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From *Topos* to *Oikos*: The Standardization of Glass Containers as Epistemic Boundaries in Modern Laboratory Research (1850–1900)

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Argument

Glass vessels such as flasks and test tubes play an ambiguous role in the historiography of modern laboratory research. In spite of the strong focus on the role of materiality in the last decades, the scientific glass vessel – while being symbolically omnipresent – has remained curiously neglected in regard to its materiality. The popular image or *topos* of the transparent, neutral, and quasi-immaterial glass container obstructs the view of the physico-chemical functionality of this constitutive inner boundary in modern laboratory environments and its material historicity. In order to understand how glass vessels were able to provide a stable epistemic containment of spatially enclosed experimental phenomena in the new laboratory ecologies emerging in the nineteenth and early twentieth century, I will focus on the history of the *material* standardization of laboratory glassware. I will follow the rise of a new awareness for measurement errors due to the chemical agency of experimental glass vessels, then I will sketch the emergence of a whole techno-scientific infrastructure for the improvement of glass container quality in late nineteenth-century Germany. In the last part of my argument, I will return to the laboratory by looking at the implementation of this glass reform that created a new *oikos* for the inner experimental milieus of modern laboratory research.

The scene is familiar to all of us: a scientist, brooding over a research object contained in laboratory glassware. This motif has become omnipresent in heroic representations of science since the late nineteenth century.[1]

[1] It can be found in the well-known portrait of Louis Pasteur, painted by Albert Edelfelt in 1885. See also the complementary description of the painting in Loslalot 1886, 459-460. For the historical development of glass vessel iconography, see also Schummer 2008; Schummer and Spector 2007.

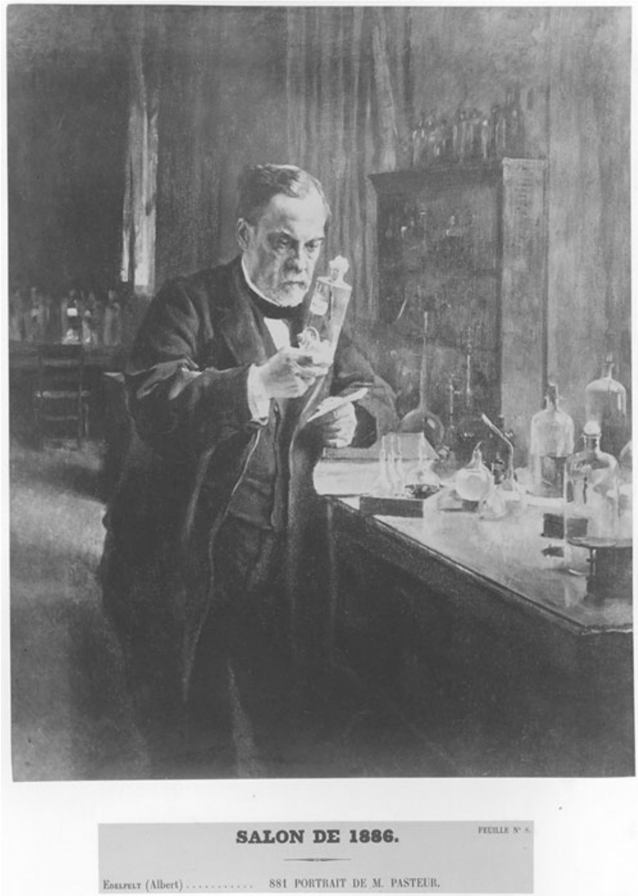


Fig. 1. Portrait de M. Pasteur (Photography, 1886). Source: Archives nationales, Paris.

But such iconic prominence of scientific glass containers has a dark side. As a matter of fact, they play at best an ambiguous role in the history of science: Although recent historical epistemology has convincingly emphasized the significance of materiality in the dynamics of experimental research, the scientific glass vessel, though symbolically established, has remained curiously invisible.[2] The glittering iconography of laboratory glassware has obstructed from view the material historicity and functionality of these objects in experimental research.[3] Based on the above, I will re-materialize

[2] There are, however, exceptions, such as for instance Müller 2004; Jackson 2006. Cf. also the chapter on glassware revolution in Jackson 2008.
[3] There are, though, numerous historiographical works on optical glass. See for instance Schaffer 1989; Jackson 2000; Hentschel 2002.

scientific glassware, which means making visible the materiality that turned glass into a constitutive inner boundary in laboratory environments. The notion of the boundary and *material boundary work* suggested in this paper does not aim at a discursive, disciplinary, or institutional level,[4] but quite literally at the physical space of the modern research laboratory.

I will focus on the early history of the standardization of laboratory glassware in the second half of the nineteenth century, more precisely on the standardization of the *material* and not the form of experimental glass containers such as flasks, test tubes, and petri dishes. The material standardization of glassware will *not* be addressed as a technical solution to a practical problem nor will it be addressed from the viewpoint of history of technology, but rather as a process of epistemic and material reconfiguration of spatial boundaries in emerging research laboratory environments, i.e. from the viewpoint of a historical material epistemology. This means that on a conceptual level, I approach the history of modern laboratory research from an environmental perspective, focusing on the genealogies not of the epistemic objects but of those enclosed ecologies, architectures, and infrastructures, in which experimental inquiry into nature has settled. Seen from this perspective, the history of glass vessels turns out to be a challenging case study.[5]

The paper starts with an outlook on the development of the container glass industry and technical glass chemistry in mid-nineteenth century. In a second step, I will follow the rise of a new awareness for measurement errors due to the chemical agency of experimental glass vessels in the context of precision research. Third, I will outline the emergence of a whole techno-scientific infrastructure for the improvement of glass container quality in late nineteeth-century Germany that equally involved the needs of glassware consumers, the rise of special glass industry, the establishment of state institutions for material standards, as well as new forms of glass research and development. In the last part of the paper, I will return to the laboratory environment focusing on the implementation of this glass reform especially the reconfiguration of glass boundaries in research.

In the history of modern laboratory research glass containers are typically perceived as ahistorical, quasi-immaterial material objects the properties of which are limited to form, transparency, neutrality, and sometimes annoying fragility. These are without

[4] Not to be confused with the notion of "boundary work" proposed by Thomas Gieryn 1983, nor with Susan Star's "boundary object" (Star and Griesemer 1989).

[5] I have developed this approach in the introduction to my dissertation thesis. In a nutshell, the main difference of such a historical ecology of modern laboratory research compared to, for example, the history of epistemic things, proposed by Hans-Jörg Rheinberger, can be described as a shift or rather an inversion of the focus of interest: The experimental system (or more generally, the laboratory context of discovery) is usually seen as the the *explanans* for the becoming of an epistemic thing, the *explanandum*. The ecological approach inverts this direction of explanation, the epistemic vector, in other words, epistemic things are conceived as explanatory factors in the history of research environments, which in this perspective shift from the periphery to the very center of interest (cf. Espahangizi 2010).

doubt fascinating qualities in their own right (and as such, the raw material of many a fragile scientific anecdote).[6] But they are also characteristics that nonetheless have not warranted further historical analysis and explanation so far. The common reference to laboratory glassware on book covers and titles is a mere *topos*,[7] given the double meaning of the term as a popular object of imagination on the one hand, and as the spatial *place* in its original Aristotelian sense on the other hand.[8] So the *topos* of laboratory glassware could be paraphrased as the *idea of an ideal place of the experiment, surgically removed from the actual, complex textures of research environments*. But having learned the lesson of the much-evoked material turn in history of science (cf. Pravica 2007), one might indeed suspect that the glass container is not the quasi-immaterial device we imagine it to be. It should rather be materially entangled with experimental research and inseparably embedded into its *oikos* – which is called *laboratory*. Thus, shifting our understanding of scientific glassware from *topos* to *oikos*, we gain access to the rich history of the formation and the contingent dynamics of these inner material boundaries so constitutive to experimental research. The introduction to a laboratory handbook on microbiology from the early twentieth century illustrates this shift in perspective. The author Ernst Küster writes:

> Microscopic as well as macroscopic organisms can be taken out of their natural habitats and transferred to artificial environments in order to be studied scientifically. All kinds of microorganisms can be cultivated under laboratory conditions, which are adapted to their natural habitats and which can be varied deliberately according to the ends of research.
>
> Therefore, we will start our considerations with water, the precondition of all organic development. . . . At this point we will only mention pure water, which cannot be understood without glass, because glass vessels as indispensible containers for water and aqueous solutions alter the contained liquids constantly by successive dissolution of their proper substance. One should not underestimate these unwanted admixtures. It seems reasonable to underestimate the quantity of the soluble substance yielded by the glass and to overestimate the need of the organisms for minerals. But, in reality the amount of potassium and magnesium originating from the glass is sufficient to feed thousands of generations of cells. (Küster 1907, 6–7)

In this quotation, the author obviously contradicts the culturally dominant image of laboratory glassware. He rather understands it as a material, spatial, and causal boundary device, as a micro-*oikos* for laboratory metabolisms. Consequently, this illustrative

[6] Breaking glassware has an established narrative function in scientific self-historization. It is often used to mark crucial moments of chance and fortune in research processes (cf. Espahangizi 2009, 61).
[7] A very illustrative example is Rheinberger 1997. Though prominently mentioned in the title, the materiality of the test tube has no relevance for the argument (cf. also the book cover of Schummer et al. 2007).
[8] Significantly, Aristotle himself abstracted the physical place, the *topos*, from the material object *vessel* (cf. Casey 1996).

paragraph leads us to a historiographical as well as epistemological problem: How was it possible that vitreous material layers came to perform their complex epistemic task (the stable causal containment of spatially enclosed phenomena in laboratory contexts) throughout the changes which the experimental sciences have undergone since the scientific revolution? Revisiting the history of the laboratory sciences from this marginal perspective means deconstructing a firmly established cultural motif, the *glassware topos*. It also means reconstructing the numerous painstaking efforts in science geared towards demarcating the non-self-evident boundaries of the innermost dwelling of experimental research, the glass house of experiment so to say.

In the following, I will focus on the material boundary work that was performed in the second half of the nineteenth century when modern laboratory research emerged. This will be done in order to understand how laboratory glassware turned into a problem for research in the first place and to grasp the ways scientists and other actors, for example in the glass industry, reacted to these situations. To do this, one has to reconstruct the glass theories that were developed in this context, the glass production, testing and standardizing technologies, as well as the entangled substances, practices, institutions and actors (Espahangizi 2010).

Glass Culture and Glass Diseases in the Nineteenth Century

When we think of glass culture in the nineteenth century, greenhouses, railway stations, and the so-called Crystal Palace in London instantly come to mind: The glass architecture of the World Exhibition in 1851, when the Empire gathered in London, formed part of an emergent glass vision of modernity (cf. Koppelkamm 1988; Armstrong 2008; Schivelbusch 1977). The new giant glass constructions provided a powerful imaginative medium for a whole new cultural outlook. At the same time, however, the glass facades in the real world inexorably suffered from chemical corrosion induced by water and other atmospheric substances (Dumas 1832, 610–611; Péligot 1862 and 1877, 54; Benrath 1875). Decades before the urban historian Lewis Mumford came to lament the actual opacity of modern glass architecture due to air pollution, the image of crystal clear translucent glass transcending materiality was already being contradicted by dull, "blind," and "sweating" surfaces in the real world (Mumford [1938] 1998, 207–208). This tension between lofty glass imaginations and the annoyingly profane material reality seems to be a characteristic inherent to the glass boom that took off in mid-nineteenth-century Europe, in the field of construction and architecture as well as in the household. Drinking glasses, bottles, vases and bowls, too, would rapidly lose their brilliance due to chemical reactions with their immediate environment, such as the surrounding atmosphere or the substances they contained (Dumas 1832, 610–611). These *glass diseases* as they were called later by the art historian G. E. Pazaurek (Pazaurek 1903), got worse with bulk production of glassware: Industrialization increased the output, but lowered the quality of the material compared to traditional glass making at first (Foerster 1911, 135). But the need to improve glass quality, not only in the case of construction glass but also for example for wine bottles,[9] heavily stimulated the interest of the new so-called technical glass chemistry in the material.

Already in the 1830s, the theoretical and methodological progress of chemistry had made it possible to analyze the substance of different glass products quantitatively, for example with the use of hydrofluoric acid (cf. Rowney 1845; Warington 1845; Vogel and Reischauer 1859). The French chemist Jean-Baptiste Dumas for instance, who is famous for his handbook on applied chemistry, had begun to study numerous commercial glass products that were on the market. By this means, he tried to derive the general glass formula, the so-called *composition générale* (Dumas 1830, 144). There was no coherent glass theory and not even a general consensus over the question whether glass should be understood as a pure chemical compound or a mixture of substances and compounds. But the observable corrosion of ordinary glassware and glass surfaces in general turned out to be a promising starting point for the inquiry into the very nature of this fascinating, but according to Dumas scientifically rather neglected material.[10]

Between the 1830s and 1850s, the new technical glass chemistry was not specifically concerned about laboratory glassware. Brilliance and crystalline transparency were essential properties for the performance of nonscientific glassware, but only secondary to experimental practice. Also, slight corrosion of laboratory glassware and material depositions on their surfaces, an everyday phenomenon for chemists, did not necessarily affect their scientific usability. Until the mid-nineteenth century experimentalists tended to overlook the chemical agency of their glassware, the same way we are used to ignoring the continuous chemical reactions between drinking water and the glass vessels in everyday life today. These physico-chemical micro-processes simply did not affect research: There were neither epistemically relevant effects and consequences tied to them, nor were there any instruments, measuring or observing procedures to exactly quantify and objectify the interactions between glassware and the substances they contained. To put it in other words: There was no epistemic awareness for these kinds of phenomena. However, this indifference of experimental research towards the chemistry of glass surfaces was questioned only when a revolution in experimental research occurred with the establishment of precision measurement around the mid-nineteenth century.

[9] The French *Societé d'encouragement pour l'industrie nationale* for example offered a prize for chemists for the improvement of wine bottles in 1830. See the bulletin of the society on Dec 29, 1830. Cf. also the glass bottle studies of Robert Warington who worked as a chemist in the Truman Breweries in the 1830s and the Society for Apothecaries (Warington 1845).

[10] For views on glass theory at that time, see Dumas 1832, 579; and also Faraday 1830, 30. For a historical account of the development of glass theories, see Ganzenmüller 1938; Beretta 2009 and 2011.

The emergence of a whole new world of experimental research in the nineteenth and early twentieth century has been studied thoroughly by historians of science in the last decades. There has been a focus on the consolidation of new scientific values like exactness and objectivity, on issues of standardization, error analysis, and instrumentation, the development of new institutional forms in research and higher education, and the coming into being of new kinds of scientific objects in the expanding and diversifying landscape of modern experimental cultures.[11] While drawing on all of these aspects and dimensions, ecological approaches to the history of this "laboratory revolution" try to understand the emergence of new specialized environments of laboratory research (Dierig 2006, 26). Various studies have shown that in order to provide the stability needed for research, this nascent modern *oikos* of experimental inquiry into nature to some extent had to be encapsulated from the immediate socio-cultural (often urban) environment (cf. Hoffmann and Schickore 2001; Hoffmann 2001; Schmidgen 2004). Its outer as well as inner boundaries had to be defined. The "well-tempered environment" of laboratory buildings – to use a term coined by the architectural critic Reyner Banham – which were supposed to buffer external acoustic, atmospheric, hygienic, physico-chemical or socio-technical, disturbances, had to be designed carefully. The outcome of this process was a multiply nested research environment – similar to a Russian doll – that reached from the outer shell of the building, the intermediary strata of administration and teaching to the innermost "extreme milieus" of the laboratory buildings, in which research was actually done (Latour 1992, 299; Felsch 2005, 30–32). In the late nineteenth and early twentieth century, even within the sanctuaries of experimental research, we witness further stratification and a rigid redefinition of spatio-functional boundaries: Experimental glass containers, in which the objects of research were enclosed and studied, turned from a handcrafted technical object into an epistemically relevant and technologically controlled boundary, forming the envelope of the material nucleus of experimentation. This technological reconfiguration commenced in the 1850s when scientists First discovered that contrary to their traditional expectations, laboratory glassware was all but chemically neutral.

Setting the Scene: Individual Glass Errors in the Laboratory

There had been doubts about the chemical neutrality of laboratory glassware and its possible effects on experiments already in the eighteenth century in the context of a debate on the possible transmutation of water into earth (Eller 1746; Pott 1756; Marggraf 1756; Lavoisier 1770) and in the context of the discovery of the element fluor (Espahangizi and Orland 2014b, 11–13). But it took until the advent of precision

[11] A few influential works in the field of historical *laboratory studies*: Wise 1995; Rheinberger 1997; Pickering 1995; Daston 2000, Daston and Galison 2007; Cahan 1985; Meine 2000; Kohler 2002.

measurement and exact experimentation in the nineteenth century, when the chemical interaction of experimental glassware with the contained substances ceased to be a marginal curiosity to experimental practice and natural philosophy. Instead, this interaction turned into a dynamic and integral factor in emerging laboratory research environments.

The first note on glass-induced measurement errors was published in 1853 in a short appendix to the third edition of the famous textbook *Quantitative Chemical Analysis* edited by the German chemist Carl Remigius Fresenius. Fresenius was working at Justus von Liebig's internationally renowned laboratory in the city of Giessen, when he noticed irregularities while weighing residues in watch-glasses. He concluded: "A lot of strange phenomena that disturb chemical analysis are due to the contamination of the evaporated substance by the material of the vessel, gross errors often originate from this source. Because of its importance, I have made further investigations on this subject" (Fresenius 1853, 76; cf. also the appendix "Analytische Belege"). Fresenius' textbook was a huge success, it was circulated widely and with it, the first notes on measuring errors caused by glassware (Poth 2006).

The second, maybe even more important reference to this issue was made by the Belgian chemist Jean Stas a couple of years later. In the late 1840s Stas' teacher, the already mentioned Jean-Baptiste Dumas, had called for a thorough reevaluation of the atomic weights measured in the early nineteenth century. The exact quantification of atomic weights was supposed to provide a solid fundament to future chemistry. Jean Stas adopted his teacher's scrutiny. No measuring error, as minimal as it was, could eventually be tolerated (cf. Schickore 2005). All marginal conditions of experimental settings and measurements had to be controlled accurately, even supposedly unsuspicious glassware. In the introduction to his influential paper on atomic weights published in 1860, Stas stated: "Indeed, I have been observing that the weight of tubes, retorts or flasks made of glass ... changes significantly. Be it because of the heat, the attack of chemical substances, which we assumed not to have any influence on glass" (Stas 1860, 220). With these remarks, and through a second more comprehensive paper in 1865, Jean Stas drew the attention of the scientific community to the chemical agency of experimental glassware (Stas 1865; Braun 1868). Shortly after, Robert W. Bunsen, professor at the University of Heidelberg, a shooting star of chemistry at that time and Stas' friend, initiated the first systematical study on the chemical agency of experimental glassware.[12] The aim of this work, executed by his assistant Adolph Emmerling, was to elicit possible regularities in the chemical interaction between the experimental container and the contained substances of interest and to derive precautionary measures in order to minimize glass errors in laboratory practice (Emmerling 1869). But beyond such limited practical rules for everyday laboratory life, like boiling the glassware beforehand, using

[12] Bunsen wrote an impressive letter of recommendation for Stas who needed financial support from the Belgian government. Cf. "Lettre à Stas pour le Ministre Rogier. Heidelberg, 23 Septembre 1860" in the Archives of the University of Bruxelles (manuscript no. 004P/18/034).

smaller amounts of experimental substances, preferring already used glassware, etc., a more sustainable solution was needed. Jean Stas, who was acquainted with technical glass chemistry due to his teacher Dumas, had come to the following conclusion: In order to re-stabilize the vitreous boundaries of experimental settings, new, specifically modified and adapted glasses had to be designed. That is, new glass types had to be invented.

Half-heartedly supported by the Belgian state, Stas commenced to work on a new glass formula. In order to translate his theoretical paper work and laboratory experience on a possibly ideal glass composition into a workable recipe for glass making, he had to collaborate with a glass manufacturer near Brussels (Stas 1865, 217–218). In 1868, he was finally able to present the results of this early cooperation between glass science and the manufacture of glassware in William Crookes' *Chemical News* (Stas 1868, 1). Jean Stas glasswork indicated the guidelines that the technology of scientific glassware would have to follow in the next decades. The glass composition had to be adapted to the exigencies of precision measurement. However, Stas' project stayed in fact singular and isolated. No doubt, Stas had generated a glass suitable for his own work and more than that his scrutiny concerning the glass error was praised by his colleagues to be an ideal role model for the ethics of exact research and scientific preciseness (Braun 1868, 160, 165). But as an individual experimentalist working in his home laboratory, he had no ambition, no support, and even less infrastructural means to improve the general quality of experimental glassware. In order to understand the limitation of Stas' efforts to deal with the glassware issue, one has to bear in mind that at the time there was no single laboratory glass on the market, but rather a wide and unclear variety of regional glass products with varying, traditionally secret recipes and therefore mostly unknown chemical compositions. Moreover, there were very different expectations with regard to the uses of glass containers in experimentation: In some contexts, glasses had to be more resistant to acids, in others more resistant to alkaline attacks or to water-induced corrosion, etc. (cf. Newton 1985). So on the one hand, there was functional heterogeneity of glass containers. But on the other hand, a certain standardization of the physico-chemical properties of scientific glass containers was essential to guarantee the general comparability of experimental outcome. In order to realize such an extensive project, the reconfiguration of the spatio-functional boundaries marked by laboratory glassware, actors and institutions from different fields, such as science, technology, industry, and politics had to come together. Existent glassware had to be analyzed, glass research had to be coordinated, uses and exigencies of glassware had to be identified, new glass batches had to be developed, standardization procedures and criteria of glass quality had to be determined, and finally, these glasses had to be distributed and brought to modern laboratories. In sum, the efforts of an individual like Jean Stas were heroic but rather insufficient. A large-scale adjustment of scientific glassware would depend on a whole techno-scientific infrastructure (cf. Edwards 2003, 188–189). In the following subchapter, I will sketch the emergence of this infrastructure in the second half of the nineteenth century.

Preparing the Ground: The Emergence of Technical Glass Chemistry

The first successful steps towards a collectively organized improvement of glassware were initiated by the industry, more precisely the *Prussian Society for the Advancement of Industry*, which had prominent members like Werner von Siemens and Hermann Helmholtz. In 1850, this influential interest group promoted the development of industrially applicable technical procedures to test and predict the "weathering" tendency of glass surfaces by offering various prizes "in the most widespread newspapers in Berlin."[13] As mentioned earlier, at that time the glass industry was taking off and material quality became an issue in the industrial production of glass products. In spite of the substantial advancements technical chemistry had made since the pioneering work of Jean-Baptiste Dumas, it took until the early 1860s when Rudolf Weber, a technical chemist from Berlin, was finally awarded the silver medal for his contribution to the glass-testing contest of the *Prussian Society*. Weber's testing procedure encompassed the following steps: First, the glass specimen had to be cleaned thoroughly with alcohol and then put beneath a bell jar filled with vapors of strong nitric acid for 24 hours. In a next step, the glass specimen had to be taken out of the bell jar for another 24 hours so that the condensed acid would evaporate from its surface – the less steamy the glass, the better the quality (Weber 1864). Weber's test was quite impractical, but due to the lack of alternatives it came into use within the glass industry in the 1890s. From a scientific viewpoint however, it was deeply unsatisfactory: It depended on a rather subjective assessment of glass quality without quantification and it did not provide any theoretical explanation of the chemical phenomena involved. Having become the Society's glass expert, Weber, too, aimed at more than only providing a quick industrial test for glass surfaces. Like Jean-Baptiste Dumas before, technical glass chemists at that time searched for the formula of a true universal glass (Stein 1862, 25), the *Normalglas*, as the young glass chemist Herman Benrath at Baltic Dorpat University named it (Benrath 1868). With statistical methods generally advancing at this time, Benrath analyzed and compared dozens of glass products on the market, applying Weber's nitric acid test among others, in order to determine the mean value of the chemical composition of all "good glasses" (Benrath 1875, 25–27).

But what was a *good glass*? What is the meaning of *good* in this context? For Benrath, this attribute referred to the combined assessment on a set of different attributes: fusibility, processability, hardness, brilliancy, and resistance to chemicals. His *Normalglas*-formula, which was supported by Rudolf Weber's results, should provide glassware suitable for every purpose (ibid., 34; and Weber 1879, 450). In contrast to the functional specificity of Jean Stas' glassware, Benrath's and Weber's standard glass formula had been derived from statistical "field work" and the formula had to be an ideal all-in-one device, be it for scientific or non-scientific purposes.

[13] Cf. the proceedings of the society in April 1850, vol. 28, p. 60.

But at the same time, the use of glassware in laboratories had diversified and intensified since the mid-nineteenth century.[14] Therewith, the problem of glass attack turned out to be more complex so that neither the idea of a mean value *Normalglas*, nor the individual enterprise of a solitary experimentalist like Jean Stas could eventually solve it. Both approaches, i.e. material standardization based on collective efforts as well as functional specificity, converged when around 1880, the needs of scientific research took the lead as the driving force in the quest for better glass containers. The techniques and criteria of laboratory measurement had changed dramatically since the early nineteenth century and so did the exigencies towards the boundaries of experimental settings. The "best" glassware was no longer needed in construction or in households, but in the laboratory. The field in which technical glass chemistry and the needs of modern laboratory research came together was, somewhat unexpectedly, scientific thermometry and not chemical glassware.

Working Together: A Standard Glass for Thermometry

By the 1870s thermometry, more precisely mercury-in-glass thermometry, had become an all-important research technology. Nonetheless, its precision suffered from a severe technological flaw. The zero point of the thermometric scale shifted with every use (Pernet 1875, 266). In 1874, the astronomer Wilhelm Foerster, one of the most prominent actors in the field of international metrology, a member of the *International Bureau of Weights and Measures* and head of the *Imperial Standards Commission* since the founding of the German *Reich*, put his assistant Leopold Loewenherz in charge of investigating this phenomenon to find a solution (Loewenherz 1877; Foerster 1911). Loewenherz, who would later become one of the founders of the influential German *Journal for the Study of Scientific Instruments*, joined the Prussian Society for the Advancement of Industry, which pushed the solution of this problem by offering yet another 1500 silver coins.[15] In the next two years, Foerster's assistants found out that the chaotic shifts of the thermometric scale were due to the complex thermal behavior of the glassware, which expanded and contracted in a non-linear way with every heating episode (Thiesen 1881). This is not the place to go into details of the history of thermometry, the important point would rather be that in the course of these collective efforts to stabilize mercury-in-glass-thermometry, the field of scientific metrology came into contact with the technology of glass chemistry. As a result, a nucleus of cooperation took shape that would be decisive for the improvement of scientific glass containers in the following years. In 1880, Hermann Wiebe, another assistant of Wilhelm Foerster at the German Standards Commission, contacted his

[14] Catherine M. Jackson has coined the term "glassware revolution" for the history of chemistry (cf. Jackson 2008, 162).
[15] Cf. proceedings of the Prussian Society for the Advancement of Industry, 1874, 53:21.

former colleague from university, the young technical glass chemist and entrepreneur Otto Schott, who had earned his PhD in 1875 with a thesis on the *Theory and Practice of Glass-Making* at the University of Jena, and asked him for help.

There is no need to emphasize the great importance of Otto Schott for the history of scientific glassware. Together with his associate, the German physicist Ernst Abbe who had been an assistant to Carl Zeiss, he founded the renowned glassworks in the city of Jena and revolutionized glass technology. But whenever the name Schott is mentioned, historians (of science) usually think of his contribution to the improvement of optical glasses (cf. Jackson 2000). Indeed, at first sight, scientific glassware seems to be a mere by-product of the success of Schott's optical glasses. But in fact, it played an important role in the consolidation of Schott and Abbe's fragile business start-up in the early 1880s (cf. Zschimmer 1909; Kühnert 1946; Kühnert 1949; Kühnert 1953; Kühnert 1957; Bayer et al. 2003). When Wiebe asked him for help, Schott was at first reluctant to being distracted from his work on optical glasses.[16] But realizing it would make a good case for governmental aid, he finally agreed on cooperating with the *Imperial Standards Commission* on thermometric glass in 1882.[17] Not surprisingly, the Prussian state granted the bitterly needed financial support shortly after.

In Schott's laboratory, state-of-the-art glass research and glass making came together in a new way. They did R&D *avant la lettre*, based on experimental glass melting, systematic variation of batch ingredients, and introduction of chemical elements guided by theoretical knowledge and minutely journalized results. Indeed, between April 1883 and November 1884, Schott was able to develop a glass batch – melt number 16^{III} – which eliminated the zero-point problem by optimizing the ratio of sodium and potassium in glass composition. Schott alone however, like Jean Stas before him, could not have accomplished the necessary distribution of this new glass. His young company would have to compete with the established glassware manufacturers in the forest of Thuringia who were in fact still helping Schott. Schott depended on temporarily hiring skilled workers of the region in order to draw the necessary fine glass tubes (Kobe 2008, 42). Schott did not yet possess the experience, the resources, the necessary commercial network, or a base of customers. Against all odds, his sales were pushed by a governmental decree issued in 1885: Mercury-in-glass-thermometers had to be certified by testing houses led by the *Standards Commission*, with Schott's new glass as the benchmark.[18] It was to a great part the authority of the state, combined with entrepreneurial ability, which ensured and enforced the diffusion of the first *specific* standard glass, the so-called *Jenaer Normalthermometerglas* in the scientific world.

[16] Letter from Otto Schott to Hermann Wiebe (October 7, 1880) (see in Kühnert 1953, 50).
[17] Letter from Otto Schott to Hermann Wiebe (October 7, 1880) (see in ibid. 5).
[18] Cf. the circular of the Imperial Standards Commission (September 27, 1885) (see in Kühnert 1957, 172-174; Wiebe 1886a, 22-25; and Wiebe 1886b, 167-171).

Getting Serious: New Glasses for New Laboratories

While Schott's sales were increasing rapidly, quintupling from 1885 to 1890, glass-induced measurement errors of all kinds, not only in thermometry, had become ubiquitous in modern laboratory research. In the mid-1880s, glass errors were noted in different branches of analytical chemistry, in gasometry, physics, cathode ray physics, hygienology, and in physical chemistry (Fresenius 1883; Bohlig 1884; Warburg 1884; Warburg and Ihmori 1886; Egger 1884; Bottomley 1885; Wartha 1885; Lunge 1885; Kohlrausch 1885; Bunsen 1883; Bunsen 1885). Experimentalists had come to the conclusion that "facing the facts ... one cannot ignore anymore that the material our indispensible chemical instruments are made of does not fulfill the requirements, and that producing a remedy is highly desirable" (Kreusler and Henzold 1884, 40). The German Standard Commission, too, realized that glass errors were far more common than initially thought. Even the use of bubble levels (small glass vessels filled with ether and air that indicate whether a surface is horizontal or not) in astronomy, geodesy, and artillery was affected by the chemical agency of glassware.[19] Material deposits on their inner surfaces impeded the free movement of the enclosed bubble and made precise surveying extremely difficult. Because of the experiences with mercury thermometers, the culprit for this phenomenon was easily identified: the substance of glassware. But Otto Schott was still working on the thermometric glass and he had no increased affection to deal with these new glassware "calamaties."[20]

It took until the foundation of the *Physikalisch-Technische Reichsanstalt* in Berlin, with its own laboratories, for the problem to be studied systematically. This state-funded institute for metrological research, which took up its work in 1887, was closely tied to the *Imperial Standard Commission*.[21] Leopold Loewenherz for example, became the director of the technical division of the *Reichsanstalt*; and Hermann Wiebe, who had initiated the collaboration with Otto Schott, would head the heat and pressure laboratory. Franz Mylius, director of the new chemical laboratory of the *Reichsanstalt* in Berlin-Charlottenburg, continued the glass cooperation with Schott in place of Wiebe (Engel 2001; Foerster 1931). In the winter of 1887, Mylius visited the glassworks at Jena for the first time.[22] Being in correspondence with Schott, Mylius quickly ascertained the reason for the problems with bubble levels. The deposits on the inner surfaces of their small glass chambers were caused by chemical attack not by the ether itself but by the small amount of water dissolved in the ether (Mylius 1888). This finding also matched perfectly with the experience of experimentalists in the 1880s. Much to their surprise, it was the precarious relationship between two supposedly pure and neutral

[19] Wilhelm Foerster complained about this issue in the *Vierteljahresschrift der Astronomischen Gesellschaft* (1883, 18:243).

[20] Letter from Otto Schott to Wilhelm Foerster (April 10, 1884) (see in Kühnert 1957, 250).

[21] The two institutions merged in 1922. For the history of the Reichsanstalt, see Cahan 1989.

[22] Letter from Franz Mylius to Otto Schott (December 19, 1887) in the Schott Archive (2/8).

substances, such as glass and water, which turned out to be the most relevant source of measurement errors caused by experimental glassware. Franz Mylius was well aware of this general situation when he and his assistant Fritz Foerster started to focus their research on the interplay of glass and water. More than that, the interaction between these two substances turned out to be the *leitmotif*, or rather Ariadne's thread, in the quest for standardized glass tests and new glassware.

The Leitmotif of Glass Reform: Hygroscopicity

Understanding the interaction of glass and water was a complex task: When Mylius and Foerster started their investigation they did not possess a theoretical model (of what happened when glass surfaces came in contact with water) nor a reliable testing procedure to measure the effects. However, since the early nineteenth century, chemists knew that watery solutions contained in glassware turned basic (cf. for example, Faraday 1830, 47–48). Mylius' experiences with bubble levels on the one hand and with organic chemistry on the other hand led him to develop a colorimetric testing procedure based on a dye synthesized in the 1870s: iodeosin. When dissolved in an aqueous ether solution, the iodeosin and the alkali would form a red-colored salt that would then precipitate on the attacked glass surfaces. Therefore, color intensity could be taken as a measure of the chemical quality of the glassware. For the first time, the glass testing procedure was expressed in a chemical formula (Mylius 1889, 52).

Nonetheless, Otto Schott did not hesitate to utter his critique. Mylius' test was still purely qualitative, like Rudolf Weber's acid nitric method at use in the glass industry. It literally stuck to the surface without getting to the core of the glass substance.[23] Challenged by these valid objections, Mylius and Foerster refined their method in the following months and presented a modified quantitative, titrimetric procedure in 1891 (Mylius and Foerster 1891). With growing concerns about the neutrality of laboratory glassware and its functioning as an experimental boundary, this turned out to be just in time. Experimentalists were already demanding "not only to differentiate between suitable and non-suitable glasses, but to *quantify* their solubility in water by *exact measuring methods* in order to assess their performance ... numerically" (Pfeiffer 1891, 264). It was the duty of the *Reichsanstalt*, directed by Hermann Helmholtz, to take these demands seriously (Helmholtz and Loewenhertz 1891). Thus, from the early 1890s, Mylius and his team started to provide a public service for testing scientific glassware that was sent in, based on their iodeosin method, while extending their glass research.

Mylius and Foerster were now able to model the interaction of water and glass as a two-stage process (Foerster 1893): In a first step, water soaked the glass surface dissolving the alkali parts of the glass substance, which was now understood as a mixture

[23] Letter from Otto Schott to Franz Mylius (January 12, 1889). See in the Schott Archive (file 2/8).

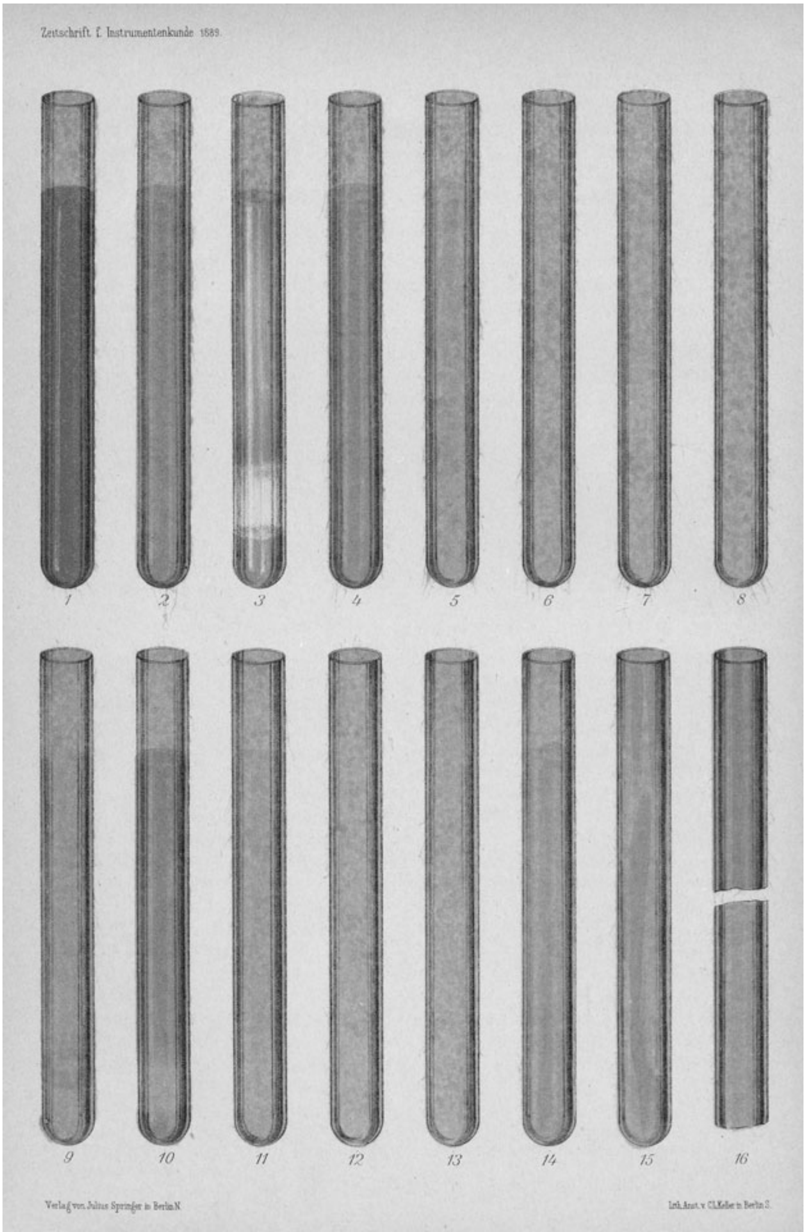


Fig. 2. Glass Testing with Iodine-Eosin. Source: Mylius 1889, 52.

of compounds as well as a frozen solution. The dissolved alkali would in a second step leach the remaining glass substance and decompose the silicates. In other words, alkaline attack on glass could be subsumed under this model. The same applied for acid attack, which was actually caused by the aqueous solution, not the acid itself (except for fluoric acid). Backed by this theoretical model, this so-called glass hygroscopicity turned out to be a valid benchmark for assessing the general chemical durability of glasses. Mylius and Foerster could therefore use their iodeosin test in order to assess and compare the general quality of all laboratory glasses sent to the *Reichsanstalt*.

Improving Glass Quality in Berlin and Jena

Otto Schott was a glass technologist and entrepreneur and he had different objectives from the *Reichsanstalt*. His plan was not to provide a liable glass test but to design and sell new glassware adapted to the needs of laboratory research. This time however, he had no official order or mandate as in 1882. Nonetheless, his contact with Mylius and the *Reichsanstalt* encouraged him to carry out this work. Since 1885 Schott had also successfully expanded his network within the German scientific community. So, he was now able to "hear" the demands of the experimentalists without any mediation from the *Reichsanstalt*. Some scientists even started to consult the "glass doctor" (Kühnert 1949, 17) on glass issues. Among them were renowned scientists like Friedrich Kohlrausch, author of the famous *Guidelines to Practical Physics* and second president of the *Physikalisch-Technische Reichsanstalt*. In 1889, Kohlrausch had noticed that the dissolution of glass introduced a significant error into the measurement of the electrical conductivity of pure water, a fundamental parameter for the nascent discipline of physical chemistry (Kohlrausch 1891). He realized that it made no sense trying to determine the electrical properties of laboratory water without taking into account its interaction with the glass container. During this research on the hygroscopicity and solubility of glass, he repeatedly contacted Schott, asking him for advice and for glass specimens.[24]

To sum up, in the aftermath of his successful collaboration with the *Standards* Commission on thermometric glassware, Schott had positioned himself strategically in the landscape of scientific research and official metrology.[25] He knew of the needs and exigencies of laboratory research at first hand and this insider expertise went directly

[24] There are seven letters between 1891 and 1893 documented in the Schott Archive (2/8). Kohlrausch's glass studies between 1890 and 1893 are well documented in his laboratory journals nos. 41, 42, 45, 49, in the Archive of the Deutsche Museum in Munich.

[25] Schott had also started to collaborate with local physicists. Together with Adolph Winkelmann, physicist at the University of Jena, he succeeded in setting up an equation, which related the composition of a given glass to some of its physical properties, like thermal expansion, specific heat, elasticity, etc. (cf. Winkelmann and Schott 1894).

into his efforts to design new adequate glasses for experimentation and precision measurement. Moreover, it also led to his glass research.

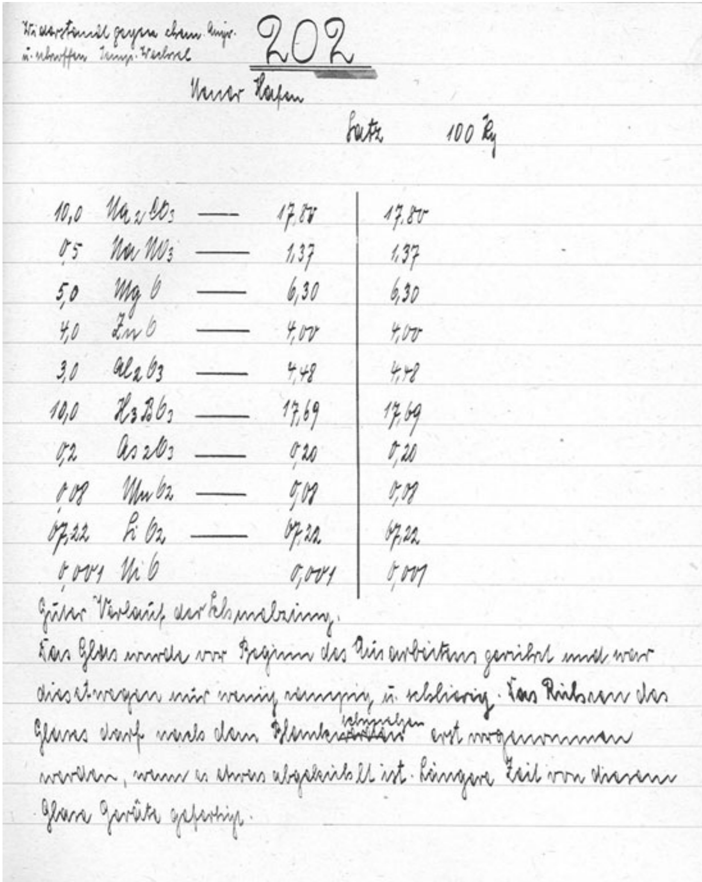
Schott too, had started to study the hygroscopicity of glass surfaces as early as 1889, finding out that glasses based on the melting agent sodium had a lower hygroscopicity than potassium (or mixed) glasses (Schott 1889). He also knew that the admixture of glass-forming borosilicates optimized the thermal durability of glassware (Schott 1891). Last but not least, analyzing the famous but "unscientific" glasses of his Thuringian neighbors, Schott discovered that their excellent processability was due to a certain amount of aluminum oxide (Schott 1887). By optimizing all of these parameters and generally benefitting from his intuition and experience in glass melting, Schott finally succeeded in spring 1892. Glass melt number 202^{III} was the first promising candidate for a new laboratory glass. In his melting journal, we find the following side note: "resistance to chemical attack and abrupt change of temperature."[26]

When Jean Stas had developed the first modern laboratory glass in the late 1860s, he published its composition in a chemistry journal. Some twenty-five years later the situation had changed completely. A complex infrastructure had come into being which involved various scientific, technical, political, and industrial actors and institutions, which was based on the strong Berlin–Jena axis. Schott's efforts to design new laboratory glasses were embedded in this partly formal, partly informal techno-scientific infrastructure, which carried out the general reform of glassware used in all kinds of laboratories in Germany. The new apparatus glass could now be sent to the *Physikalisch-Technische Reichsanstalt* in order to be tested, certified and, in a way, promoted.

Before Mylius and Foerster would publish the results of their extensive testing of German glassware in 1894, Otto Schott did not miss the opportunity to write his colleagues in Berlin a letter praising the extraordinary quality of his new glass and to ask for its adequate "appreciation" by the *Reichsanstalt*.[27] *Schott & Company*, who had already implemented new Siemens furnaces in order to start bulk production, expected this test to boost their sales – and Schott would not be disappointed. Foerster confirmed in public: Glasses from Jena had reached "the limits of what is technically possible" (Foerster 1894, 396).

Schott's glass products outmatched other glasses, but they did so only in general performance. Other glasses turned out to be more adequate to specific uses. The conclusion that Mylius and Foerster drew from their results was far-reaching: Even with the ongoing improvement of general glass quality, there was *in principle* no ideal universal glass that could possibly supersede all other glasses. In a speech at the fifth *International Conference on Applied Chemistry* in Berlin, Mylius ultimately buried the hopes of Benrath, Weber, and other technical glass chemists to find a *Normalglas*:

[26] The melting journals can be found in the Schott archive (Steiner 1993).
[27] Letter of Otto Schott to Fritz Foerster (December 30, 1893) (see in the Schott archive, file 2/8).



202

Satz 100 Kg

10,0	Na_2CO_3	—	17,80	17,80
0,5	$NaNO_3$	—	1,37	1,37
5,0	MgO	—	6,30	6,30
4,0	ZnO	—	4,00	4,00
3,0	Al_2O_3	—	4,48	4,48
10,0	H_3BO_3	—	17,69	17,69
0,2	As_2O_3	—	0,20	0,20
0,08	MnO_2	—	0,08	0,08
67,22	SiO_2	—	67,22	67,22
0,001	NiO		0,001	0,001

Fig. 3. Otto Schott, Glass Melt 202^{III} (1892). Source: Schott Archive, Jena.

> Sirs! We once imagined a universal glass to be possible, suitable for every purpose. We now know, that there is no such a glass. Quite the contrary, we know that each specific use of glassware has its own ideal standard. We are now witnessing that with every year the specialization of glasses advances ... . In fact, there is no glass, which resists equally to all kinds of chemicals, and there is no hope to ever find one. (Mylius 1903, 884)

Mylius realized that the wish to homogenize the glass material itself contradicted the ongoing functional differentiation and multiplication of glass types. But what was the alternative? How could glass quality be generally improved and harmonized in order to guarantee the comparability of experiments and measurements in different laboratory settings? Mylius' answer to that question was: standardizing the glass tests rather than the glass substance. In the course of his ongoing iodeosin tests in the 1890s, he had

Hydrolytische Klassifikation der Gläser:

Milligramme Jodeosin auf ein Quadratmeter.

Klassen	Glasarten	Verwitterungs-Alkalität	Lösungsalkalität bei Hohlglas		
		Färbung an Bruchflächen	I. Auszug 18°	II. Auszug 18°	III. Auszug 80°
I. Klasse	Wasserbeständige Gläser	0—5	?	0—5	0—20
II. Klasse	Resistente Gläser	5—10	?	5—16	20—61
III. Klasse	Härtere Apparatengläser	10—20	?	16—49	61—202
IV. Klasse	Weichere Apparatengläser	20—40	?	49—202	202—809
V. Klasse	Mangelhafte Gläser	über 40	?	über 202	über 809

Fig. 4. Mylius' Hydrolytic Classification of Glass Quality. Source: Mylius 1913, 5.

distilled the first classification system of glass quality, the so-called hydrolytic classes. Not surprisingly though, it was scaled in regard to the properties of Schott's apparatus glass, the so-called *Jenaer Geräteglas*. Mylius and his team continued to work on this classification system and improve it step by step in first decade of the twentieth century (Mylius 1907, 1910).

> We propose a division in five hydrolytic classes of chemical durability for all types of technical silicate-glasses (independent from their percentile composition). ... the terms water-resistant and resistant glass are already in use for the first and the second class; . . . as well as poor glass for the fifth class. Glass substances belonging to the third and fourth class, which are not apparatus glass, are sufficiently characterized by the numbers. (Mylius 1913, 5)

Mylius' hydrolytic classification system was the scientific basis and the starting point of the development of specialized industrial norms (Din Denog) on glass quality that started after World War I in Germany in close cooperation with the *Reichsanstalt*, the German Association for Chemical Apparatus (Dechema), the special glass industry, industrial consumers of chemical glassware and other interest groups. A whole "cosmos of norms" (Vec 2006) dealing with scientific, industrial and commercial glass emerged in the 1920s (in Germany) and 1930s (internationally),[28] and these norms based on glass hygroscopicity continue to be the general reference of glass quality until today.

Implementing New Glass Boundaries in Laboratory Research

In spite of the substantial advances in standardized glass testing and glass development, the glassware reform had by no means come to an end in mid-1890s. It still had to reach the laboratories.

In the case of thermometric glassware, governmental authority had pushed the diffusion of Schott glass in the scientific world. This time there was no decree, no mandatory testing or certifying of experimental glassware. However, the general awareness for the physico-chemical properties and unwanted effects of glassware had increased fundamentally since the 1880s. There was even a certain self-enforcing dynamic, as the ongoing debates on glassware drew the attention of even more disciplines and individual experimentalists. In the course of the collaboration between the German *Standards Commission*, the *Physikalisch-Technische Reichsanstalt* and Schott's glassworks, an informal infrastructure arose which had the epistemic, technical and normative authority and reputation to satisfy this demand and to initiate the necessary reform of laboratory glassware. The widespread diffusion of *Jenaer Geräteglas* into the laboratories is reflected in the sales figures (national and international) in the company's archives (Steiner and Hoff 1995). We can follow the path of the new glasses into the inner core of experimental research also by looking at the scientific output. From the mid-1890s, Schott glasses were mentioned more and more frequently in experimental reports, papers, and textbooks. In 1900, Schott's success as a global player and world market leader on technical glasses culminated in the World exhibition at Paris (Müller 1900).[29] Nonetheless, the work on the physico-chemical boundaries in the laboratory was by no means limited to a replacement of old glassware by Schott glasses. In spite of their general quality, Schott glasses were neither ideal nor universally suitable for all uses. Hence, other manufacturers of scientific glassware started to revise their glass batches trying to match the new criteria established by the *Reichsanstalt* in order to satisfy the specific demands of their customers and compete with Schott. From the late 1880s, certified chemical and thermal durability of glassware was a sales pitch. It was the complex interplay of market dynamics, state intervention, and techno-scientific demands that broadly raised the general level of glass quality and the new *awareness* for glass quality in modern laboratories, spreading from analytical chemistry, to gasometry, physical chemistry cathode ray and X-ray physics, medicine, and – as shown in the quoted handbook at the beginning – into microbiological disciplines like bacteriology

[28] The development of those industrial norms has a rich history of its own that will be the object of a forthcoming paper. For more details see also Espahangizi 2010.
[29] In the same year the first comprehensive book on Schott glass was published (Hovestadt, 1900).

and cell physiology (cf. Benecke 1896; Hesse 1904; Campbell-Swinton 1907; Sternberg 1914). This new glass consciousness even influenced commercial packing technology for food, beverage, and pharmaceutical products (Ford 1930). Inside the laboratory, the chemical agency of glassware had produced measurement errors. Outside the laboratory, i.e. in the sphere of industrial production and circulation of goods, it turned out to have unhealthy, painful, sometimes even lethal consequences. Glass-packed, water-based pharmaceutical substances like cocaine, strychnine, morphine, etc. for example were heavily altered by glass hygroscopicity (Grübler 1907; Stich and Wulff 1918). Again, it was the technoscientific reconfiguration of the glass boundaries, i.e. their packing material, which made these substances *immutable* and therefore *mobile*. Due to these chemically more inert glass envelopes the enclosed substances could be stored or transported for a longer time without any notable alteration.[30]

The standardization of the container material glass based on hygrospicity connected the fields of scientific research, technological application and industrial production in a productive way. One striking example for this would be Fritz Haber's work on the so-called glass cell: In 1905 Fritz Haber, famous for his method of ammonia synthesis and less known for his glass studies, had been requested to develop an easy glass-testing method for the bottle industry. Scanning the vast literature on glass-testing since the 1860s, he eventually decided to repurpose the above mentioned findings of Friedrich Kohlrausch: If the dissolution of glass in water increased its electrical conductivity, this effect could be used the other way round as a testing method for glass quality (Haber und Schwenke 1904). This finding was his starting point. Being a scientist at heart his aim, however, was not only to measure the effects, but also to understand the processes going on at the phase boundary between glass and water (ibid., appendix). Around 1907 Fritz Haber, who was familiar with the earlier debates on the electrochemistry of cells (cf. Grote 2010), realized that the hygroscopicity of glass, as first theorized by Mylius and Foerster, could also serve as a model for the so-called "phase boundary force" (i.e. an electromotive force at the boundary of two electrolytic phases) at semipermeable cell membranes (Haber and Klemensiewicz 1909).[31] The experiment that Haber designed in order to study his cell model was based on two nested laboratory glass vessels: The outer beaker was made of – significantly – *Jenaer Geräteglas* whereas the inner spheric vessel had to be made of the chemically less resistant old type of Thuringian glass. Here, water-induced corrosion was of course a desired effect. In a sense, a twofold history of glassware as a material boundary of experiment and as a medium of exploring boundaries converges in this experimental design (cf. Espahangizi 2011b): On one hand, Haber's glass cell incorporated the traditional as well as the new, modified laboratory glass types, and on the other hand, the whole setting

[30] For my generalization of Bruno Latour's concept of *immutable mobiles* from inscriptions also to non-inscripted material objects, see Espahangizi 2011a.

[31] As there was no single coherent membrane theory at that time, the glass membrane model was added to the conceptual mosaic (cf. Michaelis 1926).

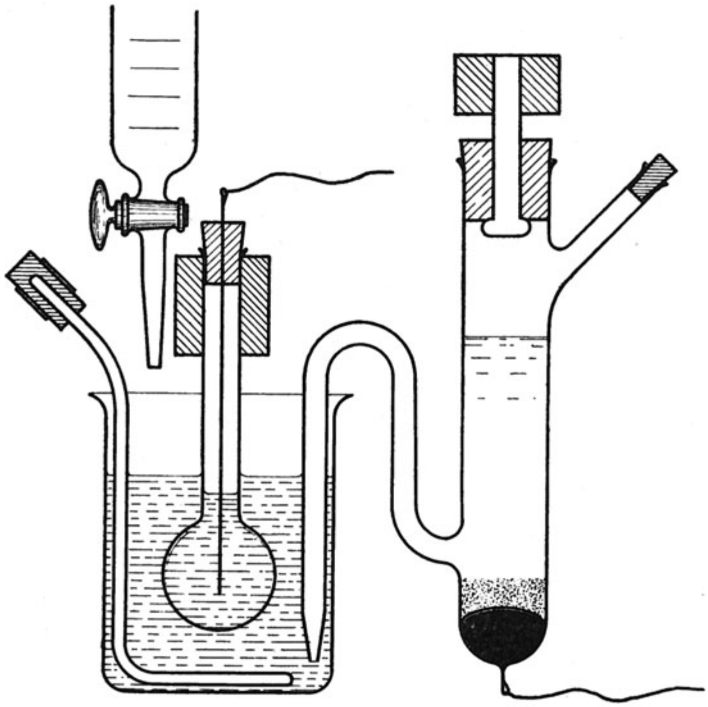


Fig. 5. Haber's Glass Cell. Source: Haber and Klemensiewicz 1909, 411.

was meant to be an experimental model for electrochemical processes at semipermeable cellular membranes.

But the importance of the glass cell went far beyond modeling bioelectric potentials. The knowledge of glass hygroscopicity also inspired the design of a measuring instrument that is still in wide use today: the glass electrode. In his experiments, Haber had noted that the "phase boundary force" between the glass and the water increased with the logarithm of the acidity and alkalinity, respectively. In other words, Haber's glass cell was potentially some kind of chemical yardstick for those parameters. In the same year Haber published his results, in 1909, and Søren Sørensen proposed the use of an index that today is known to indicate acidity/alkalinity – not only in research but also in everyday life – as the *pH-value* (Sørensen 1909). The glass electrode and its widespread use can be taken as one very illustrative example of a well-known phenomenon in the history of science, that is, the unintended epistemic productivity and unanticipated consequences of certain findings and technical development, in this case of the glassware reform in the modern laboratory. Indeed, the glass electrode turned out to be a valid measuring device for a fundamental quantitative index of (bio-)chemical milieus (Kratz 1950). Moreover, being an all-important device today for pH-measurements in ecology (within the laboratory, as well as in the field), the glass electrode whose history begins with a glass-testing procedure for the bottle industry based on hygroscopicity turns out to be a meaningful emblem for the conceptual shift in the history of scientific glass containers that guides my paper: from *topos* to *oikos*.

Outlook: From *Topos* to *Oikos*

As mentioned in the opening paragraph, the culturally established image of scientific glassware can be understood as a *topos* in both of its meanings: It symbolically outlines the ideal place of experiment *in* (imaginative) *vacuo*, i.e. a place that is not embodied and embedded in the material conditionalities of real laboratory environments and their historical trajectories. This image obstructs the view of the material historicity of scientific glassware. No one doubts that there has been historical progress in glass making techniques, but what does this tell us about the changing nature of the material itself? A more or less defined set of properties seems to constitute and define this substance, first and foremost translucency. Chemical neutrality, too, is commonly ascribed to the nature of glass, although in a more implicit way. Without doubt, the extraordinary qualities of glass are reasons for the rich cultural history of the substance. But the underlying image of glassware neutrality rendered the actual materiality of this material as something invisible for scientists until the nineteenth century as well as for historians of science today.

In my paper I have dealt with the reconfiguration of glass boundaries during the emergence of a modern laboratory environment in the late nineteenth and early twentieth century. First, I related the development of container glass industry and technical glass chemistry in the mid-nineteenth century. Then I focused on the rise of a new awareness for measurement errors due to the chemical agency of experimental glass vessels in the context of precision research. In a third step, I sketched the emergence of the techno-scientific infrastructure that fostered the improvement and material standardization of scientific glass containers in late nineteenth-century Germany.

The aim of the paper was to "re-materialize" the glass container in the history of science, which means to recover the rich materiality and historicity of its substance in the context of the modern research laboratory.[32] But what have we learned about the very nature of this material? We have seen that the uses of glassware, the theories on the nature of glass, glass research, glass classifications, glass testing procedures, glass making techniques – all these dimensions of materiality are in constant flux. It is their historical interplay in the first place, which gives meaning to the question "What is glass?" Not surprisingly, it was in the heyday of glass standardization when the nature

[32] This conceptual approach was developed in Klein and Lefèvre 2007 (cf. also Espahangizi and Orland 2014a).

of glass was again problematized and glass theory advanced fundamentally (Zachariasen 1932; Tammann 1933; Morey 1936).

From the viewpoint of historical ontology we should understand glass not as a single substance, but as a wide variety of similar substances in a phenomenological continuum, divided by knowledge, practices, and the perception of what people think glass is or what it ought to do. From this perspective, the material genealogy of glass turns out to be essentially intertwined with the development of the specific uses and functions of glassware, in this case of scientific glass containers. Hence, there is no single history of glass, not even of all glass containers. The need of laboratory research, for instance, to settle in the world, to encapsulate and demarcate its experimental milieus in relation to external disturbances, was indelibly imprinted into the materiality of material glass around 1900. New techno-scientific objects were existentially bound to their new vitreous envelopes, and vice versa. With such a shift of perspective, the glass container turns from an iconic placeholder of the experiment, a *topos*, into a material *oikos* of research objects in modern laboratory research.

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