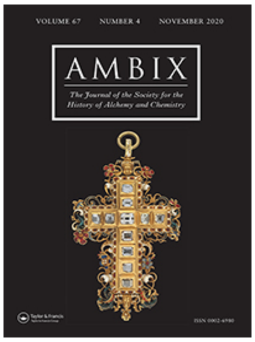

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Materials, Furnaces, and Texts: How to Write About Making Glass Colours in the Seventeenth Century

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Johann Kunckel's *Ars Vitraria Experimentalis* (1679) is arguably the most important text on seventeenth-century glassmaking. As an augmented German translation of Italian (1612) and English (1662) editions, Kunckel presented a complex and layered text that contained a plethora of recipes, elaborate commentaries and annotations, and various appendices dealing with glass-related technologies and arts. We reworked four recipes for rosichiero glass (a transparent red glass) in Kunckel's book to discover what strategies Kunckel employed to help readers engage with the recipes and to make the recipes work in the specificity of their own workshop. We learned that Kunckel regularly neglected to test the Italian recipes, and that not all of his corrections are improvements, thereby specifying our understanding of the "codification of error" as a strategy to write down colour-making knowledge. Instead, Kunckel made the choice to educate his readers on the very mechanisms of glass colouring to allow them to intervene to influence the colour of the glass and to gain further control over the making process. He argued that the colour of glass is sensitive to the manner in which ingredients are sourced and processed, and emphasised the importance of furnace management in optimising the colour of glass.

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1. Introduction

This article is about arguably the most important text on glassmaking of the seventeenth century. First published in 1612 by the Italian glassmaker and alchemist Antonio Neri (1576–1614) as *L'Arte Vetraria*, the treatise became an ever-expanding project that went through several translations and commentaries. When almost seventy years later, in 1679, the German chymist and glassmaker Johannes Kunckel (1630–1703) finished a German edition of the same treatise, with the title *Ars Vitraria Experimentalis*, it had grown into a complex and layered text that contained numerous recipes, elaborate commentaries and annotations, various appendices dealing with glass technologies, and a variety of descriptions of glass-related arts. Kunckel also included parts of a previous English edition published by Christopher Merret (1614–1695) in 1662. He translated Merret's commentaries on Neri's Italian original and even added his own commentary on Merret's commentary. By 1679, Kunckel had transformed the treatise into a complicated text that had more than quadrupled in size since its first appearance in 1612.

Over the past years we have seen a growing interest in textual technologies and the reading and writing practices developed in the arts, including the recognition of the significance of processes of copying, translating, annotating, and transforming recipes.[1] Here we take four recipes for rosichiero glass as a case and seek to answer what textual technologies were employed in the *Ars Vitraria Experimentalis* to help the reader engage with the recipes, to experiment with them, and to make them work in the specificity of their own workshop.[2] We decided to focus on this glass colour because the rosichiero recipes, originally included in Neri's first editions, are an instantiation *par excellence* of these processes of translation and annotation, especially as they come with comments and additions by Merret and Kunckel. How should we understand this process of layering and its functions? Kunckel used his commentary to identify, preserve and correct the *Fehler* (errors) that he found in Neri and Merret, a strategy that Sven Dupré calls the "codification of error."[3] Kunckel was keen on stressing that everything presented in the *Ars Vitraria Exerperimentalis* was vetted through experience.[4] This raises the question of how Neri's rosichiero recipes held up against the scrutiny of Kunckel's tests. This article

1 Elaine Leong, *Recipes and Everyday Knowledge: Medicine, Science, and the Household in Early Modern England* (Chicago: University of Chicago Press, 2018); Jenny Boulboullé, "Drawn up by a Learned Physician from the Mouths of Artisans: The *Mayerne Manuscript* Revisited," *Netherlands Yearbook for History of Art / Nederlands Kunsthistorisch Jaarboek* 68 (2019): 204–49; Pamela H. Smith, "Why Write a Book? From Lived Experience to the Written Word in Early Modern Europe," *Bulletin of the German Historical Institute* 47 (2010): 25–50; Sylvie Neven, "Transmission of Alchemical and Artisanal Knowledge in German Mediaeval and Premodern Recipe Books," in *Laboratories of Art: Alchemy and Art Technology from Antiquity to the 18th Century*, ed. Sven Dupré (Cham: Springer, 2014), 23–51.

2 Johann Kunckel, *Ars Vitraria Experimentalis, Oder Vollkommene Glasmacher-Kunst* (Franckfurt und Leipzig, 1679). All translations are ours unless otherwise indicated. All transcriptions of Kunckel's *Ars Vitraria* were obtained from the Deutches Textarchiv: http://www.deutschestextarchiv.de/kunckel_glasmacher_1679 (accessed 3 December 2019).

3 Sven Dupré, "Doing It Wrong: The Translation of Artisanal Knowledge and the Codification of Error," in *The Structures of Practical Knowledge*, ed. Matteo Valleriani (Cham, 2017), 167–88.

4 Kunckel, *Ars Vitraria*, Vorrede, n.p.

complicates the interpretation of Kunckel's commentaries and annotations as unequivocal corrections and improvements. We show that Kunckel's commentary is surprisingly ambivalent despite its strong empirical rhetoric, and this serves as an important refinement of our understanding of the codification of error. As we will see, Kunckel's discussion of Neri's recipes is significantly inaccurate at times, and it seems unlikely that Kunckel actually tested Neri's rosichiero recipes. Nevertheless, Kunckel also used his commentary to share knowledge that was unarticulated in Neri's recipes. He showed his readers the mechanisms by which colour is achieved, thus deepening their understanding of the glassmaking process and allowing them to adapt the recipes to their own needs.

Gaining a thorough understanding of the materials and furnaces involved in the making of glass colours is pivotal to assessing the textual technologies by which they were communicated. To this end, we reworked the rosichiero recipes in a collaborative settings, involving glass conservators, historians of science, technology, and art, as well as experimental archaeologists.[5] Reproductions of the glass were made at the glass studios of the VICARTE research unit in Lisbon (Portugal). VICARTE is well equipped for the scientific study of glass and has state-of-the-art facilities for the production of glass, such as electric kilns. Materials and ingredients were prepared, specifically with an eye towards their historicity, in Lawrence M. Principe's alchemy-oriented laboratory at Johns Hopkins University, Baltimore (USA). We discuss the preparation of one ingredient in particular, *crocus martis*, which plays a crucial role in the production of rosichiero glass, and show how different preparations of this ingredient were understood to cause variations in the final colour. Finally, to understand the role of fire and furnaces, we reproduced the rosichiero glass in two different wood-fired furnaces, one at a ceramics workshop in Montemor-o-Novo (Portugal) and one at the glass workshop of the Roman Villa Borg (Germany).

2. Rosichiero glass: objects, recipes and commentaries

Rosichiero, or *rouge clair* in French, is a type of transparent red glass that was mainly used for enamelling. One example of a historical object that contains this type of enamel is a pendant cross from the sixteenth century that features a translucent red enamel applied on gold (See Figure 1). A key characteristic of rosichiero glass is that it is coloured with copper-oxide. Moreover, it can be distinguished from other types of red glass, most notably gold ruby glass (which is coloured with gold colloidal particles), sanguine (which is a glass paint in which iron-oxides are responsible for the colour), or aventurine glass (which contains small crystals of

[5] For recent discussions of the 'Re-'Method, see Sven Dupré et al. eds., *Reconstruction, Replication and Re-Enactment in the Humanities and Social Sciences* (Amsterdam: Amsterdam University Press, 2020); Thijs Hagendijk, "Learning by Doing: A Methodological Reflection," in "Reworking Recipes: Reading and Writing Practical Texts in the Early Modern Arts," (PhD Diss., Utrecht University, 2020); "Rethinking Performative Methods in the History of Science," ed. Marieke M. A. Hendriksen, special issue, *Berichte Zur Wissenschaftsgeschichte* 43 (Autumn 2020); Sven Dupré and Jenny Boulboullé, "How Site Matters to Reworking with Makers," in *Burgundian Black*, ed. Jenny Boulboullé and Sven Dupré (Santa Barbara: EMC Imprint), forthcoming.

FIGURE 1 Pendant cross (back). Gold, partly enamelled. Northern European, 16th Century. (The Metropolitan Museum of Art, New York. Bequest of Michael Friedsam, 1931.) The red enamels bear similar characteristics to the rosichiero glasses described in Kunckel's *Ars Vitraria Experimentalis*. Photo: The Metropolitan Museum of Art, New York.

copper that suggest a sparkling gold effect).[6] Rosichiero enamels are mentioned in various sources from the beginning of the sixteenth century onwards, including Neri's *L'Arte Vetraria* (1612).[7]

6 Dedo von Kerrsenbrock-Krosigk, *Rubinglas des ausgehenden 17. und des 18. Jahrhunderts* (Mainz: Verlag Phillip von Zabern, 2001); Ângela Santos and Márcia Vilarigues, "*Sanguine* Paint: Production, Characterization, and Adhesion to the Glass Substrate," *Studies in Conservation* 64 (2019): 221–39; Marco Verità and Sandro Zecchin, "Scientific Investigations of a Venetian Polychrome Goblet of the 16th Century," *Journal of Glass Studies* 50 (2008), 105–115. Historical recipes for red glass have also been studied by the Making and Knowing Project, see for instance: Kathryn Kremnitzer and Pamela H. Smith, "Imitation Rubies and Failure," in *Secrets of Craft and Nature in Renaissance France: A Digital Critical Edition and English Translation of BnF Ms. Fr. 640*, ed. Making and Knowing Project et al. (New York: Making and Knowing Project, 2020), https://edition640.makingandknowing.org/#/search/annotation/ann_082_fa_15 (accessed 18 May 2020).

7 See specifically the section on "rosechiero, vetro rosso al rame" in Cesare Moretti and Tullio Toninato, *Ricette vetrarie del Rinascimento: Trascrizione da un manoscritto anonimo veneziano* (Venezia: Marsilio Editori, 2001), 40–2.

Antonio Neri was a Florentine glassmaker and alchemist.[8] His book *L'Arte Vetraria* lists 133 chapters (recipes) and deals with, among other things, colourless crystal, coloured glass, chalcedony glass, lead glass, artificial gemstones and enamels. Neri also included four recipes for rosichiero glass (chapters 124, 125, 127 and 128), the creation of which, according to Neri, is an art "much concealed" and only known to few people.[9] It has repeatedly been suggested that Neri copied the recipes from circulating manuscripts, such as an anonymous Venetian recipe collection from 1560 or the Montpellier manuscript *Recette per far vetri colorati et smalti d'ogni sort havuto in Murano* from 1536, which indeed contain several recipes for rosichiero glass.[10] The precise relationship between Neri's rosichiero recipes and those that circulated in the manuscripts remains an open question, but at least one important observation should be made at this point: it is doubtful whether Neri fully tested or critically assessed the rosichiero recipes before writing them down. It has been argued that his recipes contained errors similar to those in the manuscript sources, suggesting that they were not noticed or resolved by Neri.[11] Reworking the recipes indeed confirmed this idea, especially when we encountered serious problems in chapters 124 and 127. A crucial exception was chapter 128, which gave the best results and was indeed the only one that had explicitly been marked "proven" – Neri claimed to have successfully used it in Pisa many times.

After Neri published *L'Arte Vetraria*, the rosichiero recipes became subject to commentaries and further annotations, much like the rest of the book. Fifty years later, in 1662, an English edition was published by Christopher Merret. As a physician and founding member of the Royal Society in London, Merret valued Neri's work for its useful knowledge and experimental qualities, and positioned it directly into Francis Bacon's (1561–1626) programme of the "promotion of arts and sciences."[12] Not only did Merret publish a translation, he expanded the book by including new chapters and *observations* on Neri's recipes. The harvest with respect to rosichiero was somewhat meagre, nonetheless. Merret's observations were confined to a full quotation of a recipe for "a fair red rosichiero" or *rosa clerum* that he had found in Della Porta.[13] The recipe from Della Porta differs significantly from

[8] Sven Dupré, "The Value of Glass and the Translation of Artisanal Knowledge in Early Modern Antwerp," *Netherlands Yearbook for History of Art / Nederlands Kunsthistorisch Jaarboek* 64 (2014), 138–61; M. G. Grazzini, "*Discorso sopra la Chimica*: The Paracelsian Philosphy of Antonio Neri," *Nuncius* 27 (2012): 411–67; Marco Beretta, "Glassmaking Goes Public: The Cultural Background to Antonio Neri's *L'Arte Vetraria* (1612)," *Technology and Culture* 58 (2017): 1046–70.

[9] Antonio Neri, *L'Arte vetraria distinta in libri sette* (Firenze: 1612), 93–4.

[10] Moretti and Toninato, *Ricette vetrarie*, 79–80, and the "saggio introduttivo." L. Zecchin, "Le ricette vetrarie di Montpellier," in *Vetro e Vetrai di Murano*, 3 vols. (Venezia: Arsenala editrice, 1987), vol. 1.

[11] We would like to thank Jo Wheeler for sharing his insights. Moreover, see: Zecchin, "Le ricette vetrarie," 251.

[12] Christopher Merret, *The Art of Glass, Wherein Are shown the Wayes to Make and Colour Glass, Pastes, Enamels, Lakes, and other Curiosities* (London, 1662), 205–6; Albert J. Koinm, "Christopher Merret's Use of Experiment," *Notes and Records of the Royal Society of London* 54 (2000): 23–32; Guido Giglioni, "From the woods of experience to the open fields of metaphysics. Bacon's notion of *silva*," *Renaissance Studies* 28 (2014): 242–61; Dupré, "Doing It Wrong."

[13] Merret, *The Art of Glass*, 350.

the ones provided by Neri.[14] Whether Merret tested the rosichiero recipes, Neri's or Della Porta's, remains unclear. In general, however, his inclusion of observations was something that Kunckel would adopt and further develop in his German edition. The comments on rosichiero too, were greatly expanded in Kunckel's hands.

When Kunckel published the *Ars Vitraria Experimentalis, Oder Vollkommene Glasmacher-Kunst* (1679), the book had more than quadrupled in size compared with Neri's original. Moreover, whereas Merret devoted a significant portion of his observations to an anthology of things read in other sources, the focus in Kunckel's observations was on his personal experience as a glassmaker and chymist – experience that he had gained in the years leading up to the *Ars Vitraria Experimentalis*. In this book, Kunckel presented a German translation of Neri's recipes, which he augmented with his commentaries. He also provided a German translation of Merret's observations and elaborately discussed those too.

Johann Kunckel was raised in a family of glassmakers, trained as an apothecary, and was employed as a chymist, first in the service of the Duke of Sachsen-Lauenburg and later at the Dresden court.[15] Kunckel began to publish chymical treatises from 1676 onwards (among other things, dealing with Hennig Brand's recently discovered phosphorus) and moved to Berlin where he was introduced to the Elector of Brandenburg, Friedrich Wilhelm (1620–1688). The Elector appointed Kunckel to oversee the glassworks in Potsdam from 1678 onwards. Here, Kunckel wrote and published the *Ars Vitraria Experimentalis* (1679), and began to experiment with and succeeded in the production of gold ruby glass, an achievement that brought him fame.[16] In 1685, the Elector offered Kunckel an island, the Pfaueninsel, on which to build his own glassworks and laboratory. Archaeological excavations have revealed parts of its foundations, including shards of gold ruby glass.[17] Later in life, Kunckel continued to write books on chymistry, including the comprehensive and posthumously published *Laboratorium Chymicum* (1716).[18]

In sum, Kunckel was as experienced a glassmaker as he was a chymist, and equally versed in artisanal and scholarly cultures. Following Ursula Klein, he can be characterised as a hybrid expert, someone who connected the artisanal and scholarly world, which perhaps best speaks through the way he organised the *Ars Vitraria*

[14] It specifically lacks iron oxide as an ingredient and additionally introduces the mineral cinnabar (HgS).

[15] Ulrich Triotzsch, "Kunckel von Löwenstern, Johann," in *Neue Deutsche Biographie* 13 (Bayerischen Akademie der Wissenschaften, 1982; online ed. 2010), https://www.deutsche-biographie.de/pnd11872536X.html; Hans-Joachim Kruse, "Johann Kunckel. Der bedeutendste Plöner?" *Jahrbuch für Heimatkunde im Kreis Plön* 42 (2012): 89–150.

[16] Von Kerrsenbrock-Krosigk, *Rubinglas*.

[17] Günter Rau, "Das Glaslaboratorium des Johann Kunckel auf der Pfaueninsel in Berlin: Ergebnisse der Probegrabung 1972," in *Ausgrabungen in Berlin* 3 (1972): 148–71; Günter Rau, "Johann Kunckel, Geheimer Kammerdiener des Großen Kurfürsten, und sein Glaslaboratium auf der Pfaueninsel in Berlin," *Medizinhistorisches Journal* 2 (1976): 129–48; Gerhard Schulze, "Kunckels Glaslaboratorium auf der Pfaueninsel: Bericht über chemische Untersuchungen an einigen Fundobjekten," *Medizinhistorisches Journal* 2 (1976): 149–56.

[18] We use the term 'chymistry' in accordance with William R. Newman and Lawrence M. Principe, "Alchemy vs. Chemistry: The Etymological Origins of a Historiographical Mistake," *Early Science and Medicine*, 3 (1998): 32–65.

Experimentalis.[19] Kunckel presented his take on Neri's glass recipes using learned formats. What Kunckel called *Anmerckungen* was in fact a humanist epistemic genre that bears obvious connections to the commentary tradition found in natural philosophy.[20] Kunckel was familiar with these learned formats and did not hesitate to use them to organise practical knowledge.

Additionally, Kunckel also applied the strategy of the "codification of error."[21] Reworking two rosichiero recipes in particular taught us that Kunckel's comments should not be interpreted as straightforward corrections of Neri's recipes. His commentary remained suspiciously silent where we identified a substantial error during our reworking of chapter 124. Reproduction of the rosichiero glass using the ratios mentioned in this recipe resulted in an almost black colour. The only way to resolve this issue was by substantially "diluting" all ingredients against the original amount of crystal frit, the glass base. Only then, while keeping the rest of the procedure the same, did the glass become a red, albeit opaque, colour. While our findings fully agree with previous assertions that Neri's rosichiero recipes are erroneous in nature, the question remains whether Kunckel spotted this issue too; and if so, why did he not make the effort to set the record straight in his commentary?[22]

Another issue arose during the reproduction of rosichiero from chapter 125, which involved a special ingredient. According to Neri's recipe, "fixed sulfur" should be added to the glass in addition to the other ingredients. Kunckel, however, countered Neri's recommendation in his commentary and argued that the "fixed Sulphur does not serve any purpose here. It can as easily be left out as well as being added."[23] The reader is left with two contradictory statements. Should Neri's instructions be followed to the letter? Or should we take Kunckel's advice seriously and ignore the additional sulphur? To validate Kunckel's comment we devised a simple experiment in which we reproduced chapter 125 with and without the sulphur. We were surprised to learn that the addition of sulphur was actually essential for the colour of the glass. Without the sulphur, the glass turned green. With the sulphur however, and contrary to Kunckel's assertion, the glass turned red.

Both issues – i.e. Kunckel's apparent unawareness concerning the ratios in chapter 124 and his ill-advised characterisation of the sulphur in chapter 125 – render it unlikely that he actually tried these rosichiero recipes before writing his commentaries. This also throws new light on the codification of error as a textual strategy. Kunckel's stated ambition to correct the failures with respect to Neri in the *Ars Vitraria Experimentalis* did not necessarily correspond to what he actually pulled off in

[19] Ursula Klein, "Introduction: Artisanal-scientific Experts in Eighteenth-Century France and German," special issue, *Annals of Science* 69 (2012): 303–6; Ursula Klein, "Chemical Experts at the Royal Prussian Porcelain Manufactory," *Ambix* 60 (2013): 99–121.

[20] Dupré, "Doing It Wrong." On epistemic genres and observations as a learned format, see Gianna Pomata, "Sharing Cases: The *Observations* in Early Modern Medicine," *Early Science and Medicine*, 15 (2010): 193–236.

[21] Dupré, "Doing It Wrong."

[22] Zecchin, "Le ricette vetrarie."

[23] Kunckel, *Ars Vitraria*, 192.

his commentary. It reveals the codification of error as a rhetorical strategy, a poetics of failure, as Dupré has argued elsewhere, to cope with the imperfections of knowledge-making, and to make weak knowledge stronger.[24] This strategy allowed Kunckel to promote himself as an authority and expert at the Brandenburg court, and it is in this regard telling that the errors which Kunckel identified are those of others, not his own. This narrative strategy of attribution of errors to others, predecessors or workers of perceived lower epistemic status, was widely used at the time in artisanal writings, and it differentiates these writings from manuals, which typically fully embrace a poetics of failure by codifying one's own errors instead of those of others.

In addition to the codification of error, Kunckel also used another strategy by providing cardinal directions on the preparation and variability of ingredients and on fire management and tempo in glass colouring, as we show in this article.

3. Ingredients and the quest for perfect rust

The key ingredients in the preparation of rosichiero glass, according to the recipes Kunckel translated from Neri, are:[25]

(1) *Crystal frit*. The first step in all recipes is to produce a colourless glass that serves as the basis for the final glass composition. Chapter 124 provides the procedure in full, which is omitted in subsequent recipes that refer back to this chapter instead. The crystal frit is made from "white and finely powdered Tarso" (quartz), which is combined with the "salt from the Levantine powder" (Na_2CO_3) and calcined in a furnace.

(2) *Calx of lead and tin*. The calx possibly functions on two levels. It renders the glass opaque, and likely functions as a reducing agent necessary to bring out the final colour.[26] The author refers to another chapter (93) to explain how this ingredient should be prepared. Pieces of lead and tin are melted together to form an alloy and calcined until the alloy oxidises and a yellow substance is formed.

(3) *Cream of tartar* (*Weinstein*). The role of this ingredient is not fully understood, but it likely contributes to the strong reducing conditions necessary to obtain the red glass. Chapter 128 calls in addition for "chimney soot" which presumably serves as a reducing agent too.[27]

[24] Sven Dupré, "Failure and the Imperfections of Artisanal Knowledge in the Early Modern Period," in *Weak Knowledge: Forms, Functions, and Dynamics*, ed. Moritz Epple, Annette Imhausen, and Falk Müller (Frankfurt/New York: Campus Verlag, 2019), 163–78.

[25] For general overviews of glass ingredients and compositions, see Sandra Davison, *Conservation and Restoration of Glass*, 2nd ed. (Oxford: Butterworth Heinemann, 2003); Julian Henderson, *Ancient Glass: An Interdisciplinary Exploration* (Cambridge: Cambridge University Press, 2013); W. A. Weyl, *Coloured Glasses* (Sheffield: Society of Glass Technology, 1951); Werner Vogel, *Glass Chemistry*, 2nd ed. (Heidelberg: Springer Verlag, 1994).

[26] Mario Bandiera, Patrice Lehuédé, Marco Verità, Luis Alves, Isabelle Biron and Márcia Vilarigues, "Nanotechnology in Roman Opaque Red Glass from the 2nd Century AD: Archaeometric Investigations in Red Sectilia from the Decoration of the Lucius Verus Villa in Rome," *Heritage* 2 (2019): 2597–611; Davison, *Conservation and Restoration*, 77–8.

[27] Vogel, *Glass Chemistry*, 247.

(4) *Calcined red copper* ("Hammerschlag").[28] This copper(II) oxide (CuO) is responsible for the red colour of the glass. To bring out the red colour, a fundamentally important chemical reaction needs to take place first. The presence of Cu^{2+} would lead to a turquoise-blue glass instead of the red that is wanted in rosichiero glass. To generate the red glass, strong reducing conditions are necessary that lead to the reduction of copper and to its subsequent precipitation in the glass, either as cuprous oxide (Cu_2O, composed of Cu^+) or as metallic copper (Cu°). When the precipitated particles are of the right size and concentration, a light-scattering effect occurs that gives rise to the red colour.[29] Strong reducing conditions can be achieved by decreasing the amount of oxygen in the furnace atmosphere, or by using specific ingredients that act as reducing agents in the glass, like the mentioned lead-tin calx, but a fourth ingredient, *crocus martis*, is added for this purpose as well.

(5) *Crocus martis* or *bloodstone*. Rosichiero glass requires the addition of iron(III) oxide (Fe_2O_3). While the aforementioned copper particles are directly responsible for the red colour of the glass, this colour only appears if copper is combined with the iron(III) oxide that acts as the reducing agent for the copper particles.[30] The chemical mechanism behind this effect is complicated – iron(III) oxide needs to be reduced itself before it can reduce the copper ions – but empirical evidence is nonetheless clear. We failed to reproduce the only rosichiero recipe (127) that does not involve iron oxide as an ingredient. In sum: no iron, no red.

Because of the crucial role of iron(III) oxide (Fe_2O_3) in the production of rosichiero glass, we will elaborately discuss this ingredient as an example of Kunckel's use of providing cardinal directions for the preparation of ingredients.

Even though iron(III) oxide is a modern chemical name and not an historical term, it is precisely in the contrast between a modern chemical perspective and a seventeenth-century outlook that interesting questions arise. Early modern understanding of iron(III) oxide was complex and much refined, which is also reflected in the *Ars Vitraria Experimentalis*. Indeed, while iron(III) oxide does not differ from ordinary rust, early modern authors show us that we should not be deceived by the humble appearance of this substance. Glassmakers like Neri and Kunckel differentiated between various types of iron(III) oxide, depending on the way it was prepared or obtained as a sourced mineral. In that respect, the early modern attitude toward this substance diverges from a modern outlook, in which distinctions based on the method of preparation might appear redundant rather than useful. By contrast, each rosichiero recipe in the *Ars Vitraria Experimentalis* stipulates a different

[28] The adjective *red* might refer to copper proper in contrast with yellow copper (brass) and does not necessarily indicate the colour of the oxide.

[29] For an overview and discussion of secondary literature, see Mario Bandiera *et al.*, "Nanotechnology in Roman Opaque Red Glass," 2598; Robert H. Brill and Nicholas D. Cahill, "A Red Opaque Glass From Sardis and Some Thoughts on Red Opaques in General," *The Journal of Glass Studies* 30 (1988): 16–27; Weyl, *Coloured Glasses*, 154 et seq.

[30] Mario Bandiera *et al.*, "Nanotechnology in Roman Opaque Red Glass."

variety of iron(III) oxide. Chapter 125, for instance, prescribes *bloodstone* (hematite) which is a mineral that can be readily sourced from nature. Chapters 124 and 128 each employ a different type of *crocus martis* ("saffron of iron"), which is an artificially manufactured iron(III) oxide. A burning question is why these different origins and preparations of iron(III) oxide mattered to Kunckel and Neri. Why do the rosichiero recipes stipulate different varieties of an ingredient that appears to be chemically similar?

In total, the *Ars Vitraria Experimentalis* differentiates five types of *crocus martis*. Each of them has its own recipe that explains how to manipulate iron or steel filings to produce it. For example, the filings can be calcined in the presence of sulphur (chapter 16), or treated with vinegar (17), *aqua fortis* (18), or *aqua regia* (19). As well as these four recipes, Kunckel's commentary contains an additional procedure for *crocus martis* in which the filings are calcined without using any auxiliary substance. Not only is *crocus martis* needed for the rosichiero glass, other types of glass require it too, such as chalcedony glass, a black glaze and a variety of green glasses.

It is specifically in the context of green glass that Kunckel reveals how different *croci* can shape, steer, and affect its final colour and shade. While commenting on the recipes that Neri presented for green glass, Kunckel mentions how struck he was by "all sorts of beautiful and almost uncommon green colours" and continues with a discussion of *crocus martis* which is worth quoting in full:

> Such manifold Variations, however, consist simply and only in the Difference and Preparation of the applied Iron Powders, called *Crocus Martis*: depending on its preparation and Application, one can have Green as one pleases, because another Art or Colour originates when the Iron Powder is prepared with Vinegar, and another when prepared with Sulphur, and yet another when it is prepared by itself. Then – through the Combination of burnt Copper and the Saffron of Iron or prepared Iron Powder – all Distinct green Colours are brought about. Even though the Copper and the similarly applied *Hammerschlag* all give Green, its manifold Variations depend simply and solely on the Iron Powder, namely, on the way it is prepared and applied.[31]

For Kunckel, it is beyond dispute that various preparations and origins of *crocus martis* should be reckoned with in glassmaking practices. He deems *crocus martis* the key ingredient responsible for shifting the green colour in the glass. It is worth pointing out that glassmaking was not the only field in which different preparatory trajectories of *crocus martis* were held responsible for different effects. In his posthumously published *Laboratorium Chymicum*, Kunckel addresses the medicinal context, in which "many different Croci are being made and called by various Names."[32] Indeed, open a random contemporary (iatro)chymical textbook and chances are that one finds an assortment of *croci* that was prescribed and

[31] Kunckel, *Ars Vitraria*, 64–5.

[32] Johann Kunkel von Löwensterns, *Collegium Physico-Chymicum Experimentale. Oder Laboratorium Chymicum* (Hamburg/Leipzig, 1716), 366.

administered to remedy a range of symptoms and diseases.[33] How the *crocus martis* was prepared determined the type of illness it could treat. One could, for instance, distinguish between *crocus martis aperitivius*, which is prepared with sulphur and serves to "open up and attenuate," and *crocus martis obstructivus*, which is produced in a reverberatory fire and should be administered to relieve someone from dysentery, diarrhoea or gonorrhoea.[34] In sum, the idea that *crocus martis* can be prepared differently to suit distinct purposes had wider currency. But how exactly are the *croci* different from each other? Apart from experimentally demonstrable differences, Kunckel also offers some philosophical reflection when he suggests – in otherwise demanding alchemical language – that each *crocus martis* is a particular reorganisation of the different parts that are already present in iron as a metal. Reorganising these parts is done through a series of "separations and purifications that should not be neglected."[35] *Crocus martis* prepared with vinegar, for instance, leaves the *spiritus tingens* of iron intact, a fragile combination of the principle *mercury* and a *fixed salt*, that is lost as soon as one calcines the *crocus martis* in the presence of sulphur. Even without offering a satisfying interpretation of Kunckel's alchemical thinking, one can see how this reasoning creates the possibility of related but subtly different *croci*.

The way in which Kunckel read and dealt with Neri's recipes for green glass contains an implicit message, one in which Kunckel opens the door for intra-recipe experimentation. Kunckel, as he does in other places, lets go of the individual recipe and starts to look for the one thing that the recipes for green glass have in common as a group. In other words, he seeks precisely that thing that explains why the variations between these recipes exist in the first place and takes that as his point of departure. A consequence of this approach is that Kunckel's reading is not geared towards the identification of the best recipe out there. Rather, he emancipates his readers and encourages them to find out what works best for them. He points his readers towards the one tool they need in order to arrive at the colour "as they please," which is found in the preparation of *crocus martis*.

It is important to realise that both Neri and Kunckel lived and wrote in a non-standardised colour-world. (The earliest systematic attempts to codify and systematise colours date to the eighteenth century).[36] Getting the right colours in glassmaking was first of all a matter of experience, training, and judgment.[37] Neri explains, for instance, a rigorous procedure of repeatedly adding minute quantities of colouring agents to the glass batch while closely monitoring how the colour of the glass

33 Nicolas Lemery, *Cours de Chymie*, 5th ed. (Paris, 1683), 146–157; Pierre Thibaut, *Cours de Chymie* (Leyde, 1672), 406–7.

34 Steven Blankaart, *Theatrum chimicum, Ofte geopende deure der Chymische Verborgntheden Ontsloten* (Amsterdam, 1693), 73–4.

35 Kunkel, *Collegium Physico-Chymicum*, 367.

36 Friedrich Steinle, "Colour Knowledge in the Eighteenth Century: Practice, Systematisation, and Natural Philosophy," in *Colour Histories: Science, Art, and Technology in the 17th and 18th Centuries*, ed. Magdalena Bushart and Friedrich Steinle (Berlin/Boston: De Gruyter, 2015), 43–65.

37 Sven Dupré, "The Role of Judgment in the Making of Glass Colors in the Seventeenth Century," *Ferrum* 90 (2018): 8–17.

changes as a result. "This is the way to add all the colours, because this way you will never fail."[38] Rather than relying on exact measurement, Neri relies on experience: "Be warned in particular to give careful consideration to the colours for which exact and determined amounts cannot be given. Indeed, with experience and due practice learn, and with the eye and judgement know, when a glass is coloured sufficiently and appropriately for the work at hand."[39] The required amounts of colouring agents are usually small, thus increasing the likelihood of a mistake, while the final colour of the glass also depends on furnace conditions, crucibles' geometry, temperatures, and timing.[40] Neri knew that colours were difficult to communicate in text, a problem for which even the quantification in terms of weights and dose did not provide an immediate solution. Instead, he reminds his readers to rely on their own eyes and judgment. But Kunckel takes it one step further. What is good judgement worth if you do not know how to manipulate the colour in the first place? In his commentary on green glass, he does not identify his favourite green colour, but discloses the means by which the green colours are created, directed, and shaped. In a non-standardised colour-world, one needed the key that gives access to colour enhancement and variation, such that one could optimise it for oneself, based on judgement and experience.

So much for *crocus martis* in recipes for green glass. But what about the rosichiero recipes? The presence of three differently prepared iron(III) oxides in the rosichiero recipes enticed us to conduct an experiment that was very similar to the one that Kunckel performed on green glass. We wanted to see how different preparation methods of *crocus martis* would shape the final colour of rosichiero glass. To do so, we first had to follow the different instructions for *crocus martis* provided in the *Ars Vitraria Experimentalis*. For that purpose, we worked together with Lawrence M. Principe in Baltimore (USA) to investigate and rework the five recipes presented in the book. What we found were five *croci* with five very distinct colours (See Figure 2).

(1) *Crocus martis prepared with sulphur.*[41] Chapter 16 describes how alternate layers of steel-filings and sulphur must be placed in a crucible and calcined. We did so accordingly and found a grey-purplish structure that was reminiscent of broccoli. This was followed by reheating. After an observed colour change, the product was ground and sieved (125μm). This *crocus martis* had a deep maroon colour.
(2) *Crocus martis prepared with vinegar*.[42] Chapter 17 instructs to repeatedly moisten steel filings with "a good and strong vinegar." The colour of the

[38] Antoni Neri in Paul Engle, *The Art of Glass by Antonio Neri*, 3 vols. (Hubbardston: Heiden & Engle, 2003–2007), vol. 3, 25.
[39] Neri in Engle, *The Art of Glass*, vol. 1, 7.
[40] Henderson, *Ancient Glass*, 66–67; Dupré, "The Role of Judgment." Anne-Isabelle Bidegaray, Stéphane Godet, Michel Bogaerts, Peter Cosyns, Karin Nys, Herman Terryn, Andrea Ceglia, "To be Purple or not to be Purple? How Different Production Parameters influence Colour and Redox in Manganese Containing Glass," *Journal of Archaeological Science: Reports* 27 (2019): 101975. See also Section 4, "The Fire and the Furnace."
[41] Kunckel, *Ars Vitraria*, 27–8.
[42] Kunckel, *Ars Vitraria*, 28.

FIGURE 2 An overview of the five different *crocus martis*. Top row, from left to right: *crocus martis* prepared with sulphur (chapter 16); *crocus martis* prepared with vinegar (chapter 17); *crocus martis* prepared with *aqua fortis* (chapter 18), and *crocus martis* prepared with *aqua regia* (chapter 19). Below: the *crocus martis* prepared without additives, as described by Kunckel in his commentary. Photo: ARTECHNE/VICARTE.

filings changed during the process, starting as purplish but soon turning into a brown slurry upon remoistening. As described by the recipe, the filings pulled together "in lumps." After grinding and sieving, we obtained a *crocus martis* with a rusty brown colour, or a colour like "brick dust," as mentioned by the recipe.

(3) *Crocus martis prepared with aqua fortis*.[43] Chapter 18 involves nitric acid, which must be sprinkled on a batch of steel filings. We proceeded carefully; each drop of *aqua fortis* reacted vehemently with the filings, releasing brown clouds of nitrogen dioxide. Having repeated the procedure twice, the product was ground and sieved. This *crocus martis* had a dark brown colour.

(4) *Crcocus martis prepared with aqua regia*.[44] Chapter 19 presents perhaps the most intriguing way to prepare *crocus martis* – it involves *aqua regia*, an acid known for its ability to dissolve gold.[45] It should not come as a surprise that Neri earmarks it as "perhaps the best Art of all," even though he immediately assures that the other preparations should not be dismissed. The *aqua regia* was prepared and the steel filings were added to the liquid, which immediately dissolved while releasing brown fumes, similar to the *aqua fortis* procedure. After the reaction stopped, the solution was heated to promote evaporation.

43 Kunckel, *Ars Vitraria*, 28–9.

44 Kunckel, *Ars Vitraria*, 29.

45 The *aqua regia* was prepared by dissolving 4 grams of sal ammoniac (NH_4Cl) in 32 grams of nitric acid (HNO_3).

During heating, the remaining product turned from brown to black and finally to a red colour. The *crocus martis* was ground and sieved, and revealed an intensely deep red colour, unlike the other *croci*.

(5) *Crocus martis without additions*.[46] Next to Neri's four recipes, Kunckel gave one too in his commentary, arguing that this variety is "even more perfect." It is prepared by calcining steel filings *without* any additions, after which "the Iron will swell on high as an extraordinary beautiful red and black powder." When trying the procedure in Baltimore, nothing of the sort happened. The filings simply turned black in the crucible. We did not observe a red colour, nor did the filings swell as Kunckel described. Indeed, some of the clarity or transparency that characterise Neri's recipes – our reworkings matched the descriptions in the text – seem to be missing in Kunckel's commentary, which is a little cryptic at times. He appears to withhold information, which he admits in the very last passage of his commentary, suggesting, for instance, that his *crocus martis* "surely serves for more than I care to mention here."[47]

The five different procedures result in five different *croci*. We were struck not only by the wide range of colours that the final *croci* possessed, but also by the deep red colour that some of them exhibited. The *crocus martis* were shipped to Portugal where we used them to reproduce rosichiero recipe 128. The experiment was set up in a way that allowed us to compare the relative influence of each *crocus martis* on the colour of the glass. For that purpose, we prepared five samples of recipe 128. One sample contained the *crocus martis* that was originally prescribed by the recipe (prepared with sulphur). In the other four samples, the originally prescribed variety of *crocus martis* was substituted for the other varieties (prepared with vinegar, *aqua fortis*, *aqua regia* and without additives). All the other ingredients were kept the same, and all samples were collectively melted in the same wood-fired furnace, thus ensuring similar conditions (We used the wood-fired furnace in Montemor-o-Novo – see Section 4 below). Having manufactured the rosichiero glass with the different *croci*, we found that each variety was responsible for a different shade of red in the glass. (See Figure 3, more extensively discussed in Section 4). How these colour differences arise as a result of differently prepared *crocus martis* remains unknown. It is possible that chemical impurities, diverging particle sizes or subtle morphological differences of the *crocus martis* play a role in these processes.[48] Be that as it may, our results underscore the practical relevance of describing different preparation methods for ingredients, which is precisely the point that Kunckel tried to make in his commentary. He communicates experiential knowledge, not by picking out and recommending one type of *crocus martis*, but by encouraging readers to experiment with the different *croci* as a group.

46 Kunckel, *Ars Vitraria*, 60.
47 Kunckel, *Ars Vitraria*, 61.
48 R. M. Cornell and U. Schwertmann, *The Iron Oxides* (Weinheim: VCH Verlagsgesellschaft, 1996).

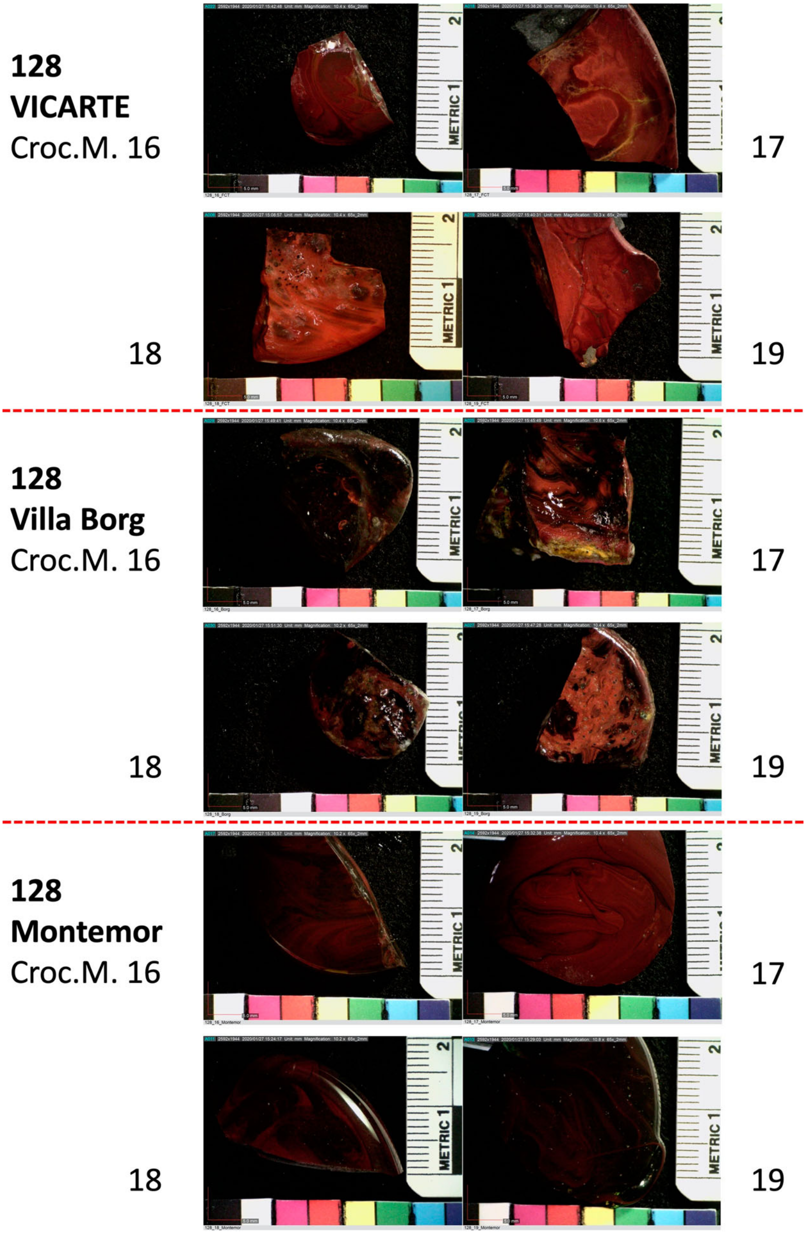

FIGURE 3 Overview of reproductions of rosichiero glass based on recipe 128 using three different furnaces and four different *crocus martis* (chapters 16–19). Note the differences in composition (due to furnace conditions) and colour shade (due to *crocus martis*). Photos: Élia Roldão.

4. The fire and the furnace

One other important factor in the production of glass colours is the furnace. How did different furnaces and furnace conditions shape the consistency and composition of the glass? We used four different furnaces to reproduce the rosichiero glass. The first two were electric kilns at the VICARTE glass studios in Lisbon. The other two were wood-fired furnaces in Montemor-o-Novo (Portugal) and the Roman Villa Borg (Germany). The furnace in Montemor-o-Novo is designed vertically and is used to fire ceramics. It has two fire holes near the ground which end up in the main chamber on top that contains the crucibles. The heat and flames are reflected back by the ceiling and go down again, touching the crucibles, and leave the chamber through the chimney-opening at the bottom in the back. During our reproductions, we had to adjust the furnace to reach higher temperatures, to which end the chimney was extended by approximately two meters. The furnace at Villa Borg is distinctly different from the one at Montemor-o-Novo. It is a reconstructed Roman glass furnace, a horizontal model, that was fully raised from cob, a combination of clay and straw.[49] It follows the archetypical design of a reverberatory furnace, in which the low ceiling radiates the heat back onto the crucibles.[50] The fire is stoked at one end and the flames are guided toward a chimney-hole at the other, such that they extend over the crucibles along the way. The crucibles are positioned behind shielded openings at each side of the furnace.

One of the interesting features of wood-fired furnaces is that one is able to play with the amount of oxygen that is present in the chamber, thus enabling oxidising or reducing conditions. For instance, when incomplete combustion takes place, the atmosphere in the furnace will be reducing in the presence of soot and carbon monoxide. Several studies have shown how furnace conditions can shape and enhance the quality and composition of the products that are being fired in the furnace, showing that wood-fired furnaces are more than just a simple source of heat.[51] There are a few sensory indicators that help in recognising a reducing atmosphere in a furnace.[52] For example, in Montemor-o-Novo (Oficinas do Convento) João Rolaça, a Portuguese artist and ceramicist who operated the furnace, told us to pay attention to the smell. An oxidising environment smells "clean," as if one is baking bread. When the smell turns unpleasant, it indicates incomplete combustion. Another way to recognise a reducing atmosphere is to watch the openings and cracks in a furnace. If soot appears on the outside, the atmosphere in the furnace is reducing, and as soon as the black disappears, the furnace is oxidising, meaning that the fire is able to clean away all unburned carbon. Considering all these variables, we expected that different furnaces would affect the glass differently. The electric kilns, in the absence of fire and combustion products, were expected to

49 Bettina Birkenhagen and Frank Wiesenberg, "Der experimentalarchäologische Werkstattbereich im Archäologiepark Römische Villa Borg," in *Experimentelle Archäologie in Europa* 18, ed. Gunter Schöbel (Unteruhldingen, 2019), 245–56.

50 J. E. Rehder, *The Mastery and Uses of Fire in Antiquity* (Montreal: McGill-Queen's University Press, 2000), 42.

51 Lawrence M. Principe, "Chymical Exotica in the Seventeenth Century, or, How to Make the Bologna Stone," *Ambix* 63 (2016): 118–44; Davison, *Conservation and Restoration*, 6–8; Donald Royce-Roll, "The Colors of Romanesque Stained Glass," *Journal of Glass Studies* 36 (1994): 71–80; Henderson, *Ancient Glass*, 65–8; John G. Hawthorne and Cyril Stanley Smith, *Theophilus on Diverse Arts: The Foremost Medieval Treatise on Painting, Glassmaking and Metalwork* (New York: Dover Publications, 1979), 52–7.

52 For sensory indicators: Thijs Hagendijk, "Learning a Craft from Books," *Nuncius* 33 (2018): 198–235.

be more oxidising than the wood-fired furnaces, which would presumably lead to different compositions of the glass. But we were also curious to see whether differences would arise between the wood-fired furnaces themselves, which might perhaps be caused by differences in design.

When we reproduced the rosichiero glass from chapter 128, we found that different furnaces indeed produced different results (See Figure 3). But it was not so much the colour, but rather the composition of the glass that changed with the furnaces. The wood-fired furnaces in particular were so strongly reducing that, throughout the glass, elemental metal was visible to the naked eye. Not only was the copper successfully reduced to produce the red colour, the lead and tin oxides too were reduced to such an extent that they had precipitated out of the glass. The furnace at Villa Borg was especially reducing; the glass we made there was the least homogenous of all and contained a high number of metallic parts (See Figure 4). The glass produced in Montemor-o-Novo contained only minute bits of metal. Unlike with the wood-fired furnaces, the glass produced with the electric kilns was completely homogenous. All in all, our reproductions clearly showed that furnace conditions strongly affect the glass that is produced within. To guarantee the production of a good quality rosichiero glass, these conditions need to be anticipated, controlled, and adjusted, which demands serious skill and practice from the glassmaker.

Working with wood-fired furnaces also acquainted us with the pyrotechnical skills that were fundamental to historical glassmaking practices more generally.

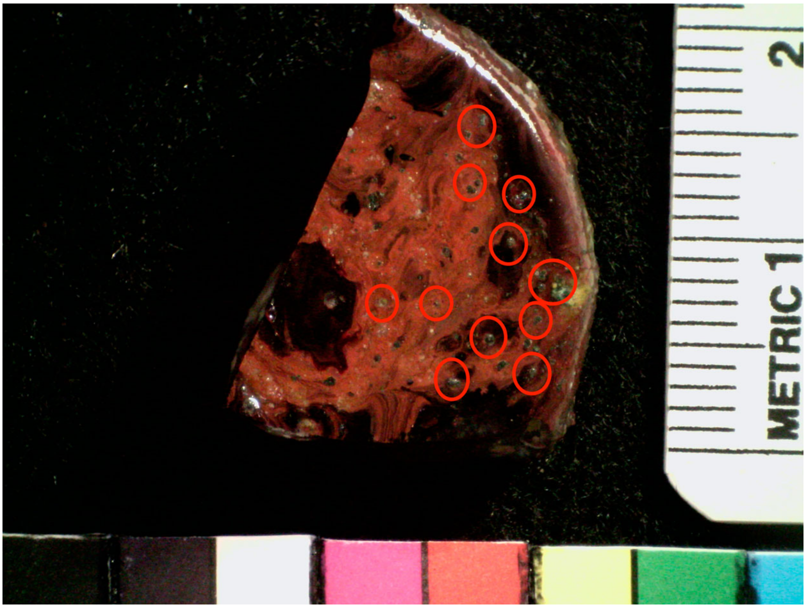

FIGURE 4 The glass produced with the furnace from Villa Borg contained a significant number of metallic parts. This is a close-up of a reproduction of rosichiero glass based on chapter 128, made with *crocus martis* from chapter 19. The red circles indicate examples of reduced metal in the glass. Photo: Élia Roldão.

Stoking a fire, raising the temperature and keeping the temperature steady at a certain level, requires the ability to read and respond to a furnace and its needs. In the seventeenth century some efforts were being made to develop temperature-controlled furnaces, but in general, gauging the temperature of a furnace was done by peeking inside and judging the colour of the fire and the insides of the furnace, which ranges from dark orange for the lower temperatures to brighter yellow for the higher temperatures.[53] However, being able to adequately read the temperature of a furnace is only one aspect of fire management and temperature control. Variations in temperature are caused by wind and weather conditions and the types of fuel used; the temperature of the crucibles also depends on their respective positions in the furnace, and the temperature drops significantly each time a new log of wood is thrown on the fire.[54] It also depends on the design of the furnaces themselves.

Some related variables in furnace management are also explicitly mentioned by Kunckel, Neri and Merret. Kunckel points out, for instance, that German furnaces are generally stoked hotter than those in Italy, because of a relative abundance of wood.[55] This has consequences for how Neri's Italian recipes should be executed in Germany. For example, a recipe for milk-coloured glass, *lattimo*, only needs to stay in the furnace for three days according to Kunckel, instead of the 18 days required by Neri.[56] Neri in turn, warns that one must be careful when using dry hard wood, because the smoke it generates is harmful to the glass that is placed inside the furnace.[57] Merret, in response to Neri's preference for oak, gives an overview of other types of wood that can be used. For example, ash wood creates a "pleasant fire," but it burns quickly.[58]

Moreover, Kunckel describes a specific and versatile furnace that he used for glass tests and experiments (See Figure 5).[59] The furnace contains a fire channel by which its residual heat can be used to feed a smaller furnace for various smaller operations, for instance to calcine or "digest" (dissolve) substances. The furnace shows that Kunckel was in the habit of testing glass, for which he purposefully scaled down the original formulas. He explains that his furnace has the capacity to conduct "twenty tests on a small scale" [*ins kleine*].[60] Indeed, making small tests is a sensible way to limit material costs – e.g. expensive colourants, costly wood for stoking – and to save someone from having to discard big batches of failed and otherwise useless glass.[61] More evidence of Kunckel's use of glass tests was found in archaeological

53 Vera Keller, "Re-entangling the Thermometer: Cornelis Drebbel's Description of his Self-regulating Oven, the Regiment of Fire, and the Early History of Temperature," *Nuncius* 28 (2013): 243–75.
54 E.g. Royce-Roll, "The Colors of Romanesque Stained Glass," 78.
55 Kunckel, *Ars Vitraria*, Vorrede, n.p.
56 Kunckel, *Ars Vitraria*, 100. Dupré, "Doing It Wrong," 184.
57 Neri in Engle, *The Art of Glass*, vol. 1, 8.
58 Merret, *The Art of Glass*, 274–5.
59 Kunckel, *Ars Vitraria*, Pars Secunda, 138–9.
60 Kunckel, *Ars Vitraria*, Vorrede, n.p.
61 E.g. Simon Werrett, *Thrifty Science: Making the Most of Materials in the History of Experiment* (Chicago: University of Chicago Press, 2019).

FIGURE 5 A sketch of Kunckel's compendious furnace that contained several small crucibles used for testing (F). Especially noteworthy is the fire channel (K) that could be used to connect to another and smaller furnace. Photo: Thijs Hagendijk.

excavations of the remains of his glass laboratory on Pfaueninsel, which were carried out in the 1970s. Many small crucibles were discovered that contained glass of various colours, ranging from green to red-brown, including shards of ruby glass.[62]

In sum, reworking the rosichiero recipes taught us that glassmaking is not only about mixing the right ingredients, but also about managing fires and furnace conditions. Difficult as it is to adequately operate a furnace, one needs to consider that a furnace shapes the final composition of the glass. Neri warned his readers in the preface of his *L'Arte Vetraria* not to underestimate the role of fire in glassmaking: "The fire in this art is of notable importance, indeed this is what perfects everything, and without which nothing can be done, therefore give it proportionate consideration."[63] In terms of the textual transmission of know-how, one might wonder

[62] Rau, "Johann Kunckel," 135; Schulze, "Kunckels Glaslaboratorium." Rau, "Das Glaslaboratorium."
[63] Neri in Engle, *The Art of Glass*, vol. 1, 8.

how the complexities involving furnaces were translated into text. How did Kunckel communicate the pyrotechnical intricacies that one inevitably runs into when executing the glass recipes from the *Ars Vitraria Experimentalis*?

Even though Kunckel neglected to test Neri's recipes for rosichiero glass, he used his commentary to present valuable advice on fire management and adequate timing in glassmaking:

> It should be known that, like all Glazes, one should just attend to the Fire. Because when the Fire is much too Strong, the Colour that one obtains will perish and another will appear that one does not desire nor wants to have.[64]

Indeed, Kunckel is keen on stressing that "the Fire is the principle thing to observe" and states more than once that colours will fade "when the Fire is even a little too strong."[65] This advice might appear a little too general to be actually helpful, but what Kunckel does is actually quite radical. He adds an entirely new and previously non-existent pyrotechnical layer to Neri's rosichiero recipes, which did not contain any furnace-related directions with respect to the glass. Kunckel thus verbalises the role of fire technologies in the making of rosichiero glass that is left unarticulated by Neri. This is a powerful epistemic move. He does not tell the readers how exactly to handle the furnace, but by revealing the fire as "the principle thing" he shows the readers the underlying mechanism by which they can optimise the glass themselves. He thus makes them understand, rather than follow.

Another topic that Kunckel addresses in his commentary concerns adequate timing and pacing of the different steps in the rosichiero recipes. Indeed, there is a specific order in which the ingredients should be added to the batch, while the intervals between the different steps further influence the composition and colour of the glass. For example, Kunckel writes about chapter 128:

> When the *Kupffer-Schlacken* [copper(II) oxide] is added here, one should not let it stay for long, otherwise is becomes Radiant Green. While initially it gives a beautiful Red, it only lasts a very short Time.[66]

There is a "right tempo" that must be "observed," and especially concerning the red rosichiero colour, there is only a small window of opportunity since the colour "changes in half a quarter of an hour."[67]

Kunckel's advice can be confirmed from two different angles. First, we carried out a very simple experiment in which we reproduced chapter 128 in an electric kiln by putting in all the ingredients at once. We thus ignored timings. As a result, we obtained a dark blue, black-inclining glass. Yet, using the same ingredients and following the order that was prescribed by the recipe, we obtained a red glass. Tempo, being the spreading of different steps through time, thus seems crucial in achieving

[64] Kunckel, *Ars Vitraria*, 193.
[65] Kunckel, *Ars Vitraria*, 194.
[66] Kunckel, *Ars Vitraria*, 194.
[67] Kunckel, *Ars Vitraria*, 193–4.

rosichiero glass. Second, Kunckel's *Ars Vitraria Experimentalis* is not the only historical source to address the relationship between time and colour-change in glassmaking. The pseudonymous medieval monk Theophilus had already remarked that various glass colours could be obtained from a single glass formula, just by varying the time in the furnace.

> If you see [the glass in] the pot changing to a saffron yellow colour, heat it until the third hour and you will get a light saffron yellow. […] And if you wish, let it heat until the sixth hour and you will get a reddish saffron yellow. Make from it what you choose.[68]

It has been suggested that furnace atmosphere and glass composition are not static but in motion during glassmaking. For example, the initial atmosphere in the furnace tends to be reducing but gradually develops towards an oxidising one, while the ashes used for the glass likely contain carbonaceous material that would contribute to reducing conditions in the glass at the beginning.[69] Both affect the colour of the glass over time, such that the glassmaker only needs to wait for the right colour to appear. To what extent these considerations apply to rosichiero glass is yet unknown, but it is clear that the colour of the glass depends on the final oxidisation state of its ingredients, and that needs time to develop.

Yet again, Kunckel complemented Neri's rosichiero recipes in his commentary. Even though Neri indicates a clear order and provides some indications with respect to the timing of different steps, he does not further specify time as a colour-changing factor. Kunckel however, sheds light on the very mechanism behind rosichiero glassmaking, and establishes that timing and tempo directly affect the colour of the glass, which prepares his readers to reckon with this factor and to put it to good use.

5. Conclusion

Kunckel's commentary is ambivalent. His discussion of the rosichiero recipes contains errors and there is no reason to assume that Kunckel actually tested Neri's rosichiero recipes. But there is another side to his commentary in which he uncovers and articulates two layers that are absent from Neri's instructions. He shows his readers that making rosichiero is not only a matter of mixing the right ingredients and melting them together, but asks them to take *fire* and *timing* into consideration as colour-effecting factors, and he provides guidance on the right ingredients by offering various ways of preparing them and showing that the colour of glass is sensitive to the manner in which the ingredients are prepared. Kunckel shows his readers *how* something works, rather than telling them precisely what to do.

It is fruitful to look at artisanal texts as ways of error management, and to consider them as textual technologies developed in a world in which it was impossible to be in full control of the process of making and in which the variability of colour

[68] Theophilus in Hawthorne and Smith, *Theophilus on Diverse Arts*, 55.
[69] Henderson, *Ancient Glass*, 66–7. Hawthorne and Smith, *Theophilus on Diverse Arts*, 56.

production was commonly recognised and accepted. In such a world the imperative to follow the recipe is a poor and unwise strategy of error management. Seventeenth-century glassmakers crafted other strategies. Neri included problem-solving advice in his recipes and told his readers what to do when, for example, the colour of the rosichiero glass is not satisfactory: "If it is over-colored, give it a little manganese to dilute it. If it is clear of color, add more of the fixed sulfur, hematite, a little red copper, and a little white wine tartar at your discretion so it becomes the desired color."[70] Neri left colour judgement to the reader, and offered him only minimal advice. Kunckel's strategy is different. One could argue that the codification of error made Kunckel's strategy of error management more refined than Neri's or any of his predecessors'. However, re-working Neri's recipes and Kunckel's annotations, as we have undertaken in this article, shows that Kunckel regularly neglected to test and that not all his corrections are improvements. This suggests that the codification of error is a rhetorical strategy empowering the author more than the reader. Kunckel therefore develops an additional strategy which helps his readers in the process by guiding their attention. He educates his readers on the mechanisms that constitute the recipes and shows them where exactly to intervene in the process to shape the colour of the glass and to gain further control over the making process. How to respond to errors and contingencies is not something that can be grasped from books, but a matter of experience, training, and judgement. Therefore, in his book, Kunckel provides cardinal directions and helps readers to personally grow into an experiential understanding of the glassmaking process by their own experimental engagement with colours and materials.

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[70] Neri in Engle, *The Art of Glass*, vol. 3, 55.

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