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Science in Glass: Material Pathologies in Laboratory Research, Glassware Standardization, and the (Un)Natural History of a Modern Material, 1900s–1930s

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Abstract: At the turn of the twentieth century, so-called "glass diseases" seriously affected the use of scientific and technical glassware. It had become apparent by 1900 that glass, a supposedly neutral and inert material, not only interacted with its environment but also interfered with anything it contained—chemically, physically, and biologically. Starting from the assumption that modern laboratory research depends on containers that regulate the spatial, material, and epistemic enclosure of its experimental milieus and objects, this essay argues that the standardization of glass quality from the 1900s to the 1930s must be understood as a reconfiguration of a "marginal" but nonetheless constitutive element of modern laboratory environments. The aim here is thus to weave various threads together into an (un)natural history of a modern material, one that considers epistemology, technology, and ontology—or, more specifically, the changing requirements and functions of glassware in the modern laboratory, the invention of specifically adapted glass substances, and the parallel advancement of glass science and its theories of what glass actually is.

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"GLASS DISEASES" AT THE TURN OF THE TWENTIETH CENTURY

> **First, cold sweat exudes from every pore, as if the poor glassware could sense its nearing end: a humor of very salty taste and smell precipitates on its outside. . . . Soon, the glassware breaks out in a rash, turning milky and dull. Then, erratic fissures appear and cover the glass surface like a spider web. The fissures multiply and worsen, even ulcerate. Parts of the epidermis begin to exfoliate; continuous cracks permeate the corrugated glass surface, which is now left to decay.**[1]

In 1903 the art historian Gustav Pazaurek presented this rather disturbing report on "glass diseases," illustrated with impressive photomicrographs of affected glass surfaces, to the International Congress of Museums in Berlin (see Figure 1). Among the art historians, curators, conservators, and collectors in the audience, his presentation ignited a certain astonishment: Could this crystal clear, transparent, and seemingly so "immaterial" material really be so earthly and perishable—just like other mundane material objects? In his discussion of glass pathologies, Pazaurek also offered evidence of glass decomposition shown by the observations of experimental scientists. He referred to the work of Franz Mylius, then-director of the chemical laboratory of the Physikalisch-Technische Reichsanstalt (Imperial Physical Technical Institute) in Berlin. In the same year as Pazaurek's report on glass diseases, Mylius addressed his scientific community at the Fifth International Congress of Applied Chemistry in Berlin: "Ideal glassware for chemical research should be colorless, homogenous, of good plasticity when heated, and it should be resistant to chemical attack. . . . Although we have come very near to ideal glass concerning these characteristics already, this is less the case with chemical durability. . . . In fact, there is no glass that is equally resistant to all kinds of chemicals, and there is no hope to ever find one."[2] Although his description was less florid than Pazaurek's, Mylius's statement on the chemical deficiencies of laboratory glassware was no less dramatic. Clearly, the chemistry of glassware posed a challenge to laboratory research and experimental practice just as serious as that to the work of art historians and conservators. In the museum, historical glassware was at risk of decomposing and vanishing into oblivion in reaction to atmospheric substances—the so-called "weathering" of glass. Conversely, in the laboratory, the physical-chemical interference between glassware and the research objects and substances contained in those vessels could introduce measurement errors capable of destabilizing entire experimental settings. Two decades earlier, concerned chemists had already warned their colleagues in the experimental sciences that "facing the facts, . . . one can no longer ignore that the material from which our indispensable chemical instruments are made does not fulfill the necessary requirements, and that the production of a remedy is highly desirable."[3]

GLASSWARE IN THE HISTORIOGRAPHY OF SCIENCE

Concern about "glass diseases"—whether expressed in the imagery of pathologization typical at the turn of the century and used by the art historian Pazaurek or registered more prosaically by

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[1] Gustav E. Pazaurek, *Kranke Gläser: Eine Untersuchung* (Reichenberg: Nordböhmisches Gewerbemuseum, 1903), p. 8 (here and throughout this essay, all translations are mine).

[2] Franz Mylius, "Ueber die Classifikation der Gläser zu chemischem Gebrauch," *Sprechsaal*, 1903, *24*:884–885, 25:924–925. On the institute see David Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt, 1871–1918* (New York: Cambridge Univ. Press, 1989); and Michael Engel, "Das chemische Laboratorium der Physikalisch-Technischen Reichsanstalt," *Mitteilungen der Gesellschaft Deutscher Chemiker, Fachgruppe Geschichte der Chemie*, 2004, *17*:177–190.

[3] U. Kreusler and O. Henzold, "Ueber die alkalische Reaktion des Glases als Fehlerquelle bei Analysen," *Berichte der Deutschen Chemischen Gesellschaft*, 1884, *17*:34–40, on pp. 34, 40.

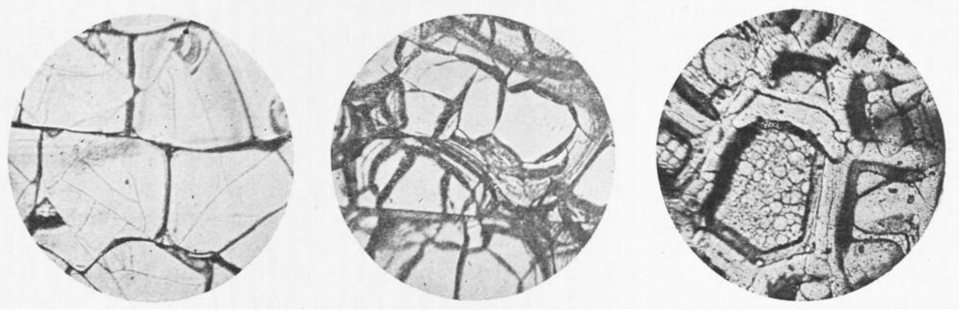

Figure 1. Glass diseases (photomicrographs). From Gustav E. Pazaurek, *Kranke Gläser: Eine Untersuchung* (Reichenberg: Nordböhmisches Gewerbemuseum, 1903), pp. 12 (left, middle), 14 (right).

researchers worried about the physical-chemical interferences between scientific glassware and experimental processes—must be seen as an integral and constitutive element in the emergence of the modern research laboratory in the nineteenth century. In recent decades, the historiography on the rise of the modern laboratory has expanded substantially. Still, historians of science have long tended to overlook the actual material agency of glass apparatus—understandable, since glassware is indeed more chemically inert than other common container materials, which explains its success in the laboratory in the first place.[4] A second possible reason for laboratory history's blind spot regarding glassware is the extraordinary presence of test tubes, retorts, flasks, petri dishes, and the like in the iconography of modern laboratory research.[5] They serve as placeholders for the microscopic objects of modern experimental research, invisible to the naked eye, as well as for the modern imaginary matrix in which a "Promethean" science creates new knowledge "in vitro."[6] This enigmatic cultural imaginary of the transparent glass vessel has

[4] More attention has been paid to the materiality of glass in recent years. See, e.g., Catherine M. Jackson, "The 'Wonderful Properties of Glass': Liebig's *Kaliapparat* and the Practice of Chemistry in Glass," *Isis*, 2015, *106*:43–69; Jackson, "Chemical Identity Crisis: Glass and Glassblowing in the Identification of Organic Compounds," *Annals of Science*, 2015, 72:187–205; Kijan Espahangizi, "From Topos to Oikos: Glassware, Boundaries, and the 'Place' of Experiment in Modern Laboratory Research (1850–1900)," *Science in Context*, 2015, 28:397–425, https://doi.org/10.1017/S0269889715000137; Espahangizi, "Vitaglass—A Modern Boundary Technology between Laboratory Research, Architecture, Public Health, and Environmentality in the 1920s and 1930s," in *Architecture/Machine: Programs, Processes, and Performances*, ed. Laurent Stalder and Moritz Gleich (Zurich: gta, 2017), pp. 98–109; and Jackson, "Glassware," in *Between Making and Knowing: Tools in the History of Materials Research*, ed. Joseph D. Martin and Cyrus Mody (New York: World Scientific, 2020), pp. 21–31. See also the work of Sven Dupré on early modern glassmaking—e.g., Sven Dupré, "The Art of Glassmaking and the Nature of Stones: The Role of Imitation in Anselm De Boodt's Classification of Stones," in *Steinformen: Materialität, Qualität, Imitation*, ed. Isabella Augart, Maurice Sass, and Iris Wenderholm (Berlin: De Gruyter, 2018), pp. 207–220.

[5] See, e.g., Joachim Schummer, "Popular Images versus Self-Images of Science: Visual Representations of Science in Clipart Cartoons and Internet Photographs," in *Science Images and Popular Images of Science*, ed. Bernd Hüppauf and Peter Weingart (New York: Routledge, 2008), pp. 69–96; and Kijan Espahangizi, "Auch das Elektron verbeugt sich: Das Davisson-Germer Experiment als Erinnerungsort der Physik," in *Mythen–Helden–Symbole: Legitimation, Selbst- und Fremdwahrnehmung in der Geschichte der Naturwissenschaften, der Medizin und der Technik*, ed. Siegfried Bodenmann and Susan Splinter (Munich: Meidenbauer, 2009), pp. 47–70.

[6] This interpretation is inspired by William R. Newman, *Promethean Ambitions: Alchemy and the Quest to Perfect Nature* (Chicago: Univ. Chicago Press, 2004). On glassware as a "placeholder" of generativity see Kijan Espahangizi, "The Twofold History of Laboratory Glassware," in *Membranes, Surfaces, and Boundaries: Interstices in the History of Science, Technology, and Culture*, ed. Mathias Grote, Max Stadler, and Laura Otis (Berlin: Preprints of the Max Planck Institute for the History of Science, 2011), pp. 17–33.

blurred its materiality—and its historicity.[7] A third explanation for laboratory glassware's particular epistemological invisibility is the subject of this essay: while laboratory glassware's physical-chemical interference with experimental processes brought the material to the attention of scientific research, its subsequent standardization into the 1930s returned it to epistemological invisibility.

The importance of glass, especially optical glass, to the advancement of modern science is undisputed among historians of science.[8] When it comes to the material history of glass apparatus and glass vessels within laboratory research, however, epistemological analyses often merely scratch the surface, as it were: since *Leviathan and the Air-Pump*, the glass vessel has been understood as the paradigmatic transparent frame of the modern "experimental space." The materiality of glass leads one to think of the art of glassmaking and glassblowing, of vitreous properties like fusibility and plasticity, or of the historical morphology of glass apparatus—such as the test tube or Justus Liebig's famous *Kaliapparat*.[9] Beyond that, there are the cultural connotations of this crystalline celestial substance and the entertaining anecdotes about its fragility. Stories of breaking or exploding glassware have an established narrative function in scientific self-historizations, often used to mark crucial moments of chance and changes in fortune in the research process.[10] Each of these aspects of glassware's materiality is in fact relevant to experimental practice, but they miss one important point: modern laboratory research depends on the *coinciding* spatial, material, and epistemic enclosure of its experimental milieus, and the old handcrafted material glass was expected to fit into this complex and very specific functional role as a multidimensional boundary layer in emerging modern laboratory ecologies.[11]

To illustrate this "marginal" but nonetheless crucial function of glass boundaries in modern laboratories, here is a typical example from the early twentieth century. In the same year that Pazaurek and Mylius lectured on deficient glassware, Gustav Hesse (the son of Walther Hesse, the assistant in Robert Koch's laboratory who initially developed the use of agar in microbiology) conducted the first foundational study on the impact of glassware on the growth of pure bacteria cultures. His results were as unambiguous as they were striking: "Colonies grow less on culture media sterilized in glassware that emits alkali. . . . It may also be that not a single germ grows into a colony if cultivated on very poor glass material. . . . One can estimate the value of bacteriological studies in aqueous media, which do not take into consideration the glassware used to sterilize culture media."[12]

This bacteriological study suggests that, around 1900, the awareness of glassware interference had reached a frontier of contemporary laboratory sciences—namely, microbiology. Experimental

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[7] On the history of fascination with glass transparency in a broader context see, e.g., Rebecca Wolf, "The Sound of Glass: Transparency and Danger," in *Performing Knowledge, 1750–1850*, ed. Mary Helen Dupree and Sean Franzel (Berlin: De Gruyter, 2018), pp. 113–136.

[8] See, e.g., Simon Schaffer, "Glass Works: Newton's Prisms and the Uses of Experiment," in *The Uses of Experiment: Studies in the Natural Sciences*, ed. David Gooding, Trevor Pinch, and Schaffer (Cambridge: Cambridge Univ. Press, 1989), pp. 67–104; and Myles W. Jackson, *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics* (Cambridge, Mass.: MIT Press, 2000).

[9] Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, N.J.: Princeton Univ. Press, 1985), p. 47. For the sorts of reflections inspired by the materiality of glass see, e.g., the chapter on the "glassware revolution" in Catherine M. Jackson, "Analysis and Synthesis in Nineteenth-Century Organic Chemistry" (Ph.D. diss., Univ. London, 2008); and Jackson, "'Wonderful Properties of Glass'" (cit. n. 4).

[10] See Espahangizi, "Auch das Elektron verbeugt sich" (cit. n. 5), p. 61. For a cultural history see Isobel Armstrong, *Victorian Glassworlds: Glass Culture and the Imagination, 1830–80* (Oxford: Oxford Univ. Press, 2010).

[11] For a sense of the importance of this issue, consider the fundamental problems of containment that thermonuclear fusion must contend with.

[12] Gustav Hesse, "Beiträge zur Herstellung von Nährboden und zur Bakterienzüchtung," *Zeitschrift für Hygiene und Infektionskrankheiten, Medizinische Mikrobiologie, Immunologie und Virologie*, 1904, 46:1–22, on p. 21.

glassware had long been a handcrafted product, as glassmakers passed their secret recipes from generation to generation. There was thus no thought of analyzing the chemical composition of laboratory glassware. By the early twentieth century, however, the situation had fundamentally changed: the stability of experimental milieus now depended on theoretical and technological knowledge about this "marginal" vitreous laboratory element. For instance, in order to study the metabolism of microorganisms, biologists now had to consult glass experts.[13] In a 1907 laboratory handbook on microbiology, the introduction summarized this shift in modern laboratory ecology:

> 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 purpose of the research.
>
> Therefore, we begin our considerations with water, the precondition of every organic development. . . . At this point, we will only mention pure water, which cannot be understood without glass, because glass vessels are indispensable containers for water and other aqueous solutions that alter the contained liquids constantly by successive dissolution of their substance. One should not underestimate these unwanted admixtures. It seems reasonable to underestimate the quantity of the soluble substance released by the glass and to overestimate the organisms' need for minerals. But, in reality, the amount of potassium and magnesium originating from the glass is sufficient to feed thousands of generations of cells.[14]

But if glassware had shifted from handcrafted vessel to integral boundary zone within the experimental milieu, how could full epistemic and material enclosure of the new "in vitro sciences" be achieved and secured? The story to be told here is twofold. On the one hand, it is the story of a material boundary in experimental settings that had to be adapted to the changing needs of modern laboratory research and precision measurement—a history of material problem solving. On the other hand, in order to adjust the marginal experimental conditions scientists needed to understand, in the first place, what glass *is* and how it interacts—chemically, physically, and biologically—with the substances and objects enclosed within it. On the basis of this new glass knowledge, the substance itself could then be transformed, standardized, and adapted to different technoscientific needs. The main argument here is that the needs of modern science and technology have changed and shaped not only our understanding of how glass works but also our understanding of what glass *is*. This historicity, not only of glass knowledge but also of the very substance itself, leads to a more general question, addressed by this essay: how to write the natural and at the same time unnatural—that is, cultural—history of modern materials whose material constitution cannot be separated from their functions in human civilization.[15] Before tracing the processes of standardization of laboratory glassware that took place from the 1900s to the

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[13] In fact, a plant physiologist studying the metabolism of mold fungus sent a query to Schott in the 1890s about the elements contained in the glass substance: Wilhelm Benecke, "Die Bedeutung des Kaliums und des Magnesiums für die Entwicklung und Wachsthum des Aspergillus niger v. Th., sowie einiger anderer Pflanzen," *Botanische Zeitung*, 1896, 54:97–132, esp. p. 104.

[14] Ernst Küster, *Anleitung zur Kultur der Mikroorganismen: Für den Gebrauch in zoologischen, botanischen, medizinischen und landwirtschaftlichen Laboratorien* (Leipzig: Teubner, 1907), p. 6. For the concept of a historical ecology of laboratory research see Espahangizi, "From Topos to Oikos" (cit. n. 4).

[15] Kijan Espahangizi and Barbara Orland, eds., *Stoffe in Bewegung: Überlegungen zu einer historischen Epistemologie der modernen materiellen Welt* (Zurich: Diaphanes, 2014). See also Ursula Klein and Wolfgang Lefèvre, eds., *Materials in Eighteenth-Century Science: A Historical Ontology* (Cambridge, Mass.: MIT Press, 2007).

1930s, I will first present a brief survey of the development of knowledge about laboratory glassware pathologies before 1900.

GLASSWARE PATHOGENESIS AND CONTAINMENT STRATEGIES BEFORE 1900

As early as the seventeenth century, chemists exchanged information about rare cases in which glass vessels suffered visible chemical attack. Yet these were seen as curiosities and exceptions to ordinary experience, a perception reflected in Robert Boyle's statement that "there is no Body that is generally reputed so close and compact as Glass."[16] In the eighteenth century, some rather marginal debates on the dissolution of glass bottles filled with wine and on glass corrosion occurred in the context of fluorspar trials, but worries about glassware in general did not affect and certainly did not destabilize experimental practice.[17] The deep confidence in chemical glassware even remained unshaken when, at the end of the eighteenth century, Antoine-Laurent Lavoisier and Carl Wilhelm Scheele ended a learned dispute by proving that the earthen residue produced during the distillation of pure water in a glass retort originated from the vessel rather than from the alleged transmutation of water into earth.[18]

It was not until the advent of exact quantitative experimentation and the growing awareness of measurement errors that glassware *curiosities* turned into glassware *pathologies*.[19] The chemists Carl Remigius Fresenius and Jean Stas first mentioned glassware-induced measurement errors in the 1850s and 1860s.[20] In 1868 Robert Bunsen initiated the first systematic study of this phenomenon, helping spread a new awareness of glassware chemistry within the landscape of experimental scientific research.[21] By the mid-1880s, glassware deficiencies had already unsettled various branches of analytical chemistry, gasometry, physics, cathode ray physics, and physical chemistry.[22] A comprehensive solution to this problem was thus needed. But what could be the remedy against these widespread measurement errors produced by laboratory glassware?

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[16] Robert Boyle, "An Essay of the Porousness of Solid Bodies (1684)," in *The Works of Robert Boyle*, Vol. 10, ed. Michael Hunter and Edward Davis (London: Pickering & Chatto, 2000), pp. 103–156, on p. 144. On Boyle's glass porology see Espahangizi, "Twofold History of Laboratory Glassware" (cit. n. 6), pp. 30–32.

[17] On wine bottles see Claude-Joseph Geoffroy, "Nouvelles expériences sur quelques especes de verre dont on fait des bouteilles," *Mémoires de l'Académie Royale des Sciences de Paris*, 1724, 32:380–399; and Charles François de Cisternay Du Fay, "Expériences sur la dissolubilité de plusieurs verres," *ibid.*, 1727, 35:32–40. On glass and fluorspar see Andreas Sigismund Marggraf, "Observation concernant une volatilisation remarquable d'une partie de l'espèce de pierre, à laquelle on donne les noms de Flosse, Flusse, Flus-Spaht, et aussi celui d'hespéros: Laquelle volatilisation a été effectuée au moyen des acides," *Histoires de l'Académie Royale des Sciences et Belles Lettres de Berlin*, 1768, 2:4–11.

[18] Antoine-Laurent Lavoisier, "Sur la nature de l'eau et sur les expériences par lequelles on a prétendu prouver la possibilité de son changement en terre," *Mém. Acad. Sci. Paris*, 1770, pp. 1–28; and Carl Wilhelm Scheele, *Chemische Abhandlung von der Luft und dem Feuer* (Uppsala/Leipzig, 1777). On earlier disputes concerning this phenomenon see Johann Heinrich Pott, *D. Ioh. Henr. Pott Animadversiones Physico Chymicae circa Varias Hypotheses et Experimenta D. Dr. et Consiliar. Elleri. Physicalisch Chymische Anmerckungen über verschiedene Sätze und Erfahrungen des Herrn Hofr. D. Eller* (Berlin, 1756).

[19] Jutta Schickore, "Through Thousands of Errors We Reach the Truth—But How? On the Epistemic Roles of Error in Scientific Practice," *Studies in the History and Philosophy of Science*, 2005, 36:539–556.

[20] Carl Remigius Fresenius, *Anleitung zur quantitativen chemischen Analyse: Dritte komplett neu überarbeitete Auflage* (Braunschweig: Vieweg, 1853), app.; and Jean Servais Stas, "Recherches sur les rapports réciproques des poids atomiques," *Bulletin de l'Académie Royale de Belgique*, 1860, *10*:208–336, esp. p. 220. See also Susanne Poth, *Carl Remigius Fresenius (1818–1897): Wegbereiter der analytischen Chemie* (Stuttgart: Wissenschaftliche Verlagsgesellschaft, 2007).

[21] The study was carried out by one of Bunsen's assistants: Adolph Emmerling, "Ueber die Einwirkung kochender Lösungen auf Glas- und Porcellangefäße," *Annalen der Chemie und Pharmacie*, 1869, *150*:257–285.

[22] See W. Fresenius, "Mittheilungen aus dem chemischen Laboratorium des Prof. Dr. R. Fresenius zu Wiesbaden: Der Arsengehalt des Glases als eine Fehlerquelle bei der Nachweisung von Arsen," *Zeitschrift für Analytische Chemie*, 1883, 22:397–404; E. Bohlig, "Löslichkeit des Glases," *ibid.*, 1884, 32:518; Emil Warburg, "Ueber die Electrolyse des festen Glases," *Annalen der Physik*, 1884, 257:622–646; Warburg and T. Ihmori, "Ueber das Gewicht und die Ursache der Wasserhaut bei Glas und anderen Körpern," *ibid.*, 1886, *263*:481–507; E. Egger, "Ueber die Einwirkung von verdünnten Säuren auf Flaschenglas," *Archiv für Hygiene*, 1884, pp. 68–74; J. T. Bottomley, "Note on the Condensation of Gases at the Surface of Glass (Preliminary)," *Proceedings of the Royal Society of*

In hindsight, we can identify three different but interrelated containment strategies during the second half of the nineteenth century: finding a formula for a "universal glass," which when instantiated would express the true "nature of glass" and possess perfect material characteristics; adapting the chemical composition of glassware to specific uses and their particular exigencies; and developing reliable glass-testing procedures in order to compare and guarantee glass quality.

In 1830 the French chemist Jean-Baptiste Dumas, a pioneer of technical glass chemistry, developed the idea of a universal glass formula. New methods and concepts in analytical chemistry—for example, recognition of the chemical disintegration of glass through contact with sodium and fluoric acid and the concept of multiple proportions of glass components—led Dumas to envision a completely new chemical theory of glass as a "mixture of silicate compounds" with a determinable "universal glass" formula.[23] The search for this ultimate glass formula was pursued until 1894, when the very possibility was refuted by Franz Mylius and his colleague Fritz Foerster at the chemical laboratory of the Physikalisch-Technische Reichsanstalt in Berlin; both were leading experts in the emerging field of glass science in the late nineteenth century.[24] Despite its failure, the quest for the holy grail of Dumasian glass chemistry had nonetheless fostered new insights into the "nature of glass," at least over a certain period. In the end, however, the restrictive focus on chemical formulas became an impediment to the development of glass science and technology.

The second, more practical, option was to develop new glass substances and adapt them to specific needs. This approach turned out to be far more fruitful: it led, for example, to Jean Stas's development of specific chemical glassware for atomic weight measurements in the 1860s; the improved "Normalthermometerglas" for glass mercury thermometers in the early 1880s; and then—in reaction to growing demand within the experimental sciences—improved glassware for laboratory research in the early 1890s.[25] The epicenter of this new technical glassware was without doubt the laboratory of the Jena "glass doctor" Otto Schott, who also cooperated with the Kaiserliche Normaleichungskommission (Imperial Standards Calibration Commission) in Berlin.[26] Schott's Jenaer Geräteglas (Jena instrument glass), first melted in 1892, was extraordinarily

London, 1885, 38:158–161; V. Wartha, "Ueber die alcalische Reaction des Glases," *Z. Analyt. Chem.*, 1885, *24*:220; Georg Lunge, "Zur Kritik verschiedener für die Maassanalyse neu vorgeschlagener Indicatoren," *Ber. Deut. Chem. Ges.*, 1885, *18*:3290–3291; Friedrich Kohlrausch, "Die electrische Leitungsfähigkeit des im Vacuum destillierten Wassers," *Ann. Phys.*, 1885, *260*:48–52; Robert W. Bunsen, "Ueber die Verdichtung der Kohlensäure an blanken Glasflächen," *ibid.*, 1883, *256*:545–560; and Bunsen, "Zersetzung des Glases durch Kohlensäure enthaltende capillare Wasserschichten," *ibid.*, 1885, *265*:161–165.

[23] Jean-Baptiste Dumas, "Recherches sur la composition des verres," *Annales de Chimie et de Physique*, 1830, *44*:144; and Dumas, *Traité de chimie appliquée aux arts*, Vol. 2 (Paris, 1830), p. 535.

[24] On Mylius's work on glass chemistry see Michael Engel, "Weshalb hakt die Libelle? Die glaschemischen Untersuchungen Frank Mylius," in *Glas—Kunst, Technik und Wirtschaft: Vorträge der Jahrestagung der Georg-Agricola-Gesellschaft 2000*, ed. Werner Kroker (Bochum: Georg-Agricola-Gesellschaft, 2001), pp. 115–129; Engel, "Das chemische Laboratorium der Physikalisch-Technischen Reichsanstalt" (cit. n. 2); and Espahangizi, "From Topos to Oikos" (cit. n. 4). For efforts to find a universal glass formula see Hermann Benrath, *Die Normal-Zusammensetzung bleifreien Glases und die Abweichungen von derselben in der Praxis: Eine technisch-chemische Studie: Eine der Hochverordneten physiko-mathematischen Facultät der Kaiserlichen Universität Dorpat behufs Erlangung der Magisterwürde eingereichte Abhandlung* (Aachen, 1868); Rudolph Weber, "Über die chemische Zusammensetzung der Gläser und die dadurch bedingte Widerstandsfähigkeit derselben gegen atmosphärische Einflüsse," *Ann. Phys.*, 1879, *242*:431–450; and Fritz Foerster, "Vergleichende Prüfung einiger Glassorten hinsichtlich ihres chemischen Verhaltens," *Z. Analyt. Chem.*, 1894, 33:381–396, esp. pp. 390, 394.

[25] Jean Servais Stas, "On the Manufacture of Glass for Vessels Employed in Chemical Researches," *Chemical News*, 1868, *17*:1; Hermann F. Wiebe, "Ueber Thermometerglas, insbesondere über das 'Jenaer Normalthermometerglas,'" *Zeitschrift für Instrumentenkunde*, 1886, 6:167–171; and Adolf Winkelmann and Otto Schott, "Einige Beobachtungen mit einem neuen Gerätheglas," *ibid.*, 1894, *14*:6–8. On the history of temperature measurement see Hasok Chang, *Inventing Temperature: Measurement and Scientific Progress* (Oxford: Oxford Univ. Press, 2007).

[26] Herbert Kühnert, *Die kulturelle Bedeutung der Jenaer Glasindustrie* (Rudolstadt: Greifenverlag, 1949), p. 17. Otto Schott founded the still-renowned glassworks and revolutionized glass technology, including through contributions to the improvement of optical glasses. See Jackson, *Spectrum of Belief* (cit. n. 8). Indeed, at first glance, scientific glassware seems to be a mere footnote in the

inert and equally resistant to chemical attack and heat. The outcome of systematic glass studies comparing various substances in the glass melt, this new apparatus glass incorporated boron—or, rather, boric acid and other borates.[27] Just as Gustav Pazaurek was introducing art historians and conservators to the problem of glass pathologies, the new borosilicate glassware from Jena (along with its Thuringian epigones) was already “alleviating” their symptoms in laboratories all over the world.

But how could this improvement in laboratory glass quality be measured and representative samples compared? This brings us to the third containment strategy against glass diseases: glass-testing procedures. Rudolph Weber, a German technical chemist at the forerunner institution of the Technical University of Berlin, who received an award from the Prussian Society for the Advancement of Industry in 1863, developed the first relevant testing procedure for glass quality. Based on a twenty-four-hour application of nitric acid vapors to the glass surface being tested, Weber’s method was neither practical nor quantitative. Moreover, it was detached from any theoretical explanation, which rendered it useless for further scientific research. It took until the late 1880s for Franz Mylius and Fritz Foerster to develop a sustainable testing method based on the so-called “hygroscopicity” of glass: they learned that the main culprit in glass diseases was a substance as ostensibly innocent and neutral as glass itself—water. By 1893 Mylius and Foerster, supported by Otto Schott, were able to describe the decay of glass caused by hygroscopicity as a two-stage process. First, water dissolved the alkali parts of the glass, which was now understood as both a mixture of compounds and a frozen solution. The dissolved alkali would, in a second step, leach the remaining glass material and disintegrate the silicates.[28] In other words, an alkaline attack on glass, too, could be subsumed under the model of hygroscopicity. The same was true of acid attacks, which were actually caused by the aqueous solution and not by the acid itself (except in the case of fluoric acid). A glass object’s hygroscopicity, measured by the changing degree of alkalinity of the water within it, was thus a valid benchmark for assessing the general chemical durability of that glass. Mylius and Foerster used titration to quantify and compare the general quality of all laboratory glasses sent to the Reichsanstalt by the technical glassware industry. A red dye, iodine-eosin, could be used to make the hygroscopicity of glassware visible.[29]

Surveying the landscape of scientific glassware technology around 1900, there was, on the one hand, no longer any hope for a single “cure” to glass disease—the notion of perfectly neutral glassware had to be abandoned for good. On the other hand, significant progress had been made on three different but closely interrelated fronts: the production of new glass materials for specific purposes, the advancement of theoretical glass knowledge, and the development of sustainable quantitative glass-testing procedures. Mylius sketched out the status quo in glassware technology at the International Congress of Applied Chemistry in 1903 mentioned at the beginning of this essay: “Sirs! We once imagined a universal glass to be possible, suitable for every purpose. We

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success story of Schott’s optical glasses, but in fact it played a not negligible role in the start-up and consolidation of Schott and Ernst Abbe’s fragile business in the early 1880s. See Kühnert, ed., *Briefe und Dokumente zur Geschichte des VEB Optik Jenaer Glaswerk Schott & Genossen*, 2 vols. (Jena: Fischer, 1953, 1957). On the Schott glassworks see also Tilda Bayer, Uta Hoff, and Wolfgang Meyer, *Schott in Jena 1884–1949* (Erfurt: Sutton, 2003).

[27] Jürgen Steiner, “Otto Schott and the Invention of Borosilicate Glass,” *Glastechnische Berichte*, 1993, *66*:165–173.

[28] Rudolph Weber, “Ueber das Beschlagen und Blindwerden des Glases und über die Methode zur Vorherbestimmung dieser Erscheinung,” *Dingler’s Polytechnisches Journal*, 1864, *171*:121–137; Franz Mylius and Fritz Foerster, “Ueber die Beurtheilung von Glasgefässen zu chemischem Gebrauche: Die Einwirkung von Wasser auf Glas,” *Z. Analyt. Chem.*, 1892, *31*:241–282; and Foerster, “Ueber die Beurtheilung von Glasgefässen zu chemischem Gebrauche, II,” *Z. Instrumentenkunde*, 1893, *13*:457–465.

[29] Franz Mylius, “Die Prüfung der Glasoberfläche des Glases durch Farbreaktion,” *Z. Instrumentenkunde*, 1889, 9:50–57, esp. p. 52. On comparative quality testing using Mylius and Foerster’s method see the report by the Reichsanstalt: Hermann Helmholtz and Leopold Loewenherz, “Die Tätigkeit der Physikalisch-Technischen Reichsanstalt bis Ende 1890,” in *Tätigkeitsberichte PTR 1890–1895: Auszug aus den Ministerial-Akten des Departements des Aeussern und Innern* (Jena: Physikalisch-Technischen Reichsanstalt, 1891).

now know that there is no such glass. Quite the contrary, we know that each specific use of glassware has its own ideal standard. With every passing year, we are able to witness the further specialization of glasses."[30] Mylius and his colleagues, who reportedly rewarded his speech with sustained applause, realized that the functional differentiation and multiplication of glass types was now a reality—and the point of departure for future glassware technology. Improvements to glass quality were a step forward, but how could the results of experiments and measurements be reliably compared if scientific laboratories all used different glassware? Mylius's answer to that question was both simple and striking: glass tests, rather than glass substances, needed to be standardized. Over the course of his ongoing hygroscopicity tests in the 1890s, he had already distilled a basic "hydrolytic scale," providing a useful tool to identify and classify the quality of glassware that forms the basis for standardized glass testing to this day.

BEYOND THE WALLS OF THE LABORATORY, 1903–1914

In the years between Mylius's and Pazaurek's 1903 reports on glassware deficiencies and the outbreak of World War I, specific glass compositions continued to be developed, glass-testing procedures were further elaborated, and more glass knowledge was generated and circulated. An awareness of the possibility of material interference of glass containers with their environments, and specifically with the technoscientific objects and substances contained within them, even spread beyond the walls of the modern laboratory: experts in nutrition technology began to consider the unwanted effects of glass containers on milk, beer, wine, and preserved food. Medical researchers took note of the fact that the physical-chemical properties of glassware interfered with syphilis diagnostics and serology, as glass alkali affected the results of the so-called "Wassermann Reaction"—known to historians of science as the case study in Ludwik Fleck's pathbreaking work on thought collectives. Most significantly, apothecaries and the pharmaceutical industry grew concerned about the effects of glass hygroscopicity as the pharmaceutical use of glass ampoules became more common in the early twentieth century.[31] Injectable alkaloid solutions could now be sterilized, sealed, stored, and distributed in the same small glass container—in theory. In 1904, however, an Italian military doctor noticed that injectable solutions enclosed in ampoules were affected by the alkali released by the glass. His paper reporting this finding triggered an avalanche of studies on the phenomenon, all pointing to the painful and even lethal consequences of these altered solutions and "crystalline precipitates" when injected.[32] The tainted pharmaceuticals included compounds such as morphine, strychnine, cocaine, La Roche's Pantopon, and Hoechst's famous syphilis drug, Salvarsan.[33] In contrast to earlier laboratory scientists, pharmacists and the pharmaceutical industry could now draw on existing technical glass

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[30] Mylius, "Ueber die Classifikation der Gläser" (cit. n. 2), p. 884.

[31] Hugo Schulz, "Der Uebergang von Kieselsäure in die Milch beim Sterilisieren in Glasflaschen," *Münchner Medizinische Wochenschrift*, 1912, 59:353–354; B. Pfyl, "Übergang von Kieselsäure in die Milch beim Sterilisieren," *Arbeiten aus dem Kaiserlichen Gesundheitsamte*, 1915, *48*:321–329; Carl Sternberg, "Versuche über die Wassermannsche Reaktion," *Verhandlungen der Deutschen Pathologischen Gesellschaft*, 1914, *17*:273–275; and Sternberg, "Versuche über die Wassermannsche Reaktion," *Wiener Klinische Wochenschrift*, 1914, 27:545–549; and Stanislas Limousin, "Ampoules hypodermiques: Nouveau mode de préparation des solutions pour les injections hypodermiques," *Bulletin Général de Thérapeutique Médicale et Chirugicale*, 1886, *110*:316–319.

[32] For the initial report see E. Baroni, "Delle iniezioni ipodermiche: Metodo facile per verificare se il vetro delle fiale è neutro," *Giornale di Farmacia, di Chimica e di Scienze Affini*, 1904, 53:481–482. For a selection of the studies on this phenomenon see Ludwig Kroeber, "Ueber Ampullen," *Apotheker-Zeitung*, 1908, 23:458–460; C. Jakobsen, "Ueber die Alkalität des Arzneiglases," *ibid.*, 1910, 25:262, 1913, 28:155; W. Lenz, "Über Anforderungen, welche man an die Güte des medizinischen Flaschenglases zu stellen hat," *ibid.*, 1915, 5:129–131; and M. Grübler, "Ueber die Wirkung von freiem Alkali auf Morfium und Adrenalin: Ein Beitrag zur Sterilisation," *Pharmazeutische Post*, 1907, *40*:579–582, on p. 579 ("crystalline precipitates").

[33] Anneler, "Über die Alkaliabgabe von Arzneiflaschen," *Pharmazeutische Zeitung*, 1913, *16*:309–310; and J. Tillmanns and H. Mildner, "Ueber die Prüfung des destillierten Wassers auf Brauchbarkeit für die Bereitung von Salvarsanlösungen," *Zeitschrift für Angewandte Chemie*, 1915, 28:469–474.

products and insights from glass chemistry. The Schott glassworks, already the global market leader for specialty glass at that time, simply modified its borosilicate glass products to meet the needs of the pharmaceutical industry, debuting its Fiolax glass in 1911. This new, specifically adapted glass material would ultimately allow for the stabilization of the pharmaceutical solutions sealed within it. The stable vitreous container transformed pharmaceutical ampoules into "immutable mobiles" ready to be distributed throughout society—and, after 1914, all the way to the battlefield.[34] Indeed, the sales figures for Schott's Fiolax ampoule glass exploded in the trenches. In Germany World War I was, not surprisingly, termed the great "Materialkrieg."[35]

While the specialty glassware industry was conquering new markets and diversifying its product portfolios, Franz Mylius continued to work on glass-testing procedures at the chemical laboratory of the Physikalisch-Technische Reichsanstalt in Berlin. While he maintained his close cooperation with the Schott glassworks in Jena, there were also exchanges with other technical glassware manufacturers. Since the early 1890s, the Reichsanstalt had certified the quality of glassware products submitted by glassware manufacturers. While these certificates were not legally required (except for glass mercury thermometry), they became useful for convincing potential customers in scientific laboratories to buy technical glass products. Just as the renown of a brand such as Schott was an argument in favor of a certain glass product, so too was the state certificate. As a state authority, Mylius was now in a unique position at the center of German glass technology, able to collect data on all German technical glassware on the market and, in turn, to use this information to improve glass testing continuously.[36] Even better, adapting the glass-testing procedures of the Reichsanstalt to the evolving needs and constraints of the specialty glassware industry in return increased their popularity and acceptance among manufacturers. In 1913 Mylius presented an elaborated classification system for glass quality, based on hygroscopic glass solubility and the effects of weathering: "We propose a division of chemical durability for all types of technical silicate-glasses (independent from their percentile composition) into five hydrolytic classes. . . . The terms water-resistant and resistant glass are already in use for the first and the second classes; . . . as is poor glass for the fifth class. Glass materials belonging to the third and fourth class, which are not apparatus glass, are sufficiently characterized by the numbers."[37]

GLASSWARE DURING WORLD WAR I, 1914–1919

World War I was a turning point in the development of the specialty glass industry: the wartime economy put an end to the global market dominance of German companies. British and American glass research and technology followed in the footsteps of Schott & Company and caught up in a relatively short time.

In Great Britain, the glass expert W. E. S. Turner turned Sheffield into the center of British glass science and technology. He cofounded the Society for Glass Technology in 1916 and the

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[34] E. Baroni, "Jenaer Normal- und Fiolax-Glas: Charakteristische Verschiedenheiten," *Apothek. Z.*, 1913, *17*:155–156; and Kijan Espahangizi, "'Immutable Mobiles' im Glas: Grenzbetrachtungen zur Zirkulationsgeschichte nicht-inskribierter Dinge," *Nach Feierabend: Zürcher Jahrbuch für Wissensgeschichte*, 2011, 7:105–125. See also Maria Rentetzi, "Trafficking Materials in Tin Boxes, Glass Bottles, and Lead Cases: Radium in Early Twentieth-Century Science, Medicine, and Commerce," in *Precarious Matters / Prekäre Stoffe: The History of Dangerous and Endangered Substances in the Nineteenth and Twentieth Centuries*, ed. Viola Balz, Alexander von Schwerin, Heiko Stoff, and Bettina Wahring, Preprint 356 (Berlin: Max Planck Institute for the History of Science, 2008), pp. 99–112.

[35] See Hermann Cron, *Die Organisation des deutschen Heeres im Weltkriege: Dargestellt auf Grund der Kriegsakten* (Berlin: Mittler, 1923), p. 175.

[36] Franz Mylius, "Die Eosinreaktion des Glases an Bruchflächen," *Zeitschrift für Anorganische Chemie*, 1907, 55:233–260; and Mylius, "Die Eosinreaktion des Glases an Bruchflächen, II: Verwitterbarkeit schwerer Glasarten," *ibid.*, 1910, 67:200–224.

[37] Franz Mylius, "Die hydrolytische Klassifikation und Prüfung der Glasarten mit Jodeosin," *Silikatzeitschrift*, 1913, *1*:2–5, 25–28, 45–48, on p. 5.

Glass Research Association in 1919, the latter a joint initiative between glass researchers, the glass industry, and various state institutions. On the other side of the Atlantic, the U.S. glass industry advanced glass technology by introducing automated bulk production machines for hollow glass, including the Owens bottle machine, the Westlake light-bulb machine, and the Danner tube-drawing machine.[38] The institutions leading glass research in the United States were located at the Carnegie Institution, the National Bureau of Standards, and the new R&D departments of glass manufacturers.[39] The Corning Glass Works presented the first U.S. borosilicate glass brand, Pyrex, in 1915. Pyrex glassware was able to match Schott's products in terms of chemical and thermic durability and soon populated laboratories and kitchens all over the world.[40]

In contrast, the German technical glass industry was severely damaged by the war: glassblowers, glassmakers, and glass scientists died in the trenches (as lists published in the journals of the glass industry showed), and their expert knowledge and skills died with them. The glass industry was also struck by a scarcity of raw materials: although the main ingredients in glass production (sand, lime, soda, and potassium) were plentiful, by the end of the war industrially refined soda and combustible materials such as carbon became hard to source in Germany. The German specialty glass industry's supply of boric acid, the key element in the melt of new laboratory glassware, which made up some 7 to 20 percent of the glass batches, was import dependent.[41] Once the war started, the supply chain for sodium borates, known as borax, which ran from Death Valley in California to Germany, was in danger. The only remaining secure source of borates available to German glassware manufacturers was located in the Ottoman Empire, south of the Marmara Sea, and had yet to become operational. Only after the victory of the Central Powers in the Dardanelles in 1916 and the construction of a direct rail link between Berlin and Constantinople was the Schott glassworks, represented by technical director Eberhard Zschimmer, able to mount an official mission (on behalf of the German War Department for Raw Materials) to Anatolia in 1917.[42] But the efforts on behalf of the German war economy came too late: the scarcity of borates, and specifically boric acid, forced the war ministry to ration the raw material. Furthermore, a state order prohibited the export of borosilicate glassware without the equivalent import of pure boron to Germany. Thus the German war economy also had a direct effect on the quality of laboratory research and scientific measurements among the nation's allies and in neutral countries such as Sweden and Switzerland. Complaints about the German glass export policy in the Schott company archive shed light on the temporal connection between the course of the war and experimental practice in modern laboratories in other countries.[43]

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[38] W. E. S. Turner, "Teaching and Research in Glass Technology at the Department of Glass Technology, University of Sheffield," *Journal of the American Ceramic Society*, 1923, 6:183–186; Turner, "The Society of Glass Technology," *ibid.*, pp. 181–183; and A. W. Kimes, "Important Developments in the Glass Industry," *ibid.*, pp. 250–253.

[39] Edward W. Washburn, "Some Aspects of Scientific Research in Relation to the Glass Industry," *J. Amer. Ceramic Soc.*, 1919, 2:855–869; and H. E. Howe, "Glass," *Scientific Monthly*, 1925, 2:397–400.

[40] W. H. Curtiss, "Pyrex: A Triumph for Chemical Research in Industry," *Journal of Industrial and Engineering Chemistry*, 1922, *14*:336; Corning Glass Works, *Sand and Imagination* (Corning, N.Y.: Corning Glass Works, 1973); Margaret B. Graham and Alec T. Shuldiner, *Corning and the Craft of Innovation* (Oxford: Oxford Univ. Press, 2001); Alexander Silverman, "Fifty Years of Glassmaking," *J. Indust. Eng. Chem.*, 1926, *18*:896–904; and George W. Morey, *The Properties of Glass* (New York: Reinhold, 1938).

[41] See Kijan Espahangizi, "Stofftrajektorien: Die kriegswirtschaftliche Mobilmachung des Rohstoffs Bor, 1914–1919," in *Stoffe in Bewegung*, ed. Espahangizi and Orland (cit. n. 15), pp. 173–208.

[42] For the history of German borate endeavors in the Ottoman Empire see Espahangizi, "Stofftrajektorien." The expedition to Anatolia is documented in Vertreter Reisebericht 1915–1919, Schott Company Archives, Jena, file no. 13/46; and Kriegsrohstoffabteilung / Austausch mit chemischen Stoffen (Pandermit, Borsäure), Bundesarchiv, Berlin, file no. PH 305.

[43] Hausbesprechung mit Vertreter L. Krempel von der Auer & Co. Zürich am 6. 3. 1918, Vertreter Reisebericht 1915–1919, Schott Company Archives, file no. 13/46. There are other, similar reports in that file.

Among many other disruptions, then, World War I disturbed the precarious balance of global material flows, including the flow of materials in and out of the technical glass melt. While sodium and silicate compounds could be mined in Germany, boron—the most significant of all the components in the new German technical glasses—could be obtained only through imports, a fact that revealed the extent to which laboratory ecologies were already embedded in global networks at that time. An appeal by the president of the Munich Association of Apothecaries to its members, shortly after the war ended, illustrates the sharp decline of glassware quality in Germany by the end of the war: "Medicinal glassware was far from perfect even before the war. But the situation has worsened dramatically in the meantime due to the scarcity of raw materials. I have had to deal with retorts, flasks, and test tubes that set out alkali and silicates in an unprecedented way: a solution of phenolphthalein turned cherry-red. The use of these glass vessels in experimentation leads inevitably to incorrect conclusions and deceptive results."[44]

THE NATIONAL STANDARDIZATION OF GLASSWARE

The German glass industry, then, had suffered during the war, sharing in the collective national experience. On the one hand, mobilizing human and material resources as well as gathering research, technology, and industry behind the flag had become crucial to modern warfare. On the other hand, German industry in general became aware of its dependence on the strength of the nation-state and its capacity to secure access to global resources and global markets. Germany's total defeat transformed and often radicalized the attitude of many German technologists, engineers, and scientists. If the whole German *Volk* was forced to unite in total mobilization in order to prevail, the same seemed true for German technology. In the cultural context of postwar Germany, even technical issues such as standardization were framed within a nationalist agenda. Technical standardization, largely a state-driven project since the nineteenth century, was now collectively taken over by scientists, engineers, technologists, industry leaders, and even interested laypeople organized in associations and interest groups. German standardization turned into a kind of grassroots technocratic movement, a bottom-up process of "rationalization through self-organization."[45] In December 1917, the newly founded Standards Committee of German Industry (Normenausschuß der Deutschen Industrie) officially proclaimed the era of *Normung* (standardization).[46] While the Association of German Engineers (Verein Deutscher Ingenieure) led the way, other sectors, such as glassware technology, soon joined the national movement for *Normung*. A union of German glass instrument factories was founded in 1919, in the heart of the Thuringian glass industry based around Jena, pointing to the contemporary tendency toward technological self-organization from below. In its early years, this umbrella organization provided an important forum for debating glassware standardization, including its two central aspects: form and material.

The plurality of glass apparatus shapes and forms was a logical outcome of their contingent historical development. One manufacturer's glass tubes (or plugs or caps) could not be connected to the tubes (or plugs or caps) of another manufacturer because of differences in diameter and size; if glassware broke, chemists could not be certain that a replacement from another manufacturer would fit their apparatus.[47] But what had been merely annoying to researchers and the

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[44] Ludwig Kroeber, "Erweist sich die Aufnahme von Glasprüfungsvorschriften im kommenden Deutschen Arzneibuch als eine Notwendigkeit?" *Pharmazeutische Zentralhalle*, 1919, 59:223–227, 233–237, on pp. 223, 235.

[45] Miloš Vec, *Recht und Normierung in der industriellen Revolution: Neue Strukturen der Normsetzung in Völkerrecht, staatlicher Gesetzgebung und gesellschaftlicher Selbstnormierung* (Frankfurt am Main: Klostermann, 2006), p. 293.

[46] G. G. Bruhns, "Über die Eichung chemischer Messgeräte" (speech to the employees of the Physikalisch-Technischen Reichsanstalt, 1927), Bundesarchiv, file no. 1519/527b (305).

[47] See F. F. Raabe, "Normalien für Geräte des Chemikers," *Z. Angewand. Chem.*, 1899, *13*:1032–1034.

chemical industry now appeared as a veritable threat through the lens of modern warfare.[48] Moreover, it seemed flatly absurd to accept more than one type of glass apparatus for a specific chemical procedure. The director of the Thuringian glassware manufacturer Greiner & Friedrichs highlighted this chaotic situation when he counted sixty-two variations of the Kali apparatus and ninety-seven variations of a particular extraction device.[49]

German chemists were the first interest group to react and take responsibility for the situation—which is no surprise, as they encountered this kind of mismatch in their daily work. In 1919, the Association of German Chemists (Verein Deutscher Chemiker) established a Special Committee for Chemical Apparatus, which took the lead in developing glassware standards.[50] The committee developed draft standards in close cooperation with consumers and manufacturers, in particular Schott. It coordinated the collective decision-making process and initiated a series of conventions and exhibitions for chemical apparatus under the banner of "ACHEMA" (Ausstellungstagung für Chemisches Apparatewesen) in order to popularize the finalized glass apparatus standards.

Beyond form, material quality was also central to standardization efforts. During the war, glass quality had become a relevant military-technological issue: the reliability and resistance to chemical attack and heat of medical glassware and pharmaceutical ampoules, chemical glassware, scientific thermometers, and glass panels for the steam engines in German warships and trains had been crucial to the war effort, raising industry awareness about the material quality of glassware to a new level.[51] The question of how to standardize the quality of German technical glassware, which had troubled Franz Mylius and his colleagues at the chemical laboratory of the Physikalisch-Technische Reichsanstalt since the 1890s, was now part of a national pursuit. Mylius's findings showed the way: since no universal glass could serve as a perfect *Normalglas*, it was necessary to standardize glass testing, rather than glass substance.

THE CURE: DIN DENOG 62

The first standard of glass quality, the German industrial norm DIN Denog 62, developed in 1935, was the result of various specific convergences within and between the pharmaceutical industry, state efforts to regulate technical calibration norms, and working chemists. Pharmacology was one of the first disciplines to debate and codify the regulation of glass quality. In 1917 the German Federal Office of Health initiated the decennial revision of its pharmacopoeia, the *Deutsches Arzneibuch*. In so doing, it sparked a resurgence of the debate about glassware quality that had crystallized over glass ampoules before the war. Pharmaceutical experts began to demand that glass-testing rules be added to the *Deutsches Arzneibuch*. Published in 1926, the sixth edition of the *Arzneibuch* subsequently codified a mandatory glass-testing procedure for ordinary "drug containers" and "glass ampoules containing solutions of alkaloid salts."[52] The required

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[48] See Johannes Dathe, "Über Normalisierung von Laboratoriumsapparaten," *Z. Angewand. Chem.*, 1919, 32:207–208.

[49] Fritz Friedrichs, "Ueber die Normierung der Glasinstrumente," *Deutsche Glasinstrumenten- und Hohlglasindustrie*, 1920, 2:2–3.

[50] Max Buchner, "Fachgruppe für chemisches Apparatewesen Abteilung Laboratoriumsapparate," *Glas und Apparat*, 1921, 2:203–204; and Hermann Rabe, "Normung der Laboratoriumsapparate: Eine der wichtigsten Aufgaben der Fachgruppe für chemisches Apparatewesen," *ibid.*, pp. 204–205.

[51] In 1919, the Reichsanstalt noted a "growing interest" within the glass industry in "improved types of glass." See Tätigkeitsberichte of the PTR, Bundesarchiv, file no. 1519/38 (159).

[52] Reichsgesundheitsamt, *Deutsches Arzneibuch*, 6th ed. (Berlin: Reichsgesundheitsamt, 1926). For insistence about adding glass-testing rules see, e.g., F. Stadelmayer, "Über die Untersuchung des für medizinische und pharmazeutische Zwecke bestimmten Glases," *Z. Analyt. Chem.*, 1919, 58:325–332; Kurt Bodendorf, "Die Prüfung der Gläser," *Apothek. Z.*, 1925, 40:166–167, 221–223; and Erich Urbschat, "Die Angreifbarkeit und ihre Prüfung bei medizinischen Gläsern," *Keramische Rundschau*, 1925, 33:812–813, 829–830.

procedure was simple. The hygroscopicity of the crushed glass material was to be measured in boiling water. Nitric acid and a methyl red solution indicated the glass's quality. The increasing alkalinity of the water boiling in the glassware would neutralize the nitric acid and thus continuously diminish the red color of the indicator. The limit value—signaling insufficient quality—was reached if the indicator became colorless within thirty minutes. Nonetheless, the description of the procedure was not terribly precise and left several technical questions unanswered, including how and to what extent the glass specimen needed to be crushed.

Similarly, the rather unspecific calibration regulations of the Imperial Standards Calibration Commission, published in 1909, stated that the glass instrument to be calibrated should be "sufficiently resistant to chemical and other attacks and be made of the most inert glass available."[53] By the end of World War I, however, the state of the art in technical calibration had changed, and demands for quantitative testing methods had grown louder. The institutional proximity between the Commission and the Reichsanstalt made the use of Franz Mylius's hydrolytic classification an easy choice. Mylius also continued to improve, adapt, simplify, and diversify his glass-testing method until his retirement in 1923. Even before the new calibration regulations were published in 1927, a provisory amendment stated that aerometers, medical syringes, and other calibrated "instruments for measurement in scientific and technical trials" were required to be manufactured out of "types of glass that meet a minimum chemical resistance of the third hydrolytic class, as determined by Mylius."[54]

Beyond the state-controlled pharmaceutical and technical calibration sectors, chemists also held a vested interest in the codification of glass-quality standards. In May 1926 the Special Committee for Chemical Apparatus broke off from the Association of German Chemists, reconstituting as the German Society for Chemical Apparatus (Deutsche Gesellschaft für Chemisches Apparatewesen [DECHEMA]) with a call to arms:

> Standardization [*Normung*], a notion of our time! . . .
>
> [The DECHEMA] has taken responsibility for replacing the countless inappropriate types of laboratory apparatus, developed over time, with standardized forms. This is where standardization, to which Dechema is dedicated, comes into play. Scientists, practitioners, and manufacturers are working hand in hand in various committees, to provide chemists with the right material for their scientific research.
>
> But standardization must not be limited to superficial form; it must also deal with the question of material. . . . For example, the alkali content of glass can lead to errors in the analysis. We therefore have to demand that all glass apparatuses are made of suitable raw materials according to their use and function.[55]

In short, various initiatives to regulate and standardize the quality of technical glass sprang up across different sectors after the war. It nonetheless took a new organization with a much broader

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[53] See Kaiserliche Normaleichungskommission, Anweisung zur Eichung chemischer und physikalischer Meßgeräte (Ausführungsbestimmungen zur Bekanntmachung vom 3. August 1909, Reichs-Gesetzbl. 1909, Beilage zu Nr. 52), Bundesarchiv, file no. 1519/527b.

[54] For the provisory amendment see Physikalisch-Technische Reichsanstalt Abt. I für Maß und Gewicht, "Verordnung, betreffend Änderung und Ergänzung der Eichordnung (§113, 139, 153)," Reichsgesetzblatt Teil 1 55 (29. Dezember), 1927, p. 503. For Mylius's last two papers see Franz Mylius, "Die alkalimetrische Prüfung der Glasgeräte," *Z. Angewand. Chem.*, 1921, *34*:281–284; and Mylius, "Thüringer Glas," *Glastech. Ber.*, 1923, *1*:33–43.

[55] E. Dulk, "Die Normung im chemischen Apparatewesen," in *ACHEMA-Jahrbuch 1926/27*, ed. Max Buchner (Berlin: ACHEMA, 1927), pp. 54–55. On the formation of the new body see Buchner, "Die Deutsche Gesellschaft für chemisches Apparatewesen," *ibid.*, pp. 46–53.

scope to tie up all these loose ends: the German Society for Glass Technology (Deutsche Glastechnische Gesellschaft [DGG]), founded in 1922. Its monthly publication, the *Glastechnischen Berichte*, became an internationally renowned public forum on the subject of glass science and technology—and technical glass quality in particular. At the third DGG congress, in June 1925, the glass expert Friedrich Späte was assigned to lead a new committee on the chemical durability of glass. His first step was to compile a historical overview of all glass-testing methods developed since the nineteenth century.[56] Of those, nine glass-testing procedures made his shortlist, with the standard grit method deemed the most promising candidate. In 1926 Ernst Fischer and Walter Tepohl, Mylius's successors at the Reichsanstalt's chemical laboratory, had enhanced their predecessor's method by applying his eosine test of alkali solubility to previously unavailable standardized glass grit.[57] Since measuring the hygroscopicity of glassware in its manufactured state generates only superficial information about a specific object during its individual usage trajectory, it was necessary to break the object into pieces. But the size of the pieces affects the final result: the smaller the pieces, the larger the available surface and the greater the amount of alkali released over time. Thanks to the ongoing broader process of *Normung*, Fischer and Tepohl were—unlike Mylius—in possession of a solution: standardized sieves. This example shows that processes of standardization in different areas were interconnected and mutually dependent.

The final push for glass standardization was launched on 20 October 1925, when representatives from the DGG, the Standards Committee of German Industry, the DECHEMA standards committee, and the German Association for Material Testing met in Berlin in order to align their efforts. They agreed that the DGG and DECHEMA glass-testing committees should coordinate the standardization of scientific glassware. The list of attendees at this historic meeting reflects the heterogeneity of the interest groups involved in glassware standardization.[58] The standardized quality of laboratory glassware, including the simple test tube, depended on the outcome of multilateral negotiations between dozens of stakeholders: the three leading associations—the DGG, DECHEMA, and the Standards Committee of German Industry; state institutions such as the State Office for Material Testing and the Physikalisch-Technische Reichsanstalt; several glass-industry associations; individual glassware manufacturers such as Schott, Greiner & Friedrichs, Gustav Fischer, and others; various industrial consumers of technical glassware, such as IG Farbenindustrie; scientific consumers of glassware, organized, for example, in the Association of German Chemists; and, last but not least, representatives from glass research, which developed rapidly in the 1920s.[59] Among them were Herman Thiene from the Schott glass laboratories; researchers at the Osram glass laboratories in Berlin-Siemensstadt, such as the director Georg Gehlhoff, who conducted research on behalf of the DGG; the renowned chemist Gustav Keppeler from the Smelter-Silicate Laboratory at the Technical University of Hannover; Fritz Eckert of the Sendlinger Optical Works laboratory in Berlin; Eberhard Zschimmer of the Glass Research Institute at the Technical University of Karlsruhe (see Figure 2), who had previously

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[56] Friedrich Späte, "Chemische Glasprüfung: Ein Entwurf zur Normung der Glasqualität: Bericht der Unterkommission für chemische Angreifbarkeit des Glases (1926)," *Fachausschussberichte der Deutschen Glastechnischen Gesellschaft*, DECHEMA Archives, Offenbach, file no. 3/FA I, pp. 1–16.

[57] Ernst Fischer and Walter Tepohl, "Zur Bestimmung der Lösungsalkalität von gekörntem Glas," *Sprechsaal*, 1928, 43:1–2. The hydrolytic class of a particular glass could now be determined with a quick test.

[58] Arbeitsausschuss für Laboratoriums-Glasgeräte, Sitzungsprotokoll der Sitzung am 23. November, DECHEMA, Berlin; and Anwesenheitsliste, Sitzung vom 19. Februar, Bundesarchiv, file no. 1519/527b.

[59] See the sixtieth anniversary issue of the first German journal of glass technology, *Sprechsaal*, published in 1927; see also W. Frommel, "Das glastechnische Laboratorium," *Sprechsaal*, 1924, 57:438–441.

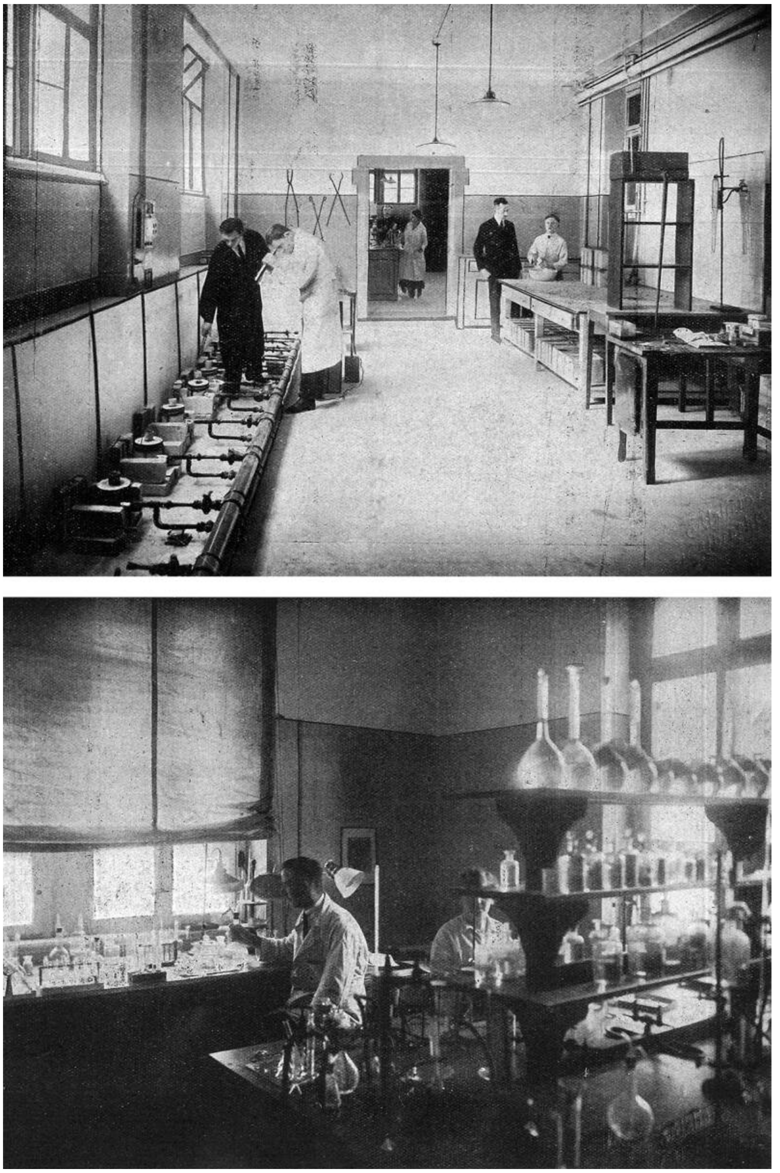

Figure 2. Raw material analysis and melting tests at the glass research laboratory of the Technische Hochschule Karlsruhe. From J. Koerner, "Ein Besuch im Glasforschungs-Laboratorium in Karlsruhe," *Sprechsaal*, 1925, 58:381–387, on pp. 381, 385.

worked at the Schott laboratory; and Walter Tepohl and Ernst Fischer from the chemical laboratory of the Reichsanstalt.[60] Other Thuringian glassware manufacturers, most notably Greiner & Friedrichs, had also copied Schott's model and established R&D divisions with glass

[60] Georg Gehlhoff, "Der Einfluss der technischen Physik auf die Glastechnik," *Sprechsaal*, 1927, *60*:1024–1025, esp. p. 1024; J. Koerner, "Ein Besuch im Glasforschungs-Laboratorium in Karlsruhe," *ibid.*, 1925, 58:381–387 (regarding Keppeler); Fritz Eckert, "Über die physikalischen Eigenschaften der Gläser," *Jahrbuch der Radioaktivität und Elektronik*, 1923, *20*:93–275; and Eberhard Zschimmer, "Geschichte der Glasforschung im Spiegel des Sprechsaal," *Sprechsaal*, 1927, 52:1016–1022.

laboratories. In 1926 the Kaiser-Wilhelm-Institut für Silikatforschung, founded with the support of the DGG and directed by Wilhelm Eitel, became another pillar of German glass research.[61]

This long list of institutions and individuals with a vivid interest in influencing the standardization of glass quality, alongside the complex "standard" procedure for developing a "DIN norm sheet," goes some way in explaining why it would take ten years—much longer than in other technical fields—to finalize the first glass standard, DIN Denog 62, in 1935.[62]

MODERN GLASSWARE FOR A MODERN SOCIETY

The German Society for Glass Technology felt itself responsible for glass quality not only in the laboratory and the chemical industry but also throughout German society and beyond. In order to assess the status quo, the DGG committee for glass durability approached various branches of the glass industry to solicit material samples. The goal was to develop nothing less than "recommendations for the necessary requirements concerning the classification of all glassware in use," including apparatus glass, hollow glass, tube glass, ordinary bottle glass, medical bottle glass, ampoule glass, glass panels for steam engines, discharge tubes, optical glass, luxury glass, sheet glass, mirror glass, window glass, and construction glass.[63]

Driven by this mission, the Society for Glass Technology became involved in the revision of the glass-testing regulations of the sixth edition of the German pharmacopoeia, heavily criticized since its publication in 1926. The DGG wanted to align pharmaceutical regulations with the broader standardization process. On 9 November 1927 the DGG succeeded in bringing together the Physikalisch-Technische Reichsanstalt, the State Office of Health, the German Association of Pharmacies, the Standards Committee for Hospitals, and the Federation of German Manufacturers of Medical Glass.[64] In a series of meetings, these organizations agreed on a new glass-testing amendment to the German pharmacopoeia and a new paragraph on glass testing to be included in the calibration regulations. Motivated by this success, the DGG moved on to glass packaging of consumer goods. A new food and beverage law, based on new nutritional science, tightened regulations on healthy packaging in 1927, and in response the DGG presented what it considered to be timely recommendations for glass quality: "Glassware used to contain food and beverages must be class IV in Mylius's hydrolytic classification system. . . . For canned [jarred] foods and feeding bottles, class III is desired. . . . It is important that glass beer, wine, liquor, milk, and water bottles do not release too much substance into their contents during pasteurization; otherwise the contained liquids will be contaminated."[65]

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[61] Wilhelm Eitel, "Das Kaiser-Wilhelm-Institut für Silikatforschung und seine Ziele in Gegenwart und Zukunft," *Glastech. Ber.*, 1926, *4*:142–144.

[62] Regarding difficulties in developing the "DIN norm sheet" see "DECHEMA Nachrichten: Entwicklung eines Normblattes," *Chemische Fabrik*, 1928, *1*:128. Other reasons for the delay in finalizing the first glass standard include the economic crisis.

[63] See the reports by the committee at the Fifth Congress of the German Society for Glass Technology, May 1926, in the *Glastechnische Berichte*. The recommendations were later published in Friedrich Späte and Rudolf Schmidt, "Vorschläge für die wünschenswerten Haltbarkeitsanforderungen an die einzelnen Glassorten (1933)," *Fachausschussberichte der Deutschen Glastechnischen Gesellschaft*, DECHEMA Archives, file no. 26/FA I, pp. 55–62.

[64] Tätigkeitsberichte (13. Medizin- und Ampullenglas), 1927, Bundesarchiv, file no. 1519/39 (4). Regarding complaints about the glass-testing regulations in the *Deutsches Arzneibuch* see, e.g., Ludwig Kroeber, "Kritische Betrachtungen zu den Glasprüfungsvorschriften des Deutschen Arzneibuches 6. Ausgabe," *Sprechsaal*, 1927, *60*:356–358.

[65] Späte and Schmidt, "Vorschläge für die wünschenswerten Haltbarkeitsanforderungen an die einzelnen Glassorten (1933)" (cit. n. 63). On glass packaging see Gustav Keppeler, "Untersuchung an Flaschengläsern," *Glastech. Ber.*, 1930, 8:65–77; Richard Mummendey, "Untersuchungen über den Einfluß des Flaschenglases auf die Qualität des Weines," *Zeitschrift für die Untersuchung der Lebensmittel*, 1931, *61*:514–519; and Keppeler, "Zusammensetzung und Brauchbarkeitseigenschaften von Wirtschaftsglas," *Glastech. Ber.*, 1933, *11*:49–58.

Despite their efforts to influence not only glass packaging but also tube glass and construction glass, as well as to direct the heated discussions surrounding the transmissibility—or lack thereof—of ultraviolet radiation through glass (which became a major health concern in 1927), the impact of the German Society for Glass Technology was in fact rather limited.[66] In a market economy, the decision to purchase high-quality glass was not only a matter of convincing technical arguments but also dependent on economic considerations, as special ingredients like boric acid raised prices. The standardization of glass quality took place across different areas of technical application, which were again embedded in contexts with different normative requirements: scientific precision, technical feasibility and reliability, legality, medical issues, hygienic considerations, and profitability. The DGG's authority was limited when it came to ordinary consumer goods. Nonetheless, as the German technical norm was becoming an internationally accepted and admired seal of quality, the idea of *Normung* and the reputation of the DIN Denog brand were also turned into useful sales arguments, even for household items.[67]

Over the course of this process, glassware manufacturers realized that the modern kitchen was potentially a lucrative market for technical glassware. As early as the 1890s, the Schott glassworks had financed technical glassware research and development for small, specialized markets (such as laboratory research) through commercial offsets of their specialty glass products. Schott earned millions by selling resistant apparatus glass to the inventor and main manufacturer of Auer gaslights, funds then reinvested in R&D, until the electrical incandescent light decimated the gaslight market. Searching for new markets, Schott learned from the United States. In a manner reminiscent of the development of Corning's Pyrex glassware, Schott adapted its apparatus glass to the universe of the modern kitchen—the laboratory of the household—with great success. Durax glass, which debuted in August 1921, was manufactured into feeding bottles and ovenware.[68]

When Otto Schott's son Erich took over the company, the Jena glassworks began to collaborate with and even hire renowned Bauhaus and Werkbund designers like Werner Gropius, Hannes Meyer, Gerhard Marcks, Wilhelm Wagenfeld, and Lázló Moholy-Nagy. For them, Schott laboratory glassware epitomized the "Form follows function" tenet, and they sought to translate that dictate into functional products such as kitchen glassware (see Figure 3). Inspired by laboratory glassware, they were given the opportunity to develop a whole marketing concept for the "modern glass kitchen" in the early 1930s. Cooking and scientific experimentation (re) converged "in vitro," giving "each housewife the opportunity to reorganize the whole household with glassware from Jena" and to preserve all "vitamins and flavors" in the dishes prepared and served in that glassware.[69]

Here, too, Schott learned from the U.S. glassware industry. The Glass Container Association of America (GCA) had already launched a similar campaign, deploying all the tools of early marketing—extensive advertisement, consumer surveys, cooking shows, short films, and display competitions. The director of the GCA laboratories argued that

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[66] The boundary function of glassware is not limited to the enclosure of substances. In 1925, it was discovered that an ordinary window absorbed nearly all the ultraviolet radiation deemed necessary for healthy organisms and adequate growth. On the subsequent scientific and public debate see Espahangizi, "Vitaglass" (cit. n. 4).

[67] The establishment of the DIN Denog norms internationally can be followed in the section entitled "Normung" in *Chemische Fabrik*. One indicator is the fact that the word "norm" itself had to be normed in 1935, as abuses increased. See *Chem. Fabrik*, 1935, 8:352.

[68] The first advertising brochure for household Jena glassware was published in March 1922.

[69] "Die Glasküche für den modernen Haushalt," Schott Company Archives, file no. 13/35. The Schott Company Archives, file no. 13/34, includes correspondence with Gropius and documentation on the work of Wagenfeld and Moholy-Nagy. See also Werner Riezler, *Die Form ohne Ornament: Werkbundausstellung 1924* (Berlin: Deutsche Verlags-Anstalt, 1924), p. 2.

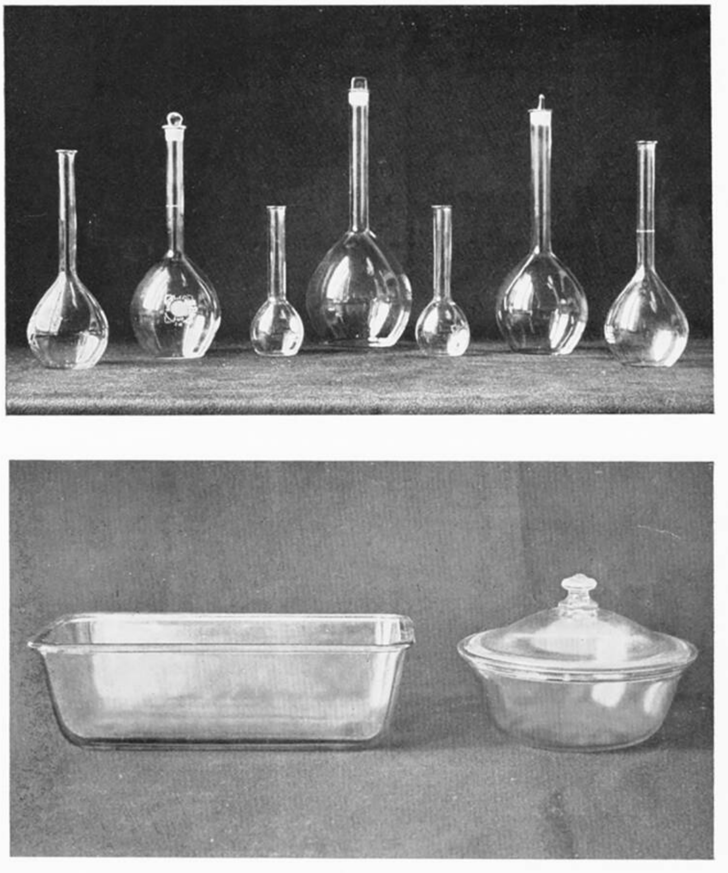

Figure 3. Form follows function. Schott laboratory and kitchen glassware at the *Werkbund*-exhibition of 1924. From Werner Riezler, *Die Form ohne Ornament: Werkbundausstellung 1924* (Berlin: Deutsche Verlags-Anstalt, 1924), p. 2.

> despite the fact that over a hundred years ago, Appert used glass as the container for his products, the glass package is a rather new entrant in the field of modern commercial packing. Glass in any form is just glass to many of its users. . . . But in reality, there exist a wide variety of glasses. . . . Adjustments of its chemical composition can change physical properties. Such changes are made to adapt glass for specific uses in industry. . . . Chemical glassware must withstand corrosive action and sudden temperature shock. We can now obtain special window glass, which transmits the ultra-violet rays of sunlight. Each of these, while of the glass family, shows different properties and widely varying applications.[70]

Thus specialty glass technology had now expanded from the chemical industry into individual households; yet establishment of the accepted norm for laboratory glassware—the so-called

[70] Karl Ford, "The Rise of the Glass Container," *Glass Container*, 1930, 9:5–7, pp. 5–6. The GCA carried out a study on glass containers in collaboration with the National Bureau of Standards: Ford, "The Weathering of Glass Containers," *J. Amer. Ceramic Soc.*, 1922, 5:837–854. On the U.S. glass container industry see Arvil W. Bitting, "Glass Containers," *ibid.*, pp. 85–94.

DIN Denog 62—was further delayed owing to conflicts over balancing the ideal types envisioned by researchers, technological feasibility, and economic considerations. During the first round of consultations, in 1925, all aspects of the project—the temperature, the size of the glass grit, the exact division of the hydrolytic classes, and so forth—were hotly disputed. As might have been expected, the first draft of the glass norm sheet was heavily criticized by the glass industry, which was unhappy with the high standards established.[71]

While the disputes surrounding the glass norm continued, the German and British glass-technological societies established an international commission for the standardization of glass testing, representing German, British, French, Italian, Spanish, and U.S. glass science and technology. Friedrich Späte and W. E. S. Turner convened the commission at the First International Congress for Glass and Ceramics, held in Milan in September 1933. The German glass norm, DIN Denog 62, was finally published in summer 1935; it serves as the prototype and model for international glass-quality standards to this day.[72]

WHAT IS (GOOD) GLASS?

In 1903, Franz Mylius had long since abandoned all hope of finding a universal glass with the perfect material characteristics (chemical neutrality, strength, heat resistance, and so forth). The most striking aspect of the universal glass theory was the notion that this glass formulation should represent the true "nature of glass." But if we compare the glass-testing regulations of DIN Denog 62 to the 1830s naturalist ideal, it becomes clear that, within a century, the quality of glass had become an entirely procedural matter. Material quality depended on scientific, technical, and cultural expectations. There was no reason for glass *by its very nature* to meet these expectations. Nonetheless, the divergence between glass theory and glass testing in this essentialist sense did not lead to a wider separation of the two sectors: to the contrary, in order to understand the physical-chemical agency of glass surfaces (for example, at the boundary of experimental milieus or in the packaging of technoscientific objects), glass theory was indispensable. Long the purview of legendary craftspeople, glassmaking had entered the spotlight of scientific research in the nineteenth century, in terms not only of optical glass but also glass apparatus. The need to understand the hygroscopicity of glassware employed in modern laboratories and thus to develop an adequate testing procedure fostered a massive increase in scientific knowledge about glass. Indeed, the nature of this fascinating substance was far more complex than Jean-Baptiste Dumas could have imagined. The rapid multiplication of specialized types of glass complicated the situation even further: What is glass and what is not? Thermodynamics, physical chemistry, and atomic physics (among other fields) have all participated in advances in glass theory into the twentieth century. In the heyday of glass standardization between 1925 and 1935, while DIN Denog 62 was being elaborated, the question "What is glass?" converged with the question "What is 'good glass'?"—as illustrated in the triaxial diagrams of ternary glass systems that had entered glass chemistry before World War I (see Figure 4).[73] Eberhard Zschimmer and Gustav Keppeler tried to represent the functional relationship between the chemical durability and composition of glass graphically in order to map and identify suitable regions and phase transitions—such as the limits of Mylius's hydrolytic classes—in a given ternary glass system. All possible glass compositions in

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[71] Arbeitsausschuss für Laboratoriums-Glasgeräte, "Normung," *Chem. Fabrik*, 1933, 2:313. The detailed committee reports were published in the *Chemische Fabrik*.

[72] Referat der Normungsvorträge, gehalten anlässlich der Exposition de la Chimie vom 27.10 bis zum 1.11.1934 in Paris, DECHEMA Archives, Offenbach; and Final draft of Din Denog 62, Mar. 1935, Bundesarchiv, file no. 1519/27d.

[73] Gustav Keppeler, ed., *Die Glasfabrikation: Zweite gänzlich umgearbeitete und verbesserte Auflage*, Vol. 1 (Munich: Oldenbourg, 1926), p. 2. See also See F. Gelstharp and J. C. Parkinson, "The Limits of Properties of Soda-Lime Glasses," *Transactions of the American Ceramic Society*, 1914, *16*:109–117.

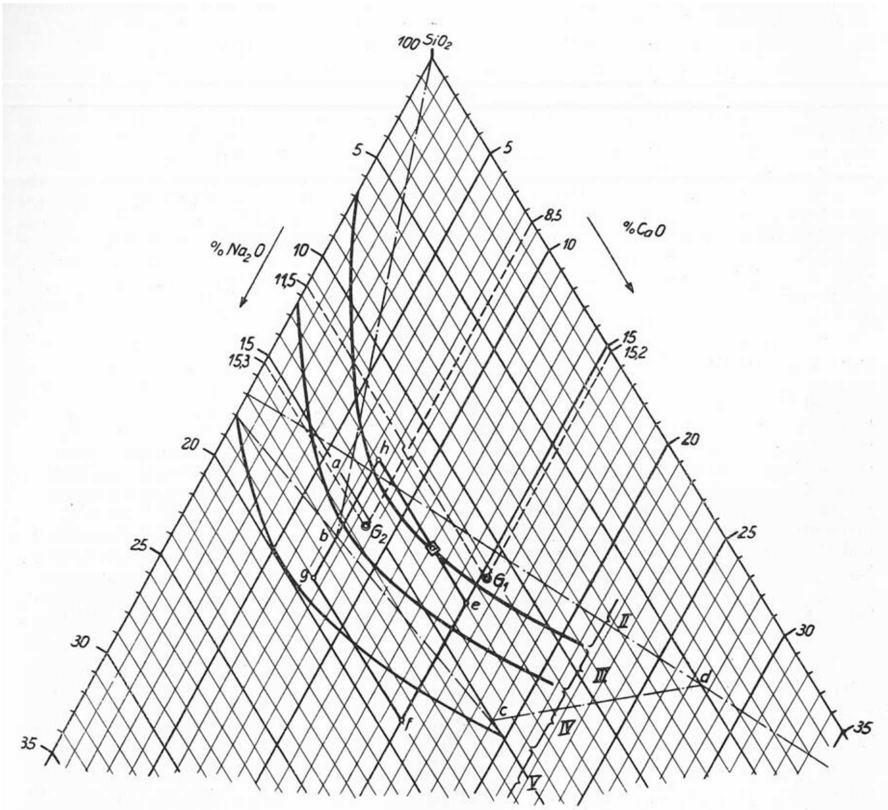

Figure 4. Mapping hydrolytic classes (II, II, IV, V) for resistant laboratory glassware in a triangular coordinate system (SiO_2, Na_2O, CaO). From Gustav Keppeler, ed., *Die Glasfabrikation: Zweite gänzlich umgearbeitete und verbesserte Auflage*, Vol. 1 (Munich: Oldenbourg, 1926), p. 101.

such a ternary system—a glass precursor (silica, boric acid), a flux agent (such as sodium or potassium), and an agent to strengthen the glass substance (such as lime)—could be depicted in a triangular coordinate system.[74]

The complex heterogeneity of groups, interests, and approaches involved in glass technology and standardization was mirrored by the heterogeneity of glass science. It comes as no surprise that participants at the first international conference on the "Constitution of Glass" in May 1925, organized by the British Society of Glass Technology, came to the conclusion that thermodynamic, chemical, atomic (x-ray spectroscopy), technological, and even cultural and historical

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[74] Keppeler, *Die Glasfabrikation*, Vol. 1, pp. 62–107; and Eberhard Zschimmer, "Bemerkungen zu den Natron-Kalk-Kieselsäure-Diagrammen von F. Gelstharp und J. C. Parkinson," *Sprechsaal*, 1924, 38:466–468. The first attempt to grasp the functional relationship between glass composition and its chemical properties in a formula was made in Emil Tscheuschner, ed., *Handbuch der Glasfabrikation: Fünfte gänzlich neubearbeitete Auflage* (Weimar: Bernhard Friedrich Vogt, 1885). Otto Schott and Adolf Winkelmann, a physicist at the University of Jena, succeeded in developing a formula that allowed for predicting and modeling certain physical properties of glass compositions, sparking the beginning of glass modeling. See Adolf Winkelmann and Otto Schott, "Über thermische Widerstandscoefficienten verschiedener Gläser in ihrer Abhängigkeit von der chemischen Zusammensetzung," *Ann. Phys.*, 1894, 287:730–746; and Winkelmann and Schott, "Über die Elastizität und über die Druckfestigkeit verschiedener neuer Gläser in ihrer Abhängigkeit von der chemischen Zusammensetzung," *ibid.*, 1894, *231*:697–729.

approaches had to be juxtaposed in order adequately to grasp the nature of glass.[75] That glass could be understood as a *frozen supercooled liquid*, the *fourth state of matter*, and a *nonperiodic two-phase network of molecules*—among numerous other perspectives—pointed to the fact that there is no "strictly valid general definition of glass for all specific cases," as Gustav Keppeler stated at the very beginning of *Die Glasfabrikation*, the fundamental compendium on glass knowledge.[76] According to Edwin Berger, one of the leading glass scientists at Schott in 1932, this kaleidoscopic plurality of vocabulary, images, and concepts surrounding glass in fact showed the path forward for "materials science":

> If the fields of physics and chemistry and particularly of colloid chemistry can be made conscious of the general importance of glass research and of glass not being a haphazard product inaccessible to science, and if experimental and theoretical men of all countries interest themselves in the problem of adding knowledge of the glassy state to the scientific knowledge of the world, then it should soon be possible that the many-thousand-year-old glass technology will develop into a science on the basis of which much progress will be made.[77]

In the regular business of the German Society for Glass Technology, the material definition of glass was also a practical problem: How far should the DGG's mission go? What materials did not count as glass? In 1933 a commission was established to standardize the term "glass," in order to create a system for deciding whether a certain material was or was not allowed to be called glass.[78] In their correspondence with Schott and the State Committee for the Terms of Commercial Delivery, the DGG declared that it was prepared to "fight against unauthorized designations." The glass society was unwilling to allow plastic products such as "Zellglas" (cellophane) and "Plexiglas," forerunners of a new material age, to benefit from the cultural cachet and the economic value of *the* modern material.[79] Simultaneously, the glass community started to compile charts of the physical and chemical properties of all known types of glass, the *Glastechnische Tabellen*. Today's digital databases continue to give a phenomenological answer to the question "What is glass?" by collecting information on the ever-growing glass family, currently nearly half a million members strong.[80]

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[75] Editors, "The Constitution of Glass: A Series of Papers Reprinted from the Journal of the Society of Glass Technology," *Nature*, 1928, *121*:239–240. Glass history also boomed during this period, often written by the glass scientists themselves. See, e.g., Eberhard Zschimmer, *Theorie der Glasschmelzkunst als physikalisch-chemische Technik*, Bk. 1: *Die Aufgabe der Theorie und die historische Entwicklung des Glasbegriffs von der Bronzezeit bis zur Gegenwart* (Jena: Volksbuchhandlung, 1923); and Wilhelm Ganzenmüller, "Die Anschauungen vom Wesen des Glases vom Mittelalter bis zum Beginn des 19. Jahrhunderts: Teil I & II," *Glastech. Ber.*, 1938, *16*:358–365, 392–398. The nature of a specific glass was also determined by its individual melt history.

[76] Keppeler, *Die Glasfabrikation* (cit. n. 73), Vol. 1, p. 1. Some of the most influential approaches are W. H. Zachariasen, "The Atomic Arrangement in Glass," *Journal of the American Chemical Society*, 1932, *54*:3841–3851; Gustav Tammann, *Der Glaszustand* (Leipzig: Voss, 1933); and George W. Morey, "The Constitution of Glass," *J. Amer. Ceramic Soc.*, 1934, *17*:315–328.

[77] Edwin Berger, "Contributions to the Theory of Glass Formation and the Glassy State," *J. Amer. Ceramic Soc.*, 1932, *15*:647–678. This would be an interesting addition to this genealogy: Bernadette Bensaude-Vincent, "The Construction of a Discipline: Materials Science in the United States," *Historical Studies in the Physical and Biological Sciences*, 2001, *31*:223–248.

[78] See the report of the Seventeenth Congress of Glass Technology in November 1933 and the corresponding committee report in the *Glastechnischen Berichte* in December 1933: *Glastech. Ber.*, *11*:473.

[79] Schreiben an Jenaer Glaswerk Schott & Gen. Betreff. Bezeichnung Glas, 10. März 1936, Schott Company Archives, file no. 25/19. See also the letter from Schott to the German Norm Committee, 4 Mar. 1936, in the same file.

[80] There are several commercial glass property databases; the largest is Sciglass.

THE (UN)NATURAL HISTORY OF A MODERN MATERIAL

When we center glass within the history of science, belief in the natural essence of this substance vanishes into thin air, revealing instead its "historical ontology": the uses of glassware, theorization about the nature of glass, glass research, glass classifications, glass-testing procedures, glass-making techniques—all dimensions of glass materiality are permanently in flux.[81] It is the historical interplay of these elements that gives meaning to the question "What is glass?" In short, the genealogy of glass is fundamentally intertwined with human existence. The need of modern laboratory research to create artificial environments—to encapsulate, to protect against and simultaneously to reflect external disturbances—was indelibly imprinted into the materiality of glass after 1850.[82] Function and being converged in the natural history of glass as experimental inquiries into nature became more "glass-y" and glass became more "research-y." The same was true for those precarious mobile technoscientific objects and substances, like pharmaceuticals, that are bound to specific glass packaging in order to circulate stably throughout society.

Looking back to 1903, when Gustav Pazaurek and Franz Mylius delivered their reports on glassware, it becomes clear that glass became "pathological" because it ceased to fit into certain modern sociotechnical and cultural contexts in flux. Within modern laboratory research and precision measurement, even seemingly inert glassware could transform into a destabilizing factor. While materials such as glass have long suggested a deep historical continuity of scientific experimentation from the era of alchemy onward, an entirely new artificial environment that emerged within experimental research in the nineteenth and early twentieth centuries reconfigured the epistemic, technical, functional, material, phenomenological, and cultural dimensions and boundaries of experimental practice in the modern laboratory. The use of scientific glassware exploded, as it expanded from a singular handcrafted material object to a globalized techno-scientific and cultural infrastructure. Paradoxically, it was the successful establishment of this infrastructure that dehistoricized the material substance of glass and crystallized the cultural imagery of the test tube as the perfectly aseptic space in which modernity ultimately and permanently rejuvenates and recreates itself. The process of material standardization described here removed glassware not only from the active awareness and everyday scope of experimental science (at least most of the time) in the twentieth century but also—at least in its actual materiality—from center stage in the history of science.

The glassware that the art historian Gustav Pazaurek tried to save from decay in the early twentieth century was never made to last forever. In contrast to today's conservation theory, in 1903 Pazaurek considered it to be the task of conservators to save "precious heritage" from the "ravages of time" and to "cure" "glass diseases" using the remedies provided by modern glass science.[83] Pazaurek's approach mirrored the ideal of glass science at the time. However, it is precisely those traces of entropy on glass surfaces—the ongoing physical-chemical (ex)change of glassware with and in certain environments, whether in the laboratory or in the museum—that reveal the material historicity of glass to the historian. In this sense, further exploration of the manifold glass objects in history of science collections, in museums, in universities, and in company archives would offer further valuable insight into their material historicity. It could also open up new perspectives that go beyond the narrative of functional differentiation and material standardization presented in this essay.

[81] On the notion of the "historical ontology" of materials see Klein and Lefèvre, eds., *Materials in Eighteenth-Century Science* (cit. n. 15).

[82] See R. E. Danforth, "Window Glass as a Factor in Human Evolution," *Sci. Monthly*, 1919, 8:537–541.

[83] Pazaurek, *Kranke Gläser* (cit. n. 1), pp. 3, 16. For a different understanding of conservation see later approaches—e.g., Cesare Brandi, *Teoria del restauro* (Turin: Enaudi, 1977).

In 1923 Eberhard Zschimmer, former director of the Schott glassworks in Jena and a renowned glass scientist and philosopher of technology, came to the conclusion that the "nature of glass" was not given or constant but, rather, always becoming and evolving alongside the progress of human culture.[84] Zschimmer's reflections on the essence of glass can be understood as an invitation to reconsider the (un)natural history of material substances. The history of modern glassware standardization suggests that it could be worthwhile to (re)invent an epistemic genre in the tradition of Plinian *historia naturalis* that allows for the juxtaposition of naturalist, cultural, and historicist accounts, along with epistemological, ontological, and technological perspectives, on glass and the many others materials that modern human civilization depends on.[85]

[84] Zschimmer, *Theorie der Glasschmelzkunst als physikalisch-chemische Technik*, Bk. 1 (cit. n. 75), p. 44; and Zschimmer, *Philosophie der Technik* (Berlin: Mittler, 1917).

[85] This reinterpretation of premodern *historia naturalis* in the Plinian tradition is inspired by Bruno Latour's reflection on the separation of the realms of nature and culture as a condition of modernity: Bruno Latour, *We Have Never Been Modern* (Cambridge, Mass.: Harvard Univ. Press, 1993).