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Replication of Replicability: Schmidt's Electrical Machine

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Abstract

We replicated G. C. Schmidt's electrical machine in order to see whether it was possible for his contemporaries to replicate the machine based on Schmidt's description. This is important inasmuch as the emerging physical discipline relied on being able to reproduce the fundamental effects of its main field, electricity. This paper focuses on the glass pieces and it turns out that the probable composition of the glass as it was usually produced in the Thuringian Forest required particular technical facilities and skills for melting and grinding which caused significant difficulties for the technicians engaged with the replication, indicating that a high standing glass industry is a prerequisite for building such an electrical machine before 1800.

Keywords: *Georg Christoph Schmidt, physics, 18th century, electrical machine, replication, glass industry*

Exploring physics in Germany around 1800

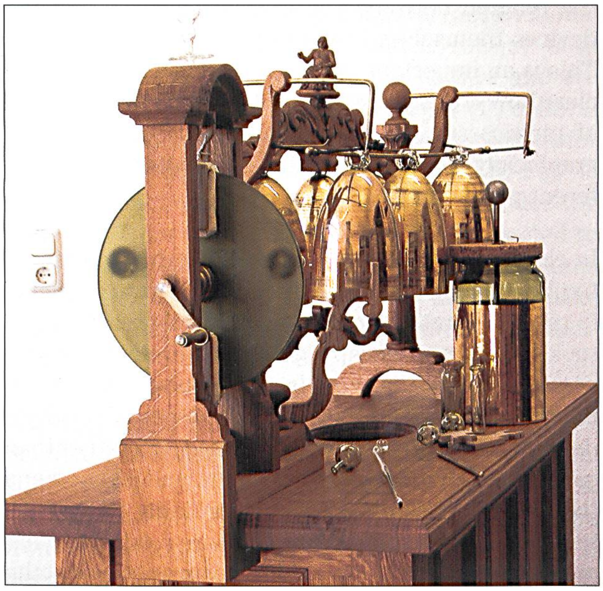
Schmidt's electrical machine is a frictional electrical machine that was built around 1770. It is accompanied by a large set of additional devices for the production of most of the then known electrical effects. The machine itself as well as most of the additional devices have been replicated under direction of the authors at the University of Jena as part of the Collaborative Research Centre 482 "Phenomenon Weimar – Jena. Culture around 1800", see Fig. 1.

The replication of Schmidt's electrical machine is part of a project reconsidering the profound transition in German physics around 1800. Roughly speaking, this consisted in the emergence of a self-sustained, nation-wide and journal-based scientific community from a number of different fields of practice. These fields include the long-standing teaching of physics at universities, courtly and popular entertainment, and instrument-making. Occasionally, this resulted in contributions to what we would now call research.

For three reasons, Schmidt's electrical machine is particularly suited for studying physics in Germany around 1800. Firstly, electricity was the main field of physics, the only one (except for the largely idle field of magnetism) which was not claimed by either applied mathematics or by chemistry. Electricity had been instrument-based right from the start, and the electrical machine was its core device, both technically and epistemologically.

Secondly, the builder of the machine, Georg Christoph Schmidt (1740–1811), belonged to three of the relevant groups of "physicists". He was an instrument-maker in Jena. When he succeeded in becoming the court mechanic for the small duchy

Fig. 1. Electrical machine, rebuilt as closely to Schmidt's electrical machine as possible, mainly based on Schmidt (1773).



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Sachsen-Weimar-Eisenach, he was involved in courtly science. And at the same time he was a lecturer at the University of Jena, teaching mechanics, geometry, architecture and the performance of electrical experiments.


Beschreibung
einer
Elektrisir-Maschine
und deren Gebrauch
von
Georg Christoph Schmidt,
Herzogl. Sächs. Weimar und Eisenachischen Hof Mechanikus zu Jena
mit einer Vorrede
des
Herrn CammerRath Wiedeburg.
Nebst zwo Kupfer-Platten.
Jena,
in der Cröckerischen Buchhandlung zu haben
1773.

Fig. 2. Title page from Schmidt (1773).

Thirdly, the electrical machine is accompanied by a book (Schmidt 1773) which describes the machine as well as a plethora of phenomena to be produced with it. The book contains two copper plates of the machine and of the additional equipment. All three components – the book, the plates and the machine – were handcrafted by Schmidt. This extraordinary fact allows for a close examination of the relation between text, image and device without fearing misunderstandings between instrument-maker, author, draughtsman and engraver.

Replication of replicability

On the one hand, the text and the plates were used as sources for the replication of the electrical machine, because only one glass plate and one Leyden jar from the original machine still exist. On the other hand, the relation between the text, the images and the devices themselves is the very topic of our inquiry. This is an important question, because it is far from clear how it was possible to establish a coherent field of physics (or, at least, of electricity) among geographically dispersed practitioners rooted in very different professions.

In electricity, knowledge was inextricably connected to phenomena, and these phenomena were artificially produced rather than being natural (recall that it took a long time to accept lightning as an electrical phenomenon). Historians of electricity have mostly been interested in the development of theories and concepts derived from instruments and phenomena rather than in the development of instruments and phenomena themselves (Heilbron 1999). Accordingly, they mostly mention those instruments that are related to what are now seen as groundbreaking discoveries. But at the time, securing a stable field of knowledge worked differently. There was neither reference to particularly telling experiments nor a widely standardised practice of use of electrical instruments. The main knowledge of electricity, i.e. the laws of (in modern terms) attraction, repulsion, conduction, and induction were abstracted from the daily use of the electrical machine. And they were demonstrated time and again in lecture halls, in courtly soirées, in private scientific societies, and on market squares by means of many different devices and substances (Hochadel 2003; Frercks 2004). By the end of the 18th century, different *types* of electrical machines had evolved for different purposes, but there was no standardisation inside every group or even mass production (Hackmann 1978; Weber, in press). Thus, in order to be part of the physical community, it was crucial to master electricity and this required access to an electrical machine. Communicating knowledge – the crucial activity of every scientific community – meant communicating phenomena and it involved exchanging instruments too.

The importance of establishing a coherent field of electrical experimentation was the guiding assumption of the project. We presuppose that there was a need to replicate scientific instruments. To be sure, our single replication cannot ascertain whether it was generally possible to rebuild Schmidt's electrical machine for contemporaries. That would require several replications at least according to different local custom and facilities, which was beyond our means. But even if this could have been done, it would not reveal anything about the general norm of replicability. What *can* be done, however, is to replicate replicability for specific circumstances. Thus we chose to rebuild the machine according to the custom and facilities of Thuringia around 1800. Our replication of Schmidt's electrical machine does not aim to come close to the practice of a particular past person – at least not to that of Schmidt. If we come close to a past person's practice at all, this person would be a Thuringian reader of Schmidt's book who tried to rebuild Schmidt's electrical machine from the textual and pictorial information given there, supplemented by locally available knowledge and skills.

We do not know whether Schmidt's electrical machine *was* actually rebuilt by contemporaries, but we aim to find out whether this *could* have been done from the information provided by Schmidt. The question is whether the explicit specifications in Schmidt's description suffice for rebuilding the machine. By means of the replication we intended to get an insight into that knowledge which is implicitly presupposed by Schmidt. At the time standardisations both for electrical machines and for their description were well established. By careful identification of the implicit and explicit specifications in this text we are able to identify the degree to which Schmidt's machine and its description fits this standardisation.

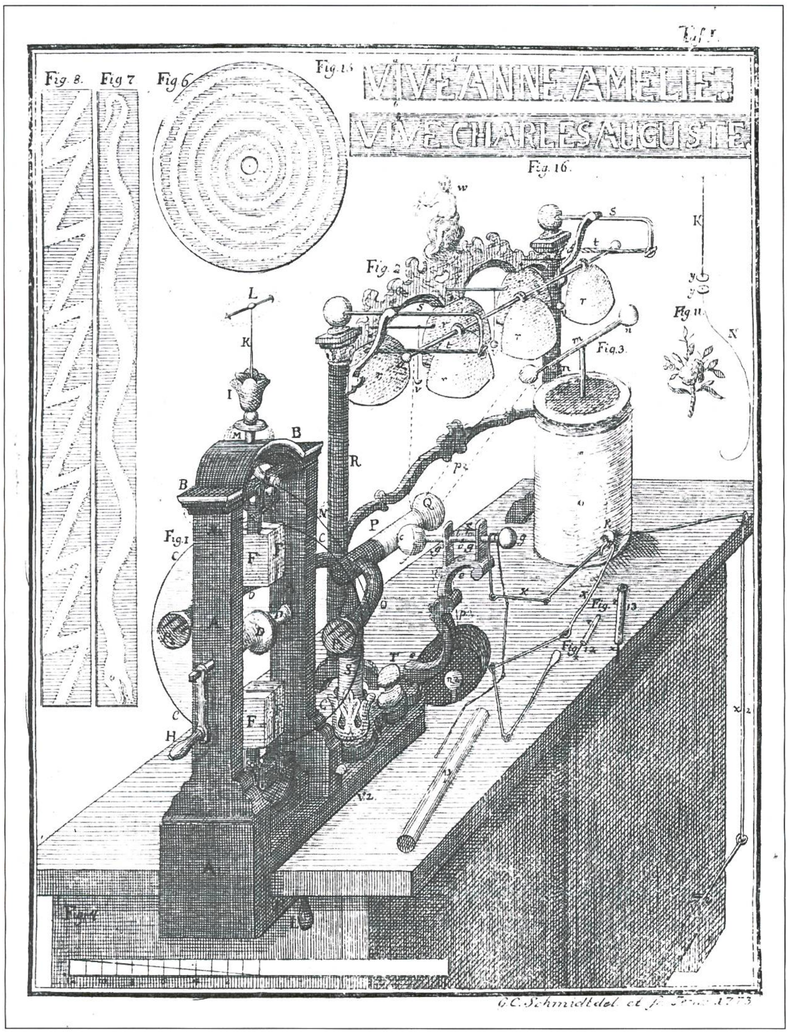


Fig. 3. Plate I from Schmidt (1773), showing the electrical machine and additional equipment.

This may then lead to an assessment of the use of the machine and of the book. The book, at least, must have been a success, because Schmidt published a second, significantly enlarged edition of it in 1778. But for what purpose did Schmidt build the machine, cut the copper plates and write the description? Were the book, the image and the machine intended to inform, to entertain, to be applied in medical treatment or to allow for research? Although there have certainly been endeavours to distinguish these different functions and to draw boundaries between different fields of practice among the practitioners themselves, these should not guide our inquiry. (This is the most important reason for aspiring to rebuild the machine in every detail and to include all additional equipment.) Although Schmidt's electrical machine certainly never led to a major discovery, it would be rash to classify it as "merely" for entertainment or lecture demonstration.

To be sure, a replication done today will face different difficulties than a contemporary replication. But it is these difficulties that hopefully lead to some insights into the difficulties at the time.

The projects consist of two steps: rebuilding Schmidt's electrical machine according to his book and trying to reproduce all of the phenomena produced by this device as it was described in the text. The first step has been successfully finished, and this will be described in the paper at hand. Except for some preliminary testing which proved that the machine "works", the main part of the second step still has to be done.

Schmidt's electrical machine

As one can see from the plates, reproduced here as Figs. 3 and 4, the electrical machine (Pl. I, Fig. 1; Pl. II, Fig. 1) is only one part of a set of instruments which allows us to produce most of the known phenomena of electricity. The machine itself is portable and can be fixed easily to a table by a hand screw (Pl. I, Fig. 1, I). By means of a crank handle (Pl. I, Fig. 1, H) the circular glass plate (C) is set into motion. The four frictional cushions (F), which rub at both sides of the glass plate, consist of leather and are filled with horn shavings. The conductor (P) collects the electricity from the glass plate and stores it for further use. Three large Leyden jars (Pl. II, Fig. 4) are placed – invisibly for the audience – under the table (Pl. I) for large effects. They are connected to a fourth Leyden jar, which stands on the table. Some smaller Leyden jars (Pl. II, Fig. 23 and 28) make electricity portable for experiments among the audience.

While the electrical machine is comparatively simple, Schmidt has applied much decoration to some of the additional devices. Most impressive is the electrical carillon with six gold-plated glass bells suspended from a carefully crafted oak frame (Pl. I, Fig. 2). A peculiarity of Schmidt's apparatus consists of five different glass plates, partially covered with gold foil. The gold foil is interrupted at regular intervals producing sparks across the interruptions, which makes

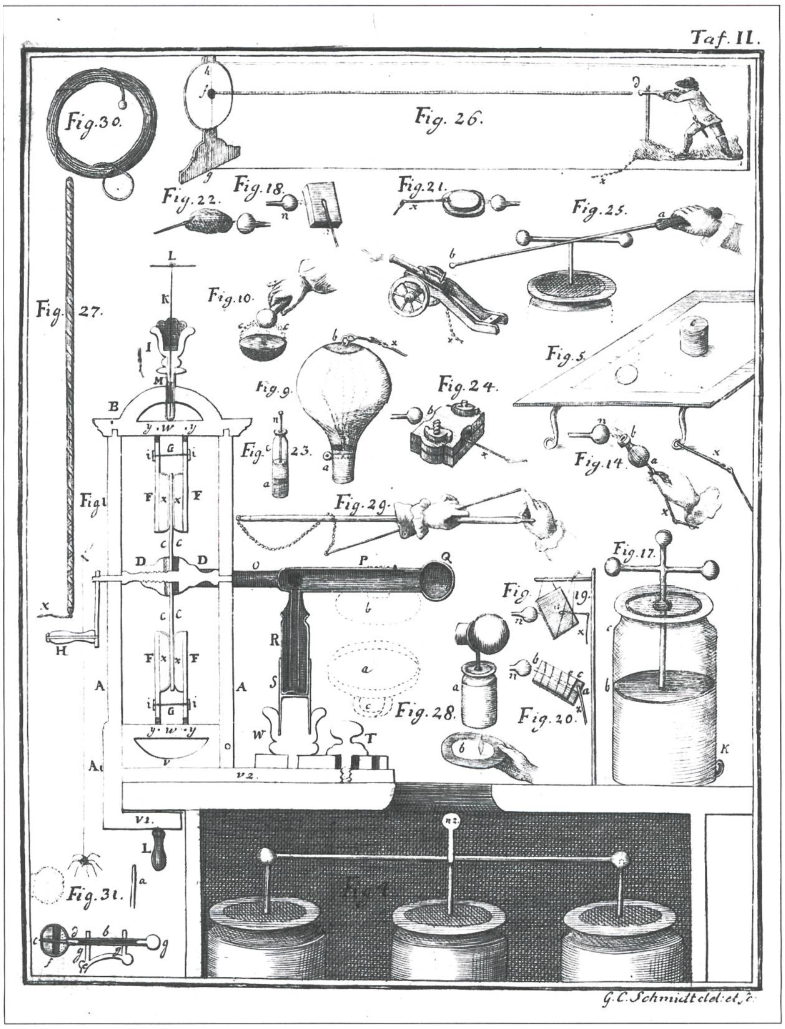


Fig. 4. Plate II from Schmidt (1773), showing the additional equipment of the electrical machine.

the figures shine. The figures include a snake (Pl. I, Fig. 7), a spiral (Pl. I, Fig. 6), and the words "Vive Anne Amelie" and "Vive Charles Auguste" in honour of the duchess of *Sachsen-Weimar-Eisenach*, Anna Amalia (1739–1807) , and her son, the later duke Carl August (1757–1828) (Pl. I, Fig. 15 and 16).

The replication of the set of apparatus was based on Schmidt's text and the two plates. As was common practice, Schmidt only rarely provided sizes. The scale at the bottom of Plate I is of limited use, because it is not clear how it has to be applied to the third dimension in the perspective drawing. The scale of the drawing can be reconstructed from the size of the glass plate of the electrical machine, the diameter of which Schmidt (1773, p. 9) indicates as "wenigstens einen Schuh" (at least one shoe) (282 mm). Fortunately, the preserved glass plate with a spiral-shaped metal coating in possession of the *Klassik Stiftung Weimar* allowed us cross-check the measure of the drawings from Schmidt. It turned out that its scale corresponds neatly to the size given in Pl. I, Fig. 6. Therefore it is safe to conclude that the plates are drawn true to scale.

This, however, does not apply to every detail. For example, the length of the table as shown in Plate II is most probably shorter than in reality (see Plate I in comparison). Likewise, the bells of the carillon most likely had a different shape. The glass makers from the glass-works of Horst Grimm in Gehlberg informed us that bells of the shape shown in Plate I would not give a clear sound.

The wooden parts of the apparatus have been skilfully crafted by Ingo Runge, a local cabinet maker. The metal parts were built in the workshops of the University of Jena under guidance of its director Bernhard Klumbies. Although there would be much to tell about these works, we will restrict ourselves to the parts made of glass, the replication of which constituted the most interesting and most difficult part of the whole endeavour.[1]

Glass serves different functions in the apparatus and appears in different shapes and colours. The glass plate of the electrical machine for producing electricity and the Leyden jars used for increasing and storing electricity were made of green glass. The gold wire electrometers (Pl. II, Fig. 9 and 21), the insulating stand of the conductor, the calyx and the top of the machine for electrifying plants (Pl. I, Fig. 1, I), the bases of the golden spark-chains, the gold-plated condensers (Pl. II, Fig. 5), and the bells of the electrical carillon were made of uncoloured glass. While there may have been aesthetic reasons for this choice, there may have been technical reasons as well. Coloured glass was generally assumed to be more conductive than white glass. Therefore, green glass was used for those parts that need to transfer electricity, while uncoloured glass was used for those parts that need the highest possible insulation.
Accordingly, the reconstruction started with finding out the composition of these two sorts of glass.

[1] This is described in more detail in Weber et al. (in press).

N°	Glass	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO	MnO	P_2O_5
1	Glass from excavation of a glass pot, Eichsfeld, ca. 1500	55.1	9.2	0.3	4.9	3.4	23.9	4.0	-	-
2	Excavation in Hanover, hollow glass ca. 1500	55.0	5.3	0.2	7.8	2.3	22.9	1.0	1.5	3.2
3	Window glass, Hanover 1530	58.3	2.8	0.35	8.1	1.8	21.8	1.1	2.0	2.9
4	Utility glass ware from Hanover, 18th century	58.3	1.7	0.4	9.1	3.3	21.2	1.0	1.1	2.5
5	Utility glass ware from Hanover, 18th century	58.3	2.6	0.4	6.6	3.7	21.4	1.9	1.1	3.1
6	Glass from scientific apparatus used by J. W. Ritter, ca. 1800	77.6	0.9	0.4	9.1	0.7	9.8	0.3	-	-
7	Ordinary chemical glass, pale green, 1830	63.5	4.5	2.5	10.5	-	16.2	-	-	-
8	Thuringian chemical glass, 1869	74.1	1.2	0.7	0.6	15.7	6.9	0.2	0.5	-
9	Insulator glass, green, 1st half of the 20th century	68.1	7.2	1.9	2.2	5.7	14.1	0.8	-	-
10	Standard chemical glass 1800, pale green	65	4.0	1.0	9.0	3.0	14.0	3.0	0.8	-

Table 1: Composition in % of some historical glasses and the glass used for the replication. Sources: 1: Wedepohl 1998, p. 24; 2: Geilmann 1955, p. 151; 3: Bezborodov 1975, p. 270-271; 4: Geilmann 1955, p. 151, (sample 4.4); 5: Geilmann 1955, p. 151, (sample 4.5); 6: Analysis of a sample in the possession of the Deutsches Museum (Munich), done by Günter Völksch, Institut für Glaschemie of the University of Jena; 7: Thiene 1939, p. 944; 8: Thiene 1939, p. 938; 9: Schmidt 1953, p. 197; 10: inferred from the available historical information and adjusted to today's technical feasibility.

The composition of the glass

Owing to curatorial reasons, it was not possible to analyse the chemical composition of the preserved glass plate. Instead, the reconstruction of the composition of the glass was based on a combination of scarce information to be found in contemporary literature (N° 7 and 8 in Table 1), of the analysis of relics from excavations and preserved artefacts (N° 1 through N° 6, and N° 9), and of the assessment about technical feasibility from experts such as the glass technician Horst Grimm (Gehlberg) and the historian of technology Peter Lange (Jena).

The reconstruction of the glass was based on the assumption that the machine was built in Weimar, Jena or nearby.[2] Furthermore, it seems likely that a chemical glass was used rather than glass usually used for dishes, although Schmidt characterises the glass as "ordinary" glass or "conserving" glass (*Konservenglass*). The only technical information given by Schmidt is that the molten glass mass had to be processed very quickly. What was aimed at, then, was not to reconstruct the particular glass of Schmidt's electrical machine, but a plausible composition of a chemical glass in that region.

There seems to have been no glass factories in Weimar or Jena due to the immense need of wood, both for heating the furnace and for producing potash (K_2O) as a fluxing agent for the glass melting process. Most probably, the glass was produced somewhere in the Thuringian Forest, some 50 km south of Weimar, with its long-standing tradition in glass production (see Pischel 1928; Kühnert 1973). Possible sites are situated in the region of Stützerbach/Gehlberg or in Lauscha (Ganzenmüller 1934, 1935; Hoffmann 1993; Kühnert 1973).

Did the ensemble of different devices required for Schmidt's apparatus, serving different functions, cause major problems for contemporary glass factories? Not very much has been published about glass making at the time, firstly, because it was a typical non-literate craft and secondly, because of the commercially crucial secrecy with regard to the constituencies and procedures. Exceptions are Le Bieil (1780), Hochgesang (1780) and Bowles (1833).

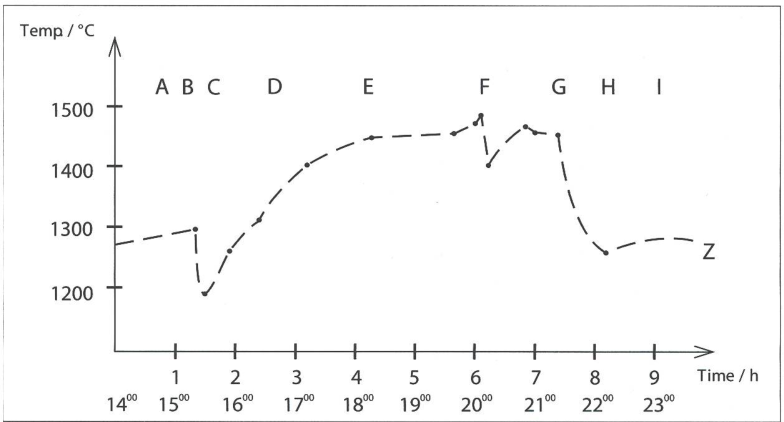
The composition of the starting batch mix largely determines its melting and processing properties. This was reason enough for trying to reconstruct the original composition as far as possible.

Unlike glass from early modern times or from the end of the 19th century, there are very few analyses of ordinary glass from the time around 1800. Table 1 lists the information on compositions of glass dating from around 1800 to be found in the literature, added by some analyses from around 1500. Based on the assumption that ingredients of ordinary glass - unlike those of crystal glass - had to be cheap and easily available, it seems likely that the following substances were used: sand (rich in aluminium oxide, from Martinroda or Neuhaus), wood ash (from own production), sodium (from kitchen salt, imported soda or broken glass), manganese dioxide (for decolourisation and as a fluxing agent), lime powder and dolomite powder. This resulted in a (hypothetical) "standard chemical glass 1800, pale green" (N° 10 in Table 1). It was this glass which we aimed to produce in the replication.

2 Even if this was not the case (Schmidt moved from Stettin to Jena in 1773, the year of the publication of his book), the replication nevertheless reveals what it meant to rebuild Schmidt's electrical machine in this region.

The quantities of SiO_2 and Al_2O_3 are typical for glass based on sand to be found in the Thuringian Forest (Thiene 1939). The component of SiO_2 should have been higher according to glass N° 2 and N° 3, because we wanted to produce a chemical glass rather than a utility glass, but a proportion higher than 65 % was judged to be unworkable. (This seems to be a technical rather than a historical criterion, but, given that glass makers in the past *did* somehow manage to produce the glass with more SiO_2, the distinction looses its meaning. The seemingly impersonal criterion "technical" basically means nothing other than "adapted to the abilities of a particular historical period": ours!) The quantities of Fe_2O_3 and Al_2O_3 were adjusted during five melting processes until the colour of the glass resembled that of the remaining Leyden jar. This was the case with 1.6 % Fe_2O_3 and 0.4 % Al_2O_3. In addition, a melting was done for a glass as white as possible. The amounts of K_2O and CaO represent the components in the wood ash and lime powder, which correspond nicely with the other examples (in particular N° 4) listed in Table 1. The quantity of CaO was reduced according to the higher quantity of SiO_2. The quantity of Na_2O was fixed at an intermediate value, since the transition from medieval glass (with K_2O and some Na_2O, produced by burning plant material) to modern glass (with more Na_2O, produced from minerals) had not yet been accomplished. MgO was added for technical reasons for preventing crystallisation. The quantity of MnO was fixed rather small in order to prevent a brown colour. P_2O_5 was not used, because there is no indication that it was used in Thuringian glass factories.

Fig. 5. Temporal course of the melting procedure.A: glass pot partially prepared (Hafen halb ausgearbeitet); B: inserting 5 shovels of cullet; C: inserting 16 shovels of batch; D: melting operation, adjusted to maximum fire; E: batch melted-off; F: insertion of another 4 shovels of cullet; G: furnace temperature sunk down, unmelted batch removed; H: heat required during idling time, unmelted batch added to the glass melt; I: left to settle (abstehen lassen); Z: heat required during idling time (Haltebetrieb).



Melting the glass

Producing a homogeneous mass of glass from a given batch mix is no easy task. The batch was placed in a one-pot oven which was heated by natural gas. In the first melting, the not yet molten batch sank beneath the melted mixture and interrupted the conduction of heat and prevented the melting of the whole batch. Adding some feldspar prevented bubbles and adding broken glass from the first trial facilitated the start of the process in the second trial. The colour of the first glass had been amber, which was far from the desired colour. If several metals are involved, there is no clear-cut recipe for getting a particular shade, but after five trials, the resulting glass was olive-green like the preserved Leyden jar.

Fig. 5 shows the course of the last melting process. The work took more than eight hours and required several readjustments and sometimes adding some broken glass. The melting temperature for the "Standard chemical glass 1800, pale green" was particularly high. It is not clear how these temperatures could have been reached and maintained for several hours around 1800.

Casting the glass plate

Schmidt's electrical machine was the first one built in the German-speaking lands that used a glass plate rather than a glass sphere or cylinder as its central piece. The advantages of using a plate consisted in a higher stability against the pressure put on it by the cushions and by thermal expansion of gas in the glass. But glass plates were more difficult to build.

In preliminary tests, Schmidt found that thin glass (window glass) and thick glass (mirror glass) produce the same amount of electricity. More important were clean and well polished surfaces. The yield could be increased by wiping it with fat or soot, or by applying and removing glue. Equally important was a perfectly plane shape for smooth running.

In principle, there are three different ways of producing a glass plate (Glocker 1992; Jaschke 1997). The first consists in blowing a glass sphere and then rapidly rotating the blow pipe until the sphere flattens to a disc (the so-called moon-glass method). This was impossible for the replicated glass with a high proportion of SiO_2 because of the short time-frame of workability. The second way consists in blowing a cylinder, and then cutting and unfolding it. Again, this cannot be done with the glass. The remaining way consists in directly casting the melted glass into a disc-shaped mould. This was done in the replication, see Fig. 6.

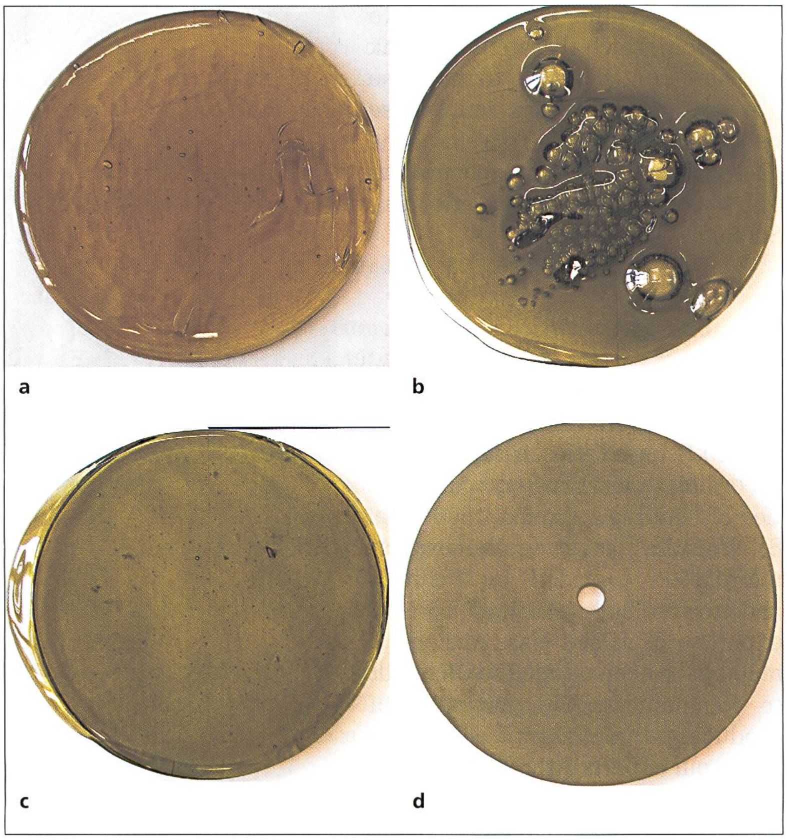


Fig. 7. Preliminary results of casting trials. The sequence (a-c) reveals the gradual progress in terms of colour, absence of bubbles and shape.

In order to prevent rapid cooling of the glass, the mould had to be heated from below. This, however caused the release of carbon oxides, built from residual carbon in the mould made of cast iron. Accordingly, the glass plate contained large gas bubbles inside, see Fig. 7b. This could be prevented by the use of a mould made of carbon-free steel.

The use of carbon-free steel is a typical move in a replication in three respects. Firstly, its necessity turned out only during the replication itself, the problem to be solved by it could not have been foreseen without using the real materials. As is so often the case, failure is more revealing than success here. Secondly, we do not know *how* past technicians managed to circumvent these problems, although it is very probable that they faced similar problems, furthermore, it is sure that they *did* solve them somehow. Thus the historiographical gain consists in the general insight of a high-standing art of glass making, without, however, it being possible to further specify what technique was used for this particular step of the process. Thirdly, a solution available and workable today was chosen in order to go on with the replication at all.

Fig. 6. Casting the glass plate in a heated mould made of steel in a workshop in Gehlberg.

Our solution, however, caused further difficulties. By heating the steel from below, it went out of shape, so that the resulting glass plate was free of bubbles, but not at all plane. This required a further step in producing the required piece: grinding it into shape.

Grinding

Whether this step is an artefact of the previous difficulties with casting is difficult to say with certainty. Not all electrical machines have ground glass plates, but some indeed do. This, for example, is the case for a machine in the possession of Adolph Traugott Gersdorf (1744–1807), whose glass plate was made by Dutch glassworks.[3] This makes plausible that not only chemical glass produced in the Thuringian Forest had this characteristically limited range of workability which necessitates follow-up treatment, but also glass from other glassworks.
It was difficult to find someone who was able to grind glass pieces with a large surface. The problem is that

[3] This machine is in the possession of the *Physikalisches Kabinett, Kulturhistorisches Museum, Barockhaus Görlitz* (see also Hackmann 1978, Pl. 32).

grinding sets the glass piece into oscillation, which threatens to break it. The essential skill is to stick the glass piece onto a dampening base covered with mastic. Therefore, the glass plates for the spark chains had to be built shorter than described by Schmidt.

Conclusion

The main result of the first part of the project is that it *was* possible to rebuild Schmidt's electrical machine according to local custom and facilities of Thuringia around 1800 (Fig. 8). For this, however, the explicit information provided by Schmidt had to be supplemented by the expertise of skilled glass makers. It might have been difficult for Schmidt to communicate the procedure of producing the glass pieces. Even today, our experts (who, tellingly, are still from the Thuringian Forest) used expressions (as for example *abgesoffene Schmelze* or *Schmelzkuchen*) which are not even listed in specialist dictionaries and of which we could only guess their meaning. Apart from such difficulties, there was no need for Schmidt to be more explicit, because general readers would hardly have grasped what was meant.

Fig. 8. Details of the replication of Schmidt's electrical machine (side view, the cushions and a carved figure of Zeus).

But even if readers knew a lot about glass making, there was no need to be more detailed because the glass would have been produced according to local custom and based on the implicit technical knowledge of instrument workers anyway.

As a consequence, replication of instruments could not have meant replication in every detail. We suspect that the detailed description of phenomena was intended to provide criteria for judging whether any rebuilt machine was sufficiently similar to the original. Whether this applies for our replication will only be revealed by extended use.

This raises the question as to what was taken to be the essential components of Schmidt's machine, which was highly ornamented and rich in additional devices. It is possible that others rebuilt it selectively according to their particular needs. Thus, Schmidt's description of the phenomena to be produced may have been not only an instruction for demonstration or a sales pitch, but also a cross-check as to whether the replication was *sufficiently* close to the original. We, at least, will use Schmidt's description in this way when our rebuilt machine is put to extensive use.

Acknowledgements

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