 2025); Giacomo Montanari, Mariana Marchini, and Lucia Maini, "The Historical Chemist," *Ambix*, *71* (2024): 123–31; Lawrence M. Principe, *The Aspiring Adept: Robert Boyle and His Alchemical Quest* (Princeton. NJ: Princeton University Press 1998); Dagmar Wujastyk, "Understanding Indian Alchemy: Textual and practical approaches," virtural lecture, posted 24 January 2022, by Ghent University, YouTube, https://www.youtube.com/watch?v=CDKoZYC77yI&t=1s (accessed 8 Oct 2025).

7 Hjalmar Fors, Lawrence M. Principe, and Otto Sibum "From the Library to the Laboratory and Back Again: Experiment as a Tool for Historians of Science," special issue, *Ambix* 63 (2016): 85–183.

8 See, for instance, Thijs Hagendijk, Márcia Vilarigues & Sven Dupré, "Materials, Furnaces, and Texts: How to Write About Making Glass Colours in the Seventeenth Century," *Ambix* 67 (2020): 323–45.

9 Sigrid von Osten: *Das Alchemistenlaboratorium von Oberstockstall. Ein Fundkomplex des 16. Jahrhunderts aus Niederösterreich*. (Innsbruck: Universitätsverlag Wagner, 1998). Umberto Veronesi and Marcos Martinón-Torres, "The Old Ashmolean Museum and Oxford's Seventeenth-Century Chymical Community," *Ambix* 69 (2022): 19–33; Yi-Ting Hsu and Marcos Martinón-Torres, "Fire Assay and Cupellation at the Late Medieval Porto Mint, Portugal: A Technological Study," *Journal of Archaeological Science: Reports* 24 (2019): 496–506.

10 Michael W. Coy, *Apprenticeship: From Theory to Method and Back Again* (Albany: State University of New York, 1989); Trevor H. J. Marchand, *The Masons of Djenné* (Bloomington: Indiana University Press, 2009); Brian Moeran, *Lost Innocence* (Berkley: University of California Press, 1984).

11 Erin E. O'Connor, *Fire Craft: Art, Body, and World Among Glassblowers* (New York: Columbia University Press, 2025)

12 Émile Durkheim, *Rules of the Sociological Method* (New York: Free Press, 1982).

discipline, that contextualises the practical activity. In this sense, there is a concurrence between these methodologies and the tenets of experimental reconstruction in the history of science as laid out by Fors, Principe, and Sibum.

The assay furnace: an instrument of power

Precious metals rarely occur naturally in isolation. Gold is often found combined with copper, and silver with lead, though gold and silver can also be found together in an alloy called electrum. Similarly, manufactured gold and silver objects are usually made of an alloy of precious and base metals. There are practical reasons for doing so, as these alloys are typically more robust than the pure precious metal. However, reducing the precious metal content further for financial reasons is also commonly encountered. This potential for variability led to a need to determine an alloy's gold and silver content, which could be met by the fire assay.

A form of cupellation was practised throughout the classical and early medieval periods; a similar process is described in detail in Arabic scientific texts from the tenth and thirteenth centuries.[13] Cupellation also informed medieval and early modern alchemists' reflections on the nature of matter and the possibility of transmutation.[14]

The ongoing centrality of silver coins in European economies and a resurgence in the circulation of gold coins across Europe during the late medieval and Renaissance periods meant fire assay took on increasing importance in the management of the money supply.[15] This became even more relevant during the nineteenth century, when the major world powers, their colonies, and client states all became dependent on the gold standard.[16] Fire assay was also in demand in colonial mining operations, as the extraction of local mineral wealth was a fundamental driver behind European colonial expansion, starting with the conquest of the Americas and continuing into the twentieth century.[17] Fire assay was essential for determining the precise value of mineral deposits being discovered across the globe.[18]

As noted previously, historians' understanding of how fire assaying was practised in the sixteenth century is heavily influenced by the writings of two early modern authors and, in the anglophone world, their twentieth-century translators: Hoover & Hoover's 1950 English translation of *De Re Metallica* by Georgius

[13] Sébastien Moureau and Nicolas Thomas, "Understanding Texts with the Help of Experimentation: The Example of Cupellation in Arabic Scientific Literature," *Ambix* 63 (2016): 98–117.

[14] William R. Newman, "Alchemy, Assaying, and Experiment," in *Instruments and Experimentation in the History of Chemistry*, ed. Frederic L. Holmes and Trevor H. Levere, 2nd ed. (Cambridge MA: MIT Press, 2002), 35–54.

[15] John Porteus, *Coins* (London: Octopus Publishing Group, 1973); Yi-Ting Hsu, "Fire Assay, Cupellation and the Dissemination of Technical Knowledge in Post-Medieval Europe," (PhD thesis, University of Cambridge, 2023): https://www.repository.cam.ac.uk/handle/1810/350986 (accessed 1 September 2025).

[16] Barry Eichengreen and Marc Flandreau, *The Gold Standard in Theory and History* (New York: Routledge, 1997), 229–31.

[17] The impact of the colonial project on indigenous communities and local goldworking practices in the Americas are discussed by Andrés Vélez-Posada and Ana-María Jiménez, "Blowing Fire: Exploring Ancient Amerindian Metallurgy Through a Furnace Model" (this special issue).

[18] Peter L. Bernstein, *The Power of Gold: The History of an Obsession* (New York: Wiley, 2004).

Agricola, published in 1556, and Sisco & Smith's *Treatise on Ores and Assaying*, a translation of Lazarus Ercker's *Beschreibung allerfürnemisten mineralischen Ertzt und Berckwercksarten*, published in 1574. The authors' biographies illustrate the close links between assaying and economic governance during the early modern period. Agricola, trained as a doctor, became a professional diplomat and court official. *De Re Metallica* is a distillation of his lifetime of engagement with mining communities and the mine surveys he undertook on behalf of two Saxon electors.[19] Ercker had a more direct relationship with princely courts. He spent his entire life as a professional assayer, working for twenty-nine years in mints or mining towns in the service of the Habsburg Emperors, a career that culminated as Master of the Prague Mint.[20] Ercker describes the social elevation and political influence a novice assayer could aspire to: "those who have made assaying their occupation, and who have worked at it thoroughly and diligently, not only have earned the sincere gratitude of princes, landowners and well-known city states but have also been distinguished and well recompensed ahead of others."[21]

As both authors attest, the process of cupellation was best undertaken using a piece of specialist equipment: the assay furnace. Ercker's descriptions of the furnace used by "the old assayers," the more recent Nuremburg furnace, and the newer designs he promoted illustrate how furnace design had evolved over preceding decades.[22] It continued to do so over the following centuries. The most obvious and fundamental changes occurred between the second half of the nineteenth century and the mid twentieth century; these can be attributed to the adoption of new energy sources: oil, kerosene, gas, and electricity.[23] The largest variety of design options can be found in technical manuals for assayers published around 1910, midway through this period of change.[24] But the preceding century had also seen significant developments connected to the adoption of industrial manufacture and an associated drive for standardisation.

The test furnace reconstructions

Before embarking on building a functioning furnace, it was necessary to develop a robust understanding of the principles and practice behind the design and management of solid-fuel assay furnaces. As a consequence of the dominance of electric reverberatory assay furnaces from the mid twentieth century onwards, this skill set is no longer found in European or North American assay offices, laboratories,

[19] Agricola *De Re Metallica*, vi–xii.
[20] Ercker, *Treatise on Ores and Assaying,* vii-xix; R. J. W. Evans, *Rudolf II and his World* (London: Thames and Hudson, 1997).
[21] Ercker, *Treatise on Ores and Assaying,* 10.
[22] Ercker, *Treatise on Ores and Assaying,* 19–23.
[23] Evan W. Buskett, *Fire Assaying* (New York: D. Van Nostrand Company, 1907).
[24] See, for example, Charles H. Fulton, *A Manual of Fire Assaying,* 2nd ed. (New York: McGraw-Hill Book Company Ltd, 1911), 1–20; "Assaying" in *International Library of Technology 95* (Scranton: International Textbook Company, 1907), 21–32; Earnest A. Smith, *The Sampling and Assay of the Precious Metals* (London: Charles Griffin & Company Ltd, 1913), 17–35.

factories, or workshops, nor is it taught in technical colleges. It had already vanished from technical manuals by the 1970s.[25] As a starting point, I read a selection of nineteenth – and early-twentieth-century technical books, including the 1823 *Encyclopaedia Britannica*, technical educational textbooks, and manuals for assay masters managing an assay office.[26] I was also fortunate enough to have previously seen and photographed an early nineteenth-century furnace held by the Birmingham Museum Service and to have found illustrations of an extant sixteenth-century furnace in the holdings of the *Kunstgewerbemuseum*, *Staatliche Kunstsammlungen,* Dresden.[27]

An examination of the assayer's manuals provided evidence for general principles of furnace design during the late nineteenth and early twentieth centuries. By this time, portable solid fuel furnaces had become tall hollow cuboids made of refractory bricks, which were then either skinned with sheets of iron or strapped with iron bands (Figure 2). The interior fire chambers had a uniform rectangular profile. This was promoted as a positive attribute: "the interior being smooth and straight from top to bottom."[28] Fuel was held inside the fire chamber by an iron fire grate in the base, with an ash box directly below.

In contrast with the uniformity of the chamber profile, the position of a key component, the muffle chamber, was far more variable.[29] All assay furnaces must include some means of keeping the delicate cupels safe from disturbance or damage from the heat source. This is achieved by siting a small chamber made from a refractory material – called a muffle – in the heart of the furnace. The interior of the muffle provides a secure space, accessible through a hole in the front of the furnace, that is heated to the required temperature range (between 850°C and 950°C) by the fire in the surrounding fire chamber. However, in the nineteenth-century designs employing charcoal or coal, the muffle could be found situated anywhere from halfway up the fire chamber to close to the fire grate (Figures 2 and 3).

The cuboid nature of the nineteenth-century furnace designs made it possible for me to construct a very similar structure using standard European thin firebricks (230 mm x 114 mm x 25 mm), standard insulation bricks (230 mm x 114 mm x

[25] Joseph Haffty, L. B. Riley, and W. D. Goss, *A Manual on Fire Assaying and Determination of the Noble Metals in Geological Materials* (Washington, DC: Department of the Interior, 1973).

[26] Buskett, *Fire Assaying*; T. H. Bodemann and Bruno Kerl, *A Treatise on the Assaying of Lead, Copper, Silver, Gold, and Mercury* (New York: John Wiley & Son, 1865); Walter Lee Brown, *Brown's Assaying,* 9th ed. (Chicago, IL: E. H. Sargent & Co, 1900); Fulton, *A Manual of Fire Assaying;* International Textbook Company, *"Assaying"*; Alfred Stanley Miller, *Manual of Assaying*, 3rd ed. (New York: Wiley 1908); James Park, *A Text Book of Practical Assay*ing, 5th ed. (London: Charles Griffin & Company Ltd, 1918); H. Joshua Phillips, *Gold Assaying* (London: Crosby, Lockwood and Son, 1904); Orson Cutler Shepard and Waldmar F. Deitrich, *Fire Assaying* (New York: MacGraw-Hill Inc., 1940); Smith, *The Sampling and Assay of the Precious Metals*; Leopold Weill, *L'Or* (Paris: J. B. Balliére et Fils, 1896).

[27] See Ana Matisse Doneffer-Hickie, "The Noble Art: Alchemy and Innovation at Court," in *Making Marvels: Science and Splendor at the Courts of Europe,* ed. Wolfram Koeppe (New York: The Metropolitan Museum of Art, 2019), 129–38.

[28] Brown, *Brown's Assaying*, 92.

[29] See illustrations in Fulton, *A Manual of Fire Assaying*, 3–4; Phillips, *Gold Assaying*; 42; Shepard and Deitrich, *Fire Assaying,* 250.

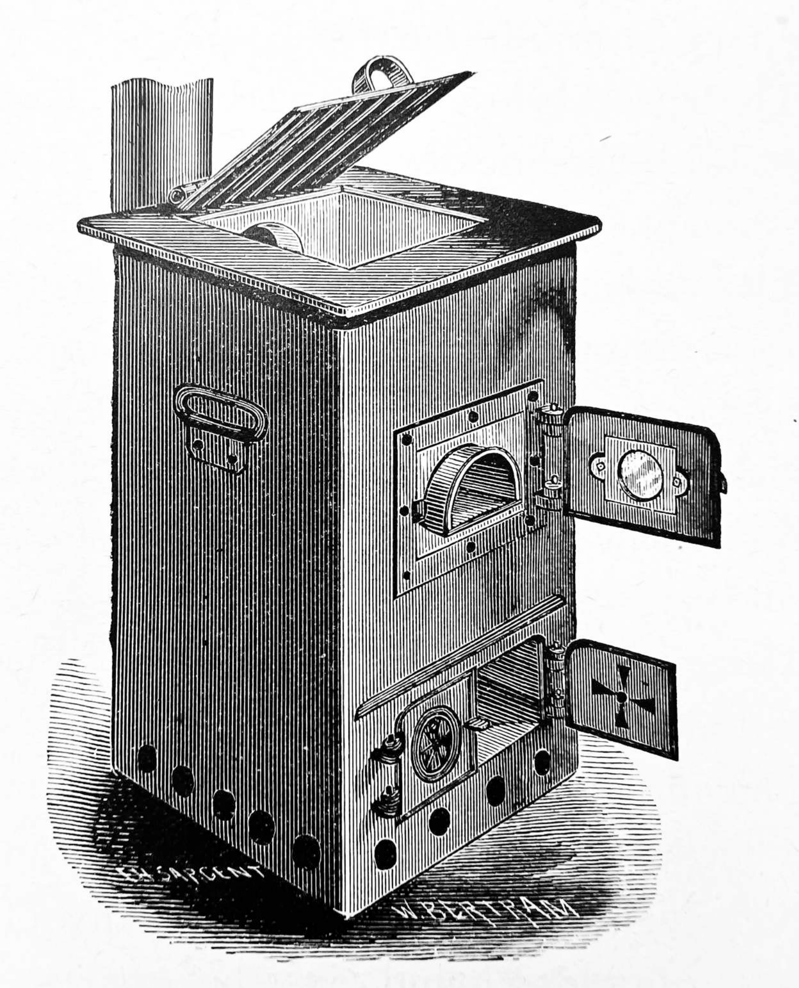


FIG. 41.

FIGURE 2 Brown's Portable Furnace, a typical nineteenth century cuboid design. In this furnace the muffle is situated halfway up the fire chamber. From *Brown's Assaying* (1900).

76 mm),[30] and off-the-shelf industrial iron fittings. A slight change in the design was necessary for the furnaces that were built in Texas, as the standard for American thin firebricks is slightly wider (1¼ inch; 230 mm x 114 mm x 31 mm).[31] The cuboid design became the blueprint for all the test furnaces used to conduct the experiments.

30 British Standards Institution, BS3056-1:1985 *Sizes of Refractory Bricks – Specification for Multi-purpose Bricks* (BSI, 1985).

31 For an explanation of the reasons behind this difference, see Frederick L. Olsen, *The Kiln Book* (Bassett, CA: Keramos Books, 1974), 2–10.

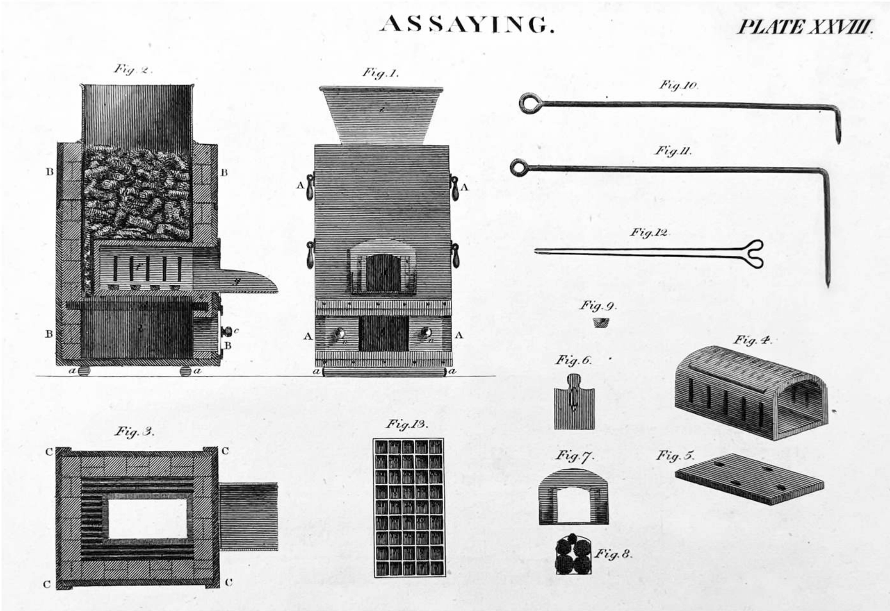


FIGURE 3 Assaying Equipment from the 1823 edition of the *Encyclopaedia Britannica*. In this design the muffle is located in the fire chamber just above the fire bars.

I made one significant change from the historical sources to the test builds: the walls of the fire chambers were given two layers – an inner skin of the thin firebricks and an outer layer of insulating bricks – whereas the nineteenth-century portable designs typically used one type of firebrick throughout (a feature observed in the nineteenth-century furnace in Birmingham). Though the change involved sourcing two types of brick and more brick-cutting, the new arrangement gave the test furnaces a robust interior surface in the fire chamber, while minimising heat loss and reducing the external surface temperature during operation. It also affected the furnace's performance in other ways, which will be described below.

The dimensions of the inner chamber were dictated by the length of the firebricks. This aligned closely with the average dimensions of the fire chambers in the "portable" furnaces described in nineteenth-century manuals. It was also comparable to the interior dimensions of the rectangular section of Ercker's sixteenth-century furnace.

The walls of the test furnace's fire chamber were built without mortar, which was facilitated by the precise standardisation of the available bricks. Their regularity, dead straight sides, and reliably right-angled corners meant they could be stacked to give closely interlocked, straight walls and crisp corners; this also meant that the inner and outer course aligned neatly. Though portable assay furnaces from the nineteenth century were encased in cast iron, sheet steel, or steel bands, I chose an alternative clamping method to provide the test furnaces with added stability: a piece of angle iron at each corner was held in place by threaded rods and bolts, an arrangement more typically found on permanent brick furnaces and large ceramic kilns.[32] This reinforcement not only allowed the test furnace to expand and contract slightly as it heated and cooled; it could also be disassembled quickly and easily. To reduce costs and further improve stability, the outer layer of the lower walls around the ash box were built using ceramic engineering bricks laid with refractory mortar (Figure 4).

The decision to construct the furnace with an inner skin of dense firebricks was based on a perceived need to protect the softer insulation bricks from abrasion, but during the firings it became apparent that they also affected the furnace's performance. Dense firebricks adsorb heat, so the fire-chamber wall acted initially as a heat sink, but subsequently it helped to stabilise the temperature. As this regulation effect turned out to be extremely valuable, it led me to wonder how erratic a furnace's performance would be without it. This would potentially be the case with Ercker's sixteenth-century steel furnace, which had no bricks in its construction.

I returned to the *Treatise* with this question in mind and the answer became obvious. The iron furnace was lined on the inside with a mixture of "good, well-kneaded loam [clay], with wool clippings and horse manure, oxblood, iron hammer scale, and common salt" then brushed on the inside with a mixture of "crushed Venetian glass, bone ash, and some thin loam." [33] When fired, this mixture of clay, fluxes, and organic material would have turned into a vitrified mass with a honeycomb of small holes (a similar process, but using less exotic and pungent ingredients, is used in the production of insulating bricks today). The result would be a lining with a consistency somewhere between a modern firebrick and an insulating brick, but with a harder surface layer. This lining would have behaved in a similar way to the firebrick core of the test furnace, contributing significantly to the furnace's thermal mass and its ability to maintain a stable temperature. Its performance depends on how dense and thick the lining was. Ercker advises that the lining should be about 50 mm, double the thickness of the dense firebricks used to line the Kent test furnaces. [34]

Will it need a chimney?

The nineteenth – and early-twentieth-century source material was not always consistent when it came to the matter of a chimney. The 1823 *Encyclopaedia Britannica* illustration and the Birmingham Museum furnace did not have any integral chimney. However, original illustrations found in different books (published in different countries) of an almost identical solid-fuel furnace in use at the Royal Mint in London included a closed cowl and chimney.[35]

To ensure operator safety and to reduce the risk of flying sparks starting a fire, the first test furnace (built in Kent in the UK) was given a cast-iron cowl with a 500 mm

[32] For examples of furnaces with such reinforcement, see Fulton, *A Manual of Fire Assaying,* 2; for kilns, see Olsen, *The Kiln Book,* 65.
[33] Ercker, *Treatise on Ores and Assaying,* 20.
[34] Ercker, *Treatise on Ores and Assaying*, 20.
[35] Phillips, *Gold Assaying*, 42; Weill, *L'Or,* 387.

FIGURE 4 The Texas 1 Test Furnace, after the chimney was extended using a steel flue. To the left is an electric blower to provide forced air. In the foreground on the right is an ad hoc cooling chamber made of insulating bricks for samples. Photograph copyright Peter Oakley.

chimney. But for the first test furnace built in Texas, the cowl initially only had a 250 mm chimney, and the furnace was unable to reach sufficient temperature. The issue was resolved by adding a 750mm-long steel flue pipe, after which the furnace's performance markedly improved (Figure 4). This unanticipated problem and its easy resolution proved salutary in demonstrating that a furnace could not be

FIGURE 5 Assay Furnace in use in Lazarus Ercker, *Beschreibung: Allerfürnemsten Mineralischen Erzt, vnnd Berckwercksarten* (*Treatise on Ores and Assaying*), 113v. Courtesy of Bayerische Staatsbibliothek/ Münicher Digitalisierungszentrum.

treated as a working core with additions. As Elmer and Hagendijk show in their contribution to this special issue, early modern chymists were also well aware of this; then as now, the assemblage needed to be understood as a *gestalt*.

This raised an important question: if the test furnaces could not function without a sufficiently tall chimney, how did the illustrated furnaces that did not have chimneys ever manage to reach temperature? Though the comparative illustration in Ercker's *Treatise* show six different types of furnace in isolation (Figure 1), the images of them in workshop environments show them resting on what appears to be a solid, waist-high hearth (Figure 5).[36] Presumably the hearth had a built-in

[36] Ercker, *Treatise on Ores and Assaying*, 9, 138; for further discussion of the importance of chimneys see Vilarigues et al. "Powder, Fire, Glass: The Reproduction of Blue Enamels and the Role of Fire in Seventeenth- and Eighteenth-Century Instructions," and Hannah Elmer and Thijs Hagendijk "The Historical Furnace as Assemblage: Space, Circulation and Early Modern Fire Management" (both this special issue).

flue that provided sufficient draw to pull enough air through the furnace to enable it to reach a working temperature. Though separate structures, in an assayer's workshop the furnace and the hearth it sat in functioned as one assemblage. This may help answer the question of why the furnaces illustrated in sixteenth-century texts looked so strange (Figures 1 and 5); they are only one part of a technical system, not an independently functioning entity.

The test-furnace muffles

Contemporary electric assay furnaces are fitted with muffle chambers and electric elements that heat the muffle slowly, consistently, and uniformly. Therefore, the muffles can be made from high-silica materials with thick walls and a shallow, arched roof. Such material and structural properties, however, reduce a muffle's resilience to the level of thermal shock a charcoal-fired furnace is prone to deliver.

Consequently, it was necessary to build bespoke muffles of a more robust design using more resilient refractories. While the nineteenth-century sources expect the assayer to buy muffles from a commercial supplier, the sixteenth-century sources explain how to make them from scratch. Ercker describes the most suitable type of clay as: "blue clay that turns white in the fire," a description that accurately describes lignite-rich ball clays. Ercker also enumerates the other necessary raw materials: "take broken earthenware, scorifers, or old crucibles, crush them fine, pass them through a little sieve, and mix so much of this with the clay that the clay can hardly be worked for brittleness."[37] This comes remarkably close to the recipe for a clay manufactured today called "industrial crank" (a high firing clay mixed with pulverised fired clay called "grog"). Crank is used to make refractory items such as saggars (containers to put fine or delicate objects in for wood or coal ceramic firings). The muffles for the test furnaces were hand built from industrial crank by the author and fired to 1260°C before use (Figure 6). The form of the test muffles came closest to the illustrations published in *De Re Metallica*, with straight side walls surmounted by a simple, semicircular arch.[38] Taking a bespoke-build approach meant that the muffles could be made to fit snugly into the fire chamber and, by adding flanges to the end of the arched roof, also slot neatly into the square recess around the aperture in the fire chamber's front wall (Figure 7).

The first muffles followed the principles of modern muffle furnaces: the muffle had no vents and an integral floor, so the interior of the muffle chamber was completely isolated from the energy source. However, when using these enclosed muffles in the test furnaces, it took a long time for the muffle atmosphere to return to the working temperature whenever the front of the muffle was opened to insert or remove a test piece.

[37] Ercker, *Treatise on Ores and Assaying,* 24.
[38] Agricola, *De Re Metallica*, 228.

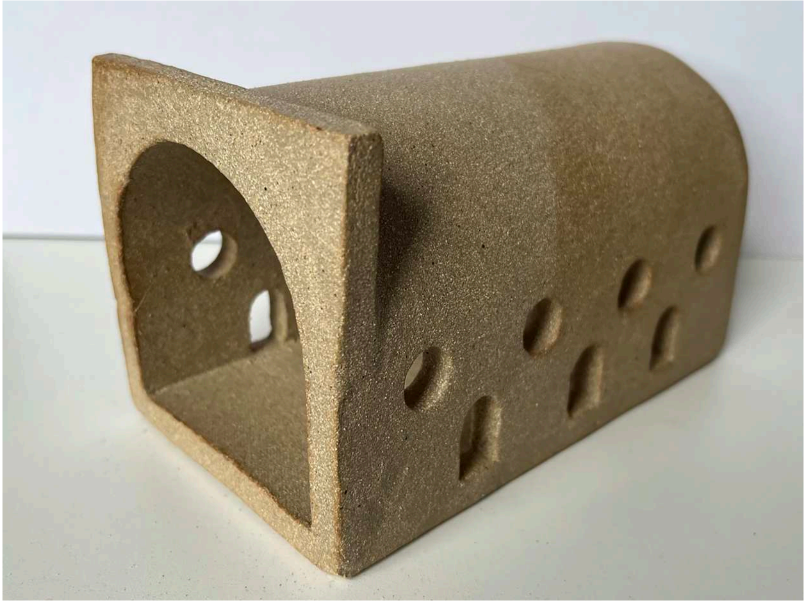


FIGURE 6 Bespoke vented muffle made for use in the test furnaces. Photograph copyright Peter Oakley.

FIGURE 7 A Muffle in situ in the empty Texas 2 test furnace. The front of the muffle sits in a recess (bottom of the image). The wider central portion added to this iteration can also be seen on the left and right sides of the fire chamber. Photograph copyright Peter Oakley.

Adding vents had a dramatic effect. As the interior of the vented muffle chamber was heated by convection as well as radiation, and the charcoal in the vicinity of the muffle vents was stimulated by the additional flow of oxygen from the muffle when it was opened, there was a noticeable rebound in temperature when the muffle was closed. This significantly reduced the overall firing time needed for tests and reduced the likelihood that samples would freeze midway through a cupellation.[39]

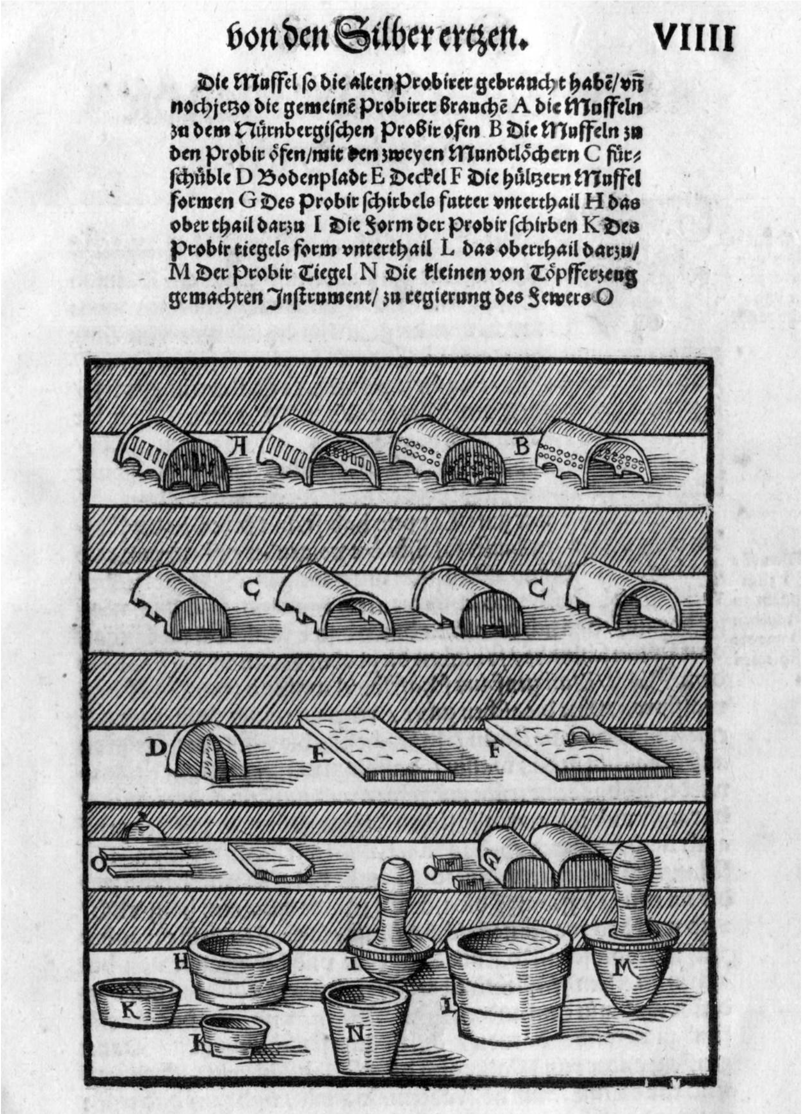
Discovering that adding vents made a significant difference in the responsiveness of the furnace led me to return to the texts again. I was immediately drawn to the fact that the sixteenth-century muffle designs had no integral floor. My initial bias for including an integral floor had been linked to the assumption that this would enhance the muffle's overall structural strength and reduce the opportunity for fly ash to ruin an assay. I had also assumed that the sixteenth-century design decision had been partially based on avoiding building a closed form: extracting a forming block is more difficult when it is enclosed by clay, but a floorless muffle can just be lifted off the block.

These assumptions were challenged by a rereading of both texts in the light of the firings already undertaken. First, Ercker describes far more complicated ceramic constructions than a muffle with a floor; the idea that an integral floor would be considered too technically demanding was evidently wrong. Second, test firings demonstrated that fly ash was not a problem, providing the vents were low enough. Notably, Ercker states that the vents in the muffle used in the most recent design of furnace should be formed by cutting notches into the bottom of the wall, rather than by piercing holes in the side of the wall. He also states each furnace works best with a particular arrangement of vents (Figure 8).[40]

But the most surprising finding came from rereading *De Re Metallica*. Instead of setting the muffle on a flat slab of fired clay, Agricola describes fitting a metal plate smeared with lute (a mixture of bone ash and clay) into the furnace as the support for the muffle. This plate also protrudes beyond the sides of the muffle almost to the walls of the furnace and has slots cut parallel to its edges. I realised that such an element would function as a grate, holding the charcoal in place against the muffle. Due to its conductivity, the plate would help return the interior of the muffle chamber to ambient temperature after the mouth had been closed. The importance of this plate was reinforced by the fact it is the shown in detail in one of only three illustrations in the book to show assay furnaces, and the only one of these to include any technical explanation (Figure 9).[41]

This led to another revelation. Following nineteenth-century convention, I had included a cast-iron fire grate. From that point, I had scarcely considered the role of the grate in the overall design. But from a closer reading of the older texts, it became apparent that the sixteenth-century assay furnaces did not possess one.

[39] Fulton, *A Manual of Fire Assaying*, 80–98.
[40] Ercker, *Treatise on Ores and Assaying,* 24.
[41] Agricola, *De Re Metallica*, 224.



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Die Muffel so die alten Probirer gebraucht habẽ/vñ nochjetzo die gemeinẽ Probirer brauchẽ A die Muffeln zu dem Nürnbergischen Probir ofen B Die Muffeln zu den Probir öfen/mit den zweyen Mundtlöchern C fürschüble D Bodenpladt E Deckel F Die hültzern Muffel formen G Des Probir schirbels futter unterthail H das ober thail darzu I Die Form der Probir schirben K Des Probir tiegels form unterthail L das oberthail darzu/ M Der Probir Tiegel N Die kleinen von Töpfferzeug gemachten Instrument/ zu regierung des Fewers O

FIGURE 8 Various muffles as illustrated in Ercker's *Treatise*: (A) muffles used by the old assayers and still used by the public assayer (b) muffles for the Nuremberg assay furnace (C) muffles for the assay furnaces with two mouth holes. From Lazarus Ercker: *Beschreibung: Allerfürnemsten Mineralischen Erzt, vnnd Berckwercksarten* (*Treatise on Ores and Assaying*), 9v. Courtesy of Bayerische Staatsbibliothek/ Münicher Digitalisierungszentrum.

The metal plate described by Agricola functioned as a grate and as a platform for the muffle, making it a hybrid element. This contrasts with the wind furnaces discussed by Elmer and Hagendijk in this issue.[42]

[42] See Hannah Elmer and Thijs Hagendijk's discussion of wind furnaces in "The Historical Furnace as Assemblage: Space, Circulation and Early Modern Fire Management" (this special issue).

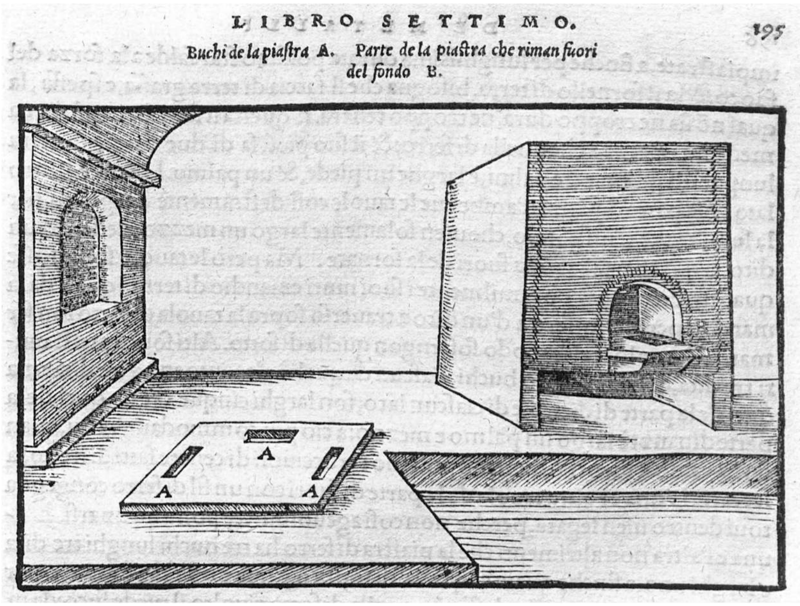

FIGURE 9 Illustration of the iron muffle plate from Agricola's *De Re Metallica,* 192. Courtesy of Bayerische Staatsbibliothek/ Münicher Digitalisierungszentrum.

It remains to be tested extensively, but preliminary firings have shown that using a muffle without a floor, resting on a 5 mm iron plate similar to the one featured in *De Re Metallica* improves the responsiveness of the test furnace. This effect is twofold: the iron plate helps retain a stable ambient temperature inside the muffle chamber, and it facilitates a quick recovery after the temperature drops when the muffle is opened. It also reduces the possibility of cold spots developing under larger objects placed in the muffle, as the iron plate can conduct heat under the object much more effectively than a ceramic plate or ceramic muffle floor.

From self-sufficiency to standardisation

Cutting the slots in the 5mm-thick furnace plate proved to be a challenging task. The experience led me to reconsider how problematic building an iron assay furnace would have been in the sixteenth century. It is salutary to recognise the implications of having to individually cut, shape, and pierce each iron sheet and rod by hand. The curvature of the plates at the top of the furnace design described by Ercker would have been exceptionally difficult to achieve manually; access to the expertise of an armourer, experienced in curving iron plates and fitting them together at varying angles, would have been highly advantageous. In connection to this, it is notable that Ercker describes the furnace as "built of sheet iron as used in armour."[43] Once assembled, the iron frame would also have to be lined with the frit mixture by hand. Achieving or accessing the combination of manual skills that the overall construction demanded must have been a daunting prospect. It is worth reflecting here how wide a skill set Ercker claims assayers should possess: "To prepare for emergencies, every assayer ought to be able to make his own assay furnaces, scorifers, crucibles, muffles and such utensils as are needed in daily in assaying, since a master who knows how to do it cannot be found everywhere."[44] Ercker repeats his claim regarding furnace-building and tool-making expertise elsewhere in the text, only excusing his assayers from creating items "made of large pieces of iron," but adding that they should also be able to make and adjust their own balances and weights.[45] A comprehensive examination of the intention of these statements and the audiences that they were intended for, or even if they express an abstract ideal or commonly held expectations, is beyond the scope of this article. The contribution this research makes is to demonstrate how advanced an assayer's practical making skills across a range of techniques and materials would have needed to be to meet this requirement.

Such expertise would have been hard to acquire without direct tutoring; even the best texts and illustrations from the period are typically partial, misleading, or obfuscating, as previous authors have identified.[46] In contrast, the later nineteenth-century assay manuals were able to exploit what were, by then, established conventions of graphic description and measurement. As noted by Ken Adler, establishing modes of graphic representation and universal measurement systems are aspects of the social project of industrialisation and its attendant demand for standardisation. Standardising image formats, technical objects, and processes of production are driven by ideological as well as practical intentions.[47] The authors and editors of the nineteenth – and twentieth-century assayers manuals were able to employ a plethora of presentational strategies including side elevations, cutaway plans, and isometric drawings, as well as photographic representations.

The existence of these assayers' manuals can also be seen as an aspect of industrialisation. The training of a small army of professional assayers, and their adoption of a common approach to conducting fire assays, was heavily dependent on these manuals as tools of communication. Their integral role in instruction enabled those at the heart of the assaying profession, working in technical colleges and the state-sponsored assay offices, to disseminate their knowledge *in absentia* to a multitude of neophytes via intermediaries. The books as entities consolidated

[43] Ercker, *Treatise on Ores and Assaying*, 22–23.
[44] Ercker, *Treatise on Ores and Assaying*, 24.
[45] Ercker, *Treatise on Ores and Assaying*, 11.
[46] For a good example, see Lawrence M. Principe, "Chymical Exotica in the Seventeenth Century, or, How to Make the Bologna Stone," in *Ambix* 63 (2016): 118–144 (on 134, 140); On codifying tacit knowledge see Pamela H. Smith, *From Lived Experience to the Written Word: Reconstructing Practical Knowledge in the Early Modern World* (Chicago, IL: University of Chicago Press, 2022).
[47] Ken Adler, "Making Things the Same: Representation, Tolerance and the End of the Ancient Regime in France," *Social Studies of Science* 28 (1998): 499–545.

these experts' positions as leaders in their field, and the self-reinforcing truth of the conventional images verified the assertiveness of the claims being made.[48] The manuals therefore enabled leaders in the assaying profession to define and thus control the accepted assaying practices over large geographical and temporal distances.

It is notable that so much of the assaying equipment described within the nineteenth – and twentieth-century manuals could be purchased as finished objects, and that the manufacturer's contact details were provided. In cases where shipping purchases would be impractical, such as fragile bone ash cupels, purchasing an automated means of onsite production (e.g. cupel-making machines) provided the necessary standardised object. Ercker's demand for self-sufficiency contrasts sharply with this global industrial network of production, distribution, and consumption, justified and underpinned by a plethora of universally agreed upon quality standards.

This shift to interdependence across a supply network reached its apogee at the mid-twentieth century, when electricity became the energy source of choice.[49] Highly controllable and easily measurable, electricity removed the need for assayers to develop any fire management expertise; henceforth this would be shouldered by the remote power plant supplying the electrical current. The late twentieth-century dominance of the electrical assay furnace can be framed as a type of "technological choice" that was selected in response to the demands of industry and facilitated by the developing infrastructure of the electric grid.[50]

Though the test furnaces I constructed were not intended to be connected to this international industrial network, I quickly became its beneficiary (and to an extent, its dependent). The availability, price, and ease of transportation of the off-the-shelf reliably standardised firebricks, insulating bricks, and robust morganite cupels (more suitable for shipping than bone ash cupels) made the building and firing of furnaces on two continents feasible in the time frame available. This can be seen as a small echo of the nineteenth – and twentieth-century networks that supplied scientific and technical equipment and materials across huge distances to remote locations and played a substantial role in colonisation projects. But the combination of the standard materials with unique elements (the angle-iron reinforcements, muffles, and iron plate) and re-purposed artifacts (e.g. the chiminea hood, stove flue, grate, and turnbuckles) turned the test furnaces into something problematic from a design theory viewpoint. They cannot be defined as either the assembled products of industrial manufacturing or as bespoke production. They are best understood as a manifestation of "adhocist" principles, benefitting from industrial

[48] Bruno Latour, "Visualisation and Cognition: Thinking with Eyes and Hands".in Henrika Kuklick ed. *Knowledge and Society Studies in the Sociology of Culture Past and Present* , 6 (Bingley: JAI Press, 1986). 1–40.

[49] Haffty, Riley, and Gossis, *Manual on Fire Assaying*, 40–44.

[50] Pierre Lemonnier ed., *Technological Choices: Transformations in Material Cultures since the Neolithic* (New York: Routledge, 2002); Rob Cochrane, *Power to the People: History of the Electricity Grid* (Littlehampton: Littlehampton Book Services Ltd, 1985); Phillip F. Schewe, *Grid: A Journey Through the Heart of Our Electrified World* (Washington D.C.: National Academies Press, 2007).

standardisation, but also accepting and incorporating bricolage and indeterminacy.[51]

Furnace design: responsiveness vs. long-run efficiency

The balance between competing but incommensurate demands that lead to the adoption of a specific design can become unsettled over time due to new external forces which disrupt the equilibrium and stimulate change.[52] The impact of industrialisation is an important consideration when reflecting on why assay furnaces mutated between the sixteenth and nineteenth centuries.

I found that when running the test furnace for a whole working day, ash build-up would start to affect the furnace's efficiency. But it was evident that most of the time, the ash dropped through the furnace unimpeded; there were very few snagging points where it could accumulate. This indicated that the nineteenth-century furnaces had been optimised for volume testing. Together, the straight-sided design and grate significantly reduced ash build-up inside the furnace. If the furnace did start to choke, the grate could be riddled in an aggressive manner to encourage the ash to drop into the ash box. Furnaces with straight-sided and grated fire chambers can therefore be run continuously for long periods at peak efficiency. This would have been important in large, commercially run assay offices undertaking hundreds of assays per day, each of which had a specific and measurable profit margin.

In contrast, the sixteenth-century furnace design, while more immediately responsive, is more prone to ash build-up. Since the composite muffle and plate setup is a much more delicate assemblage, disturbing the fuel in the fire chamber with a poker is a far riskier proposition. A poker might hit and damage the muffle, or jolt and even topple the muffle if it hit the plate. But ash will inevitably build up around the muffle and block the vents. Consequently, the undisturbed ash will eventually compromise the furnace's efficiency to the point where it has to be left to cool before being cleared out and relit.

Indeed, ash build-up is mentioned as a key flaw by Ercker with respect to the older furnace designs.[53] But while the newer furnace he recommends fared better in this regard than older versions, it was not designed to manage the number of cupellations that were typically being conducted in nineteenth – and twentieth-century assay offices. Ercker treats the assaying facility at Kuttenberg as exceptional: "where so much ore is bought that more than two hundred ore assays are made there each and every week."[54] In contrast, Shepard and Detrich provide an appendix describing the "Minimum Equipment for a Small Assay Office," which is

[51] Charles Jencks and Nathan Silver, *Adhocism: The Case for Improvisation* (Cambridge, MA: MIT Press, 2013).
[52] Annemarie Mol and John Law, "Complexities: An Introduction," in *Complexities: Social Studies of Knowledge Practice* ed. John Law and Annemarie Mol (Durham, NC: Duke University Press, 2002), 1–22.
[53] Ercker, *Treatise on Ores and Assaying,* 20–21.
[54] Ercker, *Treatise on Ores and Assaying,* 43.

identified as having a "capacity of 30–40 assays per day."[55] What was considered an exceptional number in 1574 had become a minimum expectation by 1940. The long-term operational capacity this volume of assays required of assay furnaces meant the immediate responsiveness of the muffle-and-plate arrangement had to be sacrificed.

It can therefore be proposed that the changes in furnace design were the result of multiple factors, including the alignment of precious metal and ore assays with scientific principles of analysis, which involved more test duplication and replication, as well as the growing overall volume of assays required to keep pace with industrial production in centres of jewellery and silverware production and the ever-increasing scale of mechanised mining.[56]

Conclusion

The building and firing of the test furnaces, combined with a close reading of the sixteenth-century texts, revealed three specific findings. First, the lining of the sixteenth-century iron furnace would have played a significant role in that furnace's functionality, helping to regulate the internal temperature as well as provide insulation. Given its size, complexity, and thickness, it may be better to consider the fired frit as one giant, bespoke firebrick; the term "lining" implies something less structurally and functionally significant. Second, the siting of sixteenth-century furnaces played an important part in their functionality. The workshop or laboratory architecture – specifically the hearth's flue – played an active role in providing sufficient draft to enable portable assay furnaces to run at peak efficiency.[57] With the reconstructions it proved necessary to install an integral chimney to enable the test furnace to function in a similar manner. Third, the specific muffle-and-plate arrangement described in the sixteenth-century texts also played a role in enhancing the furnace's responsivity. Drawing from the practical experience of using both alternatives, I propose that, while more responsive, the muffle-and-plate arrangement cannot be run for long periods of time, making it unsuitable for handling the larger numbers of cupellations that became the standard workload in assay offices of the industrial era. It was the emphasis on enhanced productivity that consigned the muffle-and-plate design to history.

55 Shepard and Detrich, *Fire Assaying*, 264–65.

56 The principles of following established laboratory practice and error elimination are evident in the nineteenth-century assaying manuals." For example,, Fulton devotes an entire chapter to "errors in the assay for gold and silver," Fulton, *A Manual of fire Assaying*, 160–73. I was taught a similar systematic and random error elimination approach when being trained as an assayer, with the assay master referencing ISO 11426 as the guide to correct practice (International Standards Organisation, *ISO 11426:2021)*. The same principles are applied in other branches of analytical chemistry. For an example see: Brynn Hibbert "Systematic Errors in Analytical Measurement Results," *Journal of Chromatography A*. 1158 (2007): 25–32.

57 See also Elmer and Hagendijk, "The Historical Furnace as Assemblage"; on portable furnaces, see Vilarigues et al., "Powder, Fire, Glass" and Andrés Vélez-Posada and Ana María Jiménez, "Blowing Fire: Exploring Ancient Amerindian Metallurgy Through a Furnace Model" (this special issue).

Charcoal-fired muffle furnaces are certainly capable of reaching and maintaining cupellation temperatures. In addition, once the operator has developed a sufficient understanding of the role each element of the furnace plays and has accumulated the requisite expertise in fire management, such furnaces are a surprisingly responsive and controllable piece of equipment. They do, however, demand full commitment. Running a charcoal-fired assay furnace requires constant engagement over the better part of a day. We talk of managing or regulating the fire, but at the same time the operator becomes its indentured servant.

Despite their chimeric qualities, the test furnaces were eminently successful experimental reconstructions. They throw new light onto the nature of, contrasts between, and contradictions in the primary texts. The process of building necessitated closer reading, as finding a description of each element and the means of its construction assumed greater importance. This process led to a more complete understanding of what necessary information had been omitted and what remained partial or ambiguous. It also helped expose discrepancies between the texts and the illustrations, as well as concurrence across different sources. There was more than one occasion when the full relevance of material in the text and illustrations (or their absence) came to light because of a rereading following observations made during the practical work.

The experiments also revealed an ambiguity in the value of prior practical knowledge. In some cases, such as knowing which contemporary ceramic body came closest to a recipe recommended in a sixteenth-century source and how to build bespoke muffles, or understanding the working properties of refractory bricks, prior knowledge was essential. Yet it misled in other circumstances, such as in selecting an enclosed muffle or assuming a fire grate would be necessary. Though there is a temptation to adhere as closely as possible to historic descriptions, the experimenter needs to be aware of inherent pitfalls in many material processes (including those that may have been unknown to the original author). In addition, the requirement to maintain operator safety and meet contemporary regulations need to be acknowledged. In part, the test furnaces were built as chimeras because then they could incorporate safety features such as a tensioned metal frame (enhancing structural stability) and heavily insulated walls (reducing operator burn and wider fire risks). Their overall structural similarity to contemporary ceramic kiln designs also mitigated possible collapse risks.

Finally, the reconstruction enabled the operator to experience how holistic the management of a charcoal-fired assay furnace actually is, and it facilitated the development of the fire management skills that such furnaces require. This skill set consists of two elements. First, an experiential knowledge of how to read the furnace during firings through a series of phenomenological clues, which as Ercker noted, "cannot be very well described."[58] Second, an underlying design knowledge of the furnace's construction and the effect each element has on its

[58] Ercker, *Treatise on Ores and Assaying,* 51.

performance. Once acquired, this same design knowledge can also be transposed onto abstractions, such as diagrams or narratives, enabling an experienced furnace operator to predict how cold furnaces, furnaces not yet built, or furnaces no longer in existence will all behave and need to be managed. But this skill set "can be acquired only through great practice," for fire management is a performative activity.[59]

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The first demonstration of a test furnace was the result of an invitation from Dr Tianna Helena Uchacz to attend the Fire Arts symposium at Texas A&M in November 2023, an opportunity for which I will always be grateful.

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[59] Ercker, *Treatise on Ores and Assaying,* 51.

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Appendix

Appendix 1: Test furnace construction across the four versions (2023–2024)

1. Kent 1 Furnace (constructed Sept 2023). Fire chamber profile 230 mm x 180 mm; fire chamber height 342 mm; blind muffle resting on two iron fire bars; chimney height 500 mm (plus cowl height of 300 mm).
2. Texas 1 Furnace (constructed Nov 2023). Fire chamber profile 230 × 168; fire chamber height 342 mm; blind muffle resting on two iron fire bars; chimney height 1 m (plus cowl height of 300 mm).
3. Texas 2 Furnace (constructed May 2024). Fire chamber profile 230 mm x168 mm, with a wider middle third having a profile of 292 mm x168 mm, fire chamber height 342 mm; vented muffle resting on two firebrick arches; chimney height 1 m (plus cowl height of 300 mm).
4. Kent 2 Furnace (constructed July 2024). Fire chamber profile 230 mm x 180 mm; fire chamber height 342 mm; open-based vented muffle sitting on metal plate resting on two iron fire bars; chimney height 500 mm (plus cowl height of 300 mm).

The Kent furnaces were lined with thin firebricks with dimensions 230 mm x 114 mm x 25 mm. In the Texas furnaces the thin firebricks used were 230 mm x 114 mm x 31 mm. The insulation bricks were the same dimensions (230 mm x 114 mm x 76 mm) across all builds.

The ash box cross section of 180 mm x 180 mm, and the position of the cast-iron fire grille remained consistent across all versions. The ash box height was 203 mm in the Kent versions and 197 mm in the Texas versions (due to the difference in the thickness of the firebricks used to line the floor).

All the test furnaces were fitted with an R-type thermocouple (protected by a ceramic casing) that fitted through a hole in the back wall of the furnace and an aligned hole in the back of the muffle. This pyrometer measured the air temperature in the muffle chamber. Temperature readings were taken in Celsius.