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Drying the Tears of 'Weeping' Glass—The Coburg Magnesium Chloride Experience

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Abstract

A relative humidity (RH) of 30–40% was considered optimal for the 'sick' glasses of the Veste Coburg Art Collections to prevent further corrosion at higher humidity values and crizzling on drying of the gel layer at lower levels. This has been achieved since 1993 by using saturated solutions of magnesium chloride in display cases, providing a constant humidity of 33%. These solutions also absorb volatile harmful 'carbonyl' and other pollutants. A visual survey of the glasses and recent ion chromatographic measurements of alkalis on their surfaces confirmed their stable condition after three decades: no crystals, no new haze, no tears, no fragmentation, and no further growth of crizzling.

Keywords: climate control in display cases; glass disease; magnesium chloride; pollutant absorption; saturated salt solutions; 'sick' glass; 'weeping' of glass

1. Introduction

The Veste Coburg, the former home of the Dukes of Saxe-Coburg and Gotha, hosts a famous glass collection, including Venetian glasses [1] collected by Duke Alfred (1844–1900), the second son of Queen Victoria and Prince Albert. Curator Clementine Schack von Wittenau [2] reported several cases of glass disease or 'sickness'. This degradation is

$$\equiv\text{Si-O-Si}\equiv + \text{OH}^- \rightarrow \equiv\text{Si-O}^- + \text{HO-Si}\equiv$$

caused by an unstable glass composition with excessive flux (sodium, potassium) and insufficient stabiliser (calcium) [3]. During glass disease, cations from the glass network (Na^+ and/or K^+) are exchanged for protons from water:

$$\equiv\text{Si-O}^-\text{Na}^+ + \text{H}_2\text{O} \rightarrow \equiv\text{Si-O-H} + \text{Na}^+\text{OH}^-$$

An alkaline surface film containing alkali cations is present on the glass surface. Hydroxide attacks the bridging oxygen bonds in the Si-O network:

Typical visible symptoms are the deposition of salts on the surface, which attract humidity and form drops ('weeping') in a humid atmosphere and a fine network of microscopic cracks ('crizzling'). In the later stages, cracks become deeper and lead to fragmentation.

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Instability is inherent to the composition. To date, there is no known causal treatment, although experiments with zinc ions have shown promise in blocking the surface [4]. However, degradation can be slowed by regularly washing the glass surface to remove the aggressive alkaline films [3]. The optimum relative humidity (RH) for storage and display is a compromise between lowering the humidity to avoid ion exchange and cracks from drying the water-containing altered glass ('silica gel layer'). Different recommendations have been reported in the literature [5]. Recently, Thickett et al. (Figure 8 in [6]) found that when lowering the RH around corroded glass with gel layers, the water desorption from the gel (and implicitly, the risk of cracks) increases starting between 25 and 35% (depending on the glass type).

In 1992, Ulitzka [7] recommended the use of saturated magnesium chloride solutions for climate control in Coburg display cases. In this study, the development of this proposal and the experience with it after more than three decades are reviewed (Section 3.1). The hitherto neglected absorption capacity of these solutions for corrosive pollutants is investigated (Section 3.2) and the release of alkali ions from the glass (Section 3.3), as a key indicator of glass 'sickness', is quantified.

2. Materials and Methods

2.1. Coburg Experience

Information on the research leading to the introduction of saturated magnesium chloride solutions was compiled by searching institutional archives, libraries, and the literature. The condition of the glasses after more than three decades of exposure was visually inspected.

2.2. Pollutant Absorption

The capacity to absorb pollutants has already been investigated for potassium carbonate [8] and magnesium nitrate [9], where details of the experimental procedure and further references can be found. A gas mixing apparatus (GMA) provided a constant gas stream (here: 500 mL/min) of variable trace gas concentrations in clean air humidified to 33% RH into a 500 mL bottle with 200 mL headspace over the solution. Five metal oxide semiconductor (MOS) sensors with 11 gas-sensitive layers were run downstream in a temperature cycled operation (TCO) (Figure 3 in [8]). Data were used in machine learning algorithms to estimate pollutant concentrations. Saturated magnesium chloride solutions (purissimum, Fa. Grüssing, 26489 Filsum, Germany, no. 12088100) were prepared using HPLC water with an excess of undissolved salt.

2.3. Ion Chromatography

A controlled area (4 cm^2) was swabbed with a polyester Texwipe Alpha® TX761 swab (ap-systems reinraumshop, Reutlingen, Germany) moistened with 50 µL of deionised water. The swab was extracted with 5 mL of 18.2 $M\Omega cm^{-1}$ water. The extracted solutions were analysed using a Dionex ICS 1100 ion chromatograph (Fisher Scientific, Loughborough, Leicestershire, UK) with an Ionpac CS19 column and 18 mM methane sulphonic acid eluent for cations and an Ionpac AS19 column and 10 mM potassium hydroxide eluent for anions. Certified reference material solutions were used as calibration standards for sodium, potassium, calcium, magnesium, chloride, nitrate, and sulfate. High purity (99.98%) sodium formate and acetate were also used. As the carbonation of water by atmospheric carbon dioxide during sample transport could not be avoided, carbonate and hydrogencarbonate were not analysed.

Table 1 shows the recovery values from the swabs, as reported by Verhaar [10], who developed this method.

Table 1. Ion chromatography performance [10].

Ion	Recovery (%)	Limit of Detection (μg/cm^2)	Accuracy (% of Measured Value)
sodium	94.75 ± 4.97	0.003	1.5
potassium	91.96 ± 5.98	0.002	1.7
chloride	71.37 ± 25.68	0.01	2.1
nitrate	91.93 ± 2.92	0.02	1.9
sulfate	78.15 ± 4.28	0.01	2.1
formate	94.25 ± 2.19	0.06	3.2

Whilst the ion chromatograph errors were small, the error in swabbing the 4 cm^2 area probably was much larger and likely to approximate 4%. This value will dominate the method error.

The amount in micrograms was calculated from the ion chromatography-determined solution concentration and extraction volume (5 mL). This was divided by the area swabbed (4 cm^2) and the number of years since the last cleaning.

3. Results and Discussion

3.1. Maintaining a Healthy Climate for 'Sick' Glasses: The Coburg Experience

Among the Venetian and à la façon de Venise glasses in Coburg, 5% were lightly and 2% were heavily damaged [2]. From approximately 200 cut Baroque pieces in the collection, 7% showed symptoms of 'sweating' and cloudiness and 13 'heavy crizzling' [11], according to the classification by Brill 1978 [12]. The glass disease led to a research project that was completed in 1992. Unfortunately, only a short final report by Ulitzka 1992 [7] is known, which lacks many details. The missing full report could not be verified anywhere, neither at the institute, nor at the funder, the cooperating museums and showcase manufacturers, or in the international online union catalogue worldcat.org (which has an entry for the short version).

Ulitzka [7] found, using X-ray fluorescence (XRF) analyses, that glasses with less than 6% *w*/*w* CaO showed clear signs of glass disease, whereas those with more than 7.5% were stable. Test measurements using confocal laser scanning microscopy proved that it was possible to determine the thickness of the gel layers, which was taken as a measure of glass corrosion (±0.1 μm). Using oil immersion, a weak reflection at the border between the gel and glass was observed.

Four series of model glasses (potash [23.0% *w*/*w* K_2O, 0–10.7% CaO], soda [16.4% *w*/*w* Na_2O, 0–8.4% CaO], lead [3.4–18.0% *w*/*w* PbO, 17.7–19.8% K_2O, ~1.6% CaO], and mixed alkali [0–24.5% *w*/*w* Na_2O, 28.2–0% K_2O, ~0.9% CaO]) were synthesised and exposed to 30, 40, 50, 60, or 100% RH in desiccators 'over a longer period of time' (no exact time given (p. 14 in [7]). Measurements of the gel layer thickness using scanning electron microscopy failed because of the difficulties in preparing cross-sections. The samples were then stored at 35% RH for 15 months in a display case in the laboratory, along with historic glasses. For the choice of RH, Ulitzka (p. 20 in [7]) referred to an unpublished and currently unavailable report by Horst Scholze 1976 [13]: based on infrared measurements of the H_2O content of gel layers, 30–40% RH was recommended to avoid drying and cracking of the gel layer. According to the grant application [14], Scholze studied nine historic potash glasses (17.5–22.1% *w*/*w* K_2O, 60.7–80% SiO_2, and 0.5–5.5% CaO). Samples of a model glass were exposed to various humidity levels at 60 °C. Below 40%, the leaching of potassium was low.

After 12 months, all glasses in the display case were dry, and no further cracks were observed (p. 20 in [7]). Therefore, a saturated magnesium chloride solution (Table 2) with a deliquescence relative humidity (DRH) of 33% ([7]: 34%) was chosen for climate control in the display cases [7].

Table 2. Temperature dependence of the DRH of earth alkali chlorides [15].

Salt	Formula	15 °C	20 °C	25 °C	30 °C
Calcium chloride	$CaCl_2 \cdot 6H_2O$	34.1%	30.9%	28.1%	
Magnesium chloride	$MgCl_2 \cdot 6H_2O$	33.3%	33.1%	32.8%	32.4%

Although Scholze's proposal [13] was based only on experiments with potash glass at higher temperatures, it coincides with the new finding of Thickett et al. of 2024 [6] (see above).

A saturated salt solution containing undissolved crystals maintains a constant concentration even when water is evaporated or absorbed, as long as both phases exist in equilibrium. According to Raoult's law, the constant water activity in the solution causes a constant water activity in the air above the solution (i.e., RH). Therefore, such solutions (including magnesium chloride) are used to calibrate hygrometers and maintain a constant relative humidity in laboratory experiments (ISO 483:2005; ASTM E104-20a).

Compared to calcium chloride (not considered by Ulitzka [7]), the equilibrium RH of a saturated magnesium chloride solution is nearly independent of the temperatures occurring in museums (Table 2). To achieve a fast reaction, the solution was combined with the silica gel product Art Sorb® (Long Life for Art, Eichstetten, Germany) using sheets above the solution containers on a perforated metal plate (Figure 3a in [16]). Christoph Waller filed a German utility model (G 91 01 629.0, 13 February 1991) at the German patent office for this 'tandem model', which was bought by display case manufacturer Fa. Schöninger. Indeed, our recent research now could experimentally prove that silica gel is effective in achieving quick reconditioning after opening a display case (Table 10 in [17]). However, silica gel (even when unused) can be contaminated with pollutants [18–20]. Therefore, it is now recommended, if possible, to restrict openings to times when the room climate is close to that in the display case, for example, in winter or when a mobile dehumidifier is used. Fast reconditioning is then not an issue, and the addition of silica gel can be avoided.

Tandem display cases with magnesium chloride were implemented at Veste Coburg in 1993, with a second generation installed in 2010 (Figure 1). They have been used since then [7]. After three decades of experience, this approach appears to be effective for 'sick' glasses. Unlike glasses in storage, those on display appear stable upon visual inspection and comparison with photographs. No salt crystals or tears were observed on the surface. The spots wet-swabbed for sampling (see below) did not look different after drying; therefore, there was no cloudiness or haze present. The state of crizzling [3,11] did not worsen, and no tiny glass particles or fragments fell off. The climate in the display cases is quite constant, without fluctuations (Figure 2 in [21]). As the cases are not completely airtight and some outside air enters, the RH inside is somewhat higher than expected from the DRH (35–40%). A recent online 'handbook' [22] advises on all practical details regarding the use of salt solutions in display cases.

The Bayerisches Nationalmuseum [23] started a long-term monitoring project for their 'sick' glasses using time-consuming photographic documentation under defined lighting and x-y-z positioning. If this method proves effective, it will enable a more objective control of the extent of crizzling in individual pieces.

Initially, magnesium chloride solutions were replaced annually [11], but longer intervals have since been found to be sufficient. Over time, the solutions tended to darken,

indicating their role as dust sinks. The solutions used can be repurposed as eco-friendlier road de-icers. Magnesium chloride is also used as a food additive (E511), for example, in the preparation of tofu and in nutraceutical and pharmaceutical preparations; therefore, it poses no severe health risks to humans.

Figure 1. Coburg display case with an open technical compartment for maintaining solutions in plastic containers. © Kunstsammlungen Veste Coburg.

3.2. Pollutant Absorption

At the time the display cases were set up, conservators were largely unaware of the corrosive effects of volatile organic compounds (VOCs) on glass, such as acetic and formic acids [24] or formaldehyde [25]. 'Control of pollution is essential to minimise deterioration rates.' (p. 371 in [25]).

If a liquid is in contact with air, an equilibrium between the compounds in both phases will be established (Henry's law). This indicates that air pollutants will enter the salt solution. The air becomes cleaner because of some absorption of pollutants by the liquid. Henry coefficients for water are well known [26], but not for saturated salt solutions.

The absorption of pollutants by magnesium chloride has already been demonstrated in a preliminary report: after injecting 5 ppm into the headspace of a bottle with a saturated salt solution, hydrochloric, acetic, and formic acids were readily absorbed (Figure 4 in [20]). In a display case that was not tightly sealed and initially contained 480 ppb of formaldehyde, the concentration decreased much faster when magnesium chloride solution was present (Figure 6 in [20]).

In the new experimental setup, the gas mixing apparatus (GMA) was used to provide four different pollutant concentrations in a continuous stream (black dashed curve in Figure 2) and to train a MOS sensor array in temperature cycled operation (TCO, 1 cycle = 144 s; full black curve). The closer these lines are, the better is the training. Then, a magnesium chloride solution was introduced into the test bottle, and the measured

concentration (full red curve) was compared with the one provided (dashed red curve). This difference proves pollutant absorption by the solution (for experimental details, refer to [8,9]). A fast flow of 500 mL/min through a 200 mL headspace (only 24 s retention time in the headspace) was chosen to check whether absorption could be observed even under such drastic conditions. In real display cases, there will be much more time to reach equilibrium or a steady-state. The extent to which pollutant concentrations can be reduced in realistic scenarios requires further study.

The results (Figure 2) were similar to those obtained using magnesium nitrate [9].

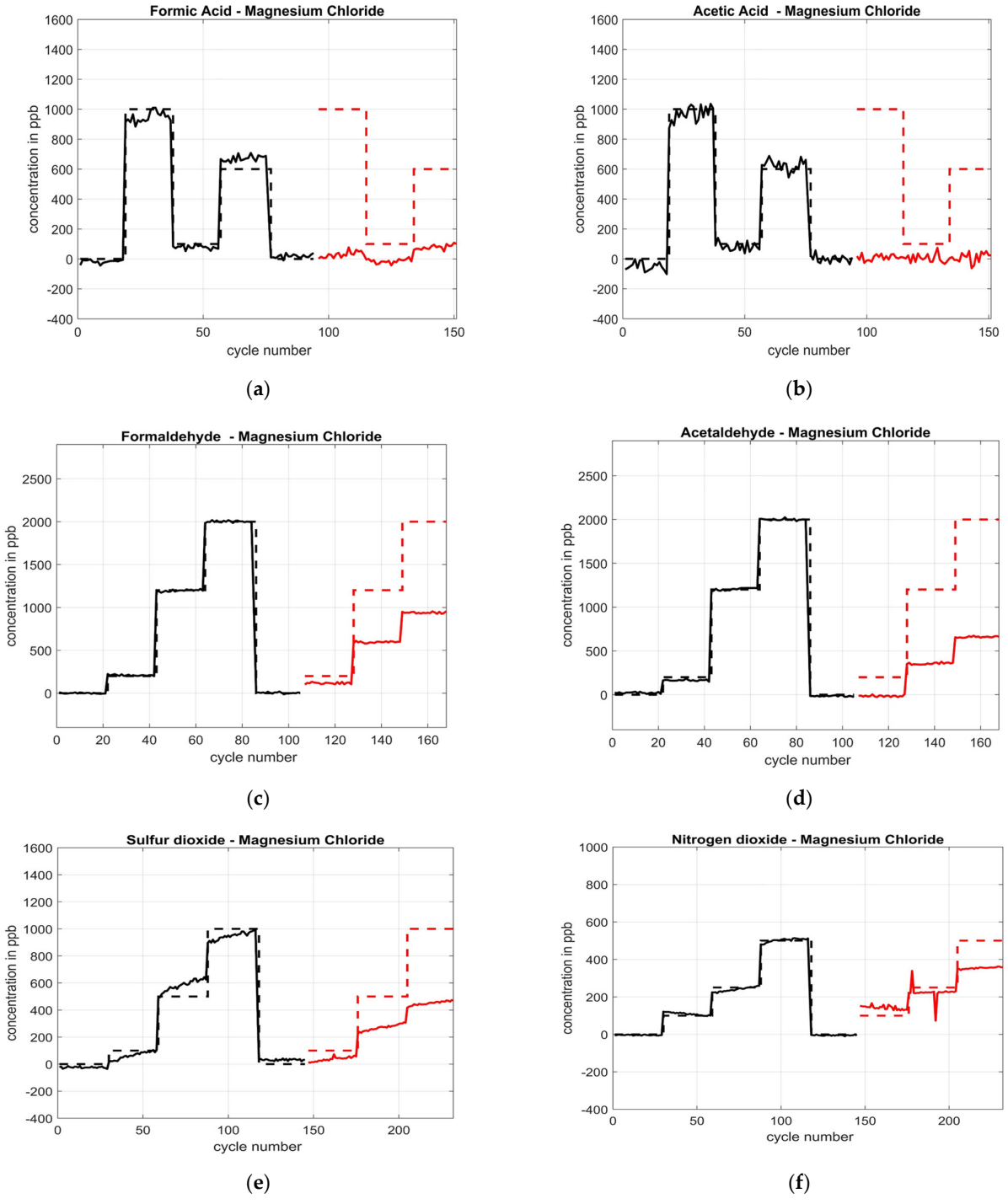
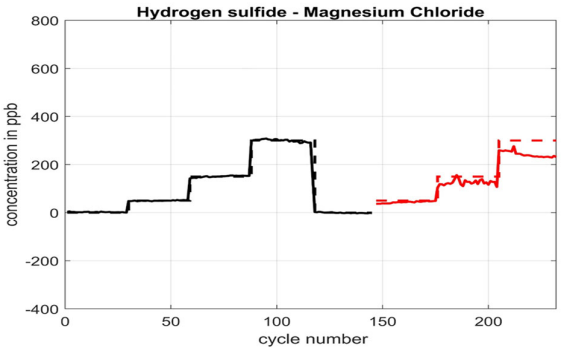


Figure 2. *Cont.*



(**g**)

Figure 2. Absorption of pollutants from a gas stream: Model estimates of a calibrated sensor array for exposure to typical pollution in a Duran bottle. Black: without salt solution; red: with magnesium chloride. The dashed lines indicate the concentration set using the gas mixing apparatus. Solid line: Model estimate, that is, the output of the calibrated sensor array. From top left to bottom: (**a**) Formic acid (methanoic acid, HCOOH), (**b**) acetic acid (ethanoic acid, CH_3COOH), (**c**) formaldehyde (methanal, H_2CO), (**d**) acetaldehyde (ethanal, CH_3CHO), (**e**) sulfur dioxide (SO_2), (**f**) nitrogen dioxide (NO_2), (**g**) hydrogen sulfide (H_2S).

As shown in Figure 2a,b, the measured concentrations of formic and acetic acids above the magnesium chloride solution were nearly zero, even at the highest tested concentrations, demonstrating the excellent absorption capacity of the solution for these acids.

Aldehydes (Figure 2c,d) were also effectively absorbed by the magnesium chloride solution, although not completely under the experimental conditions described above. These compounds, along with the acids, are classified as harmful 'carbonyls'—polar substances capable of forming hydrogen bonds with water and exhibiting high Henry coefficients in pure water (Table 2 in [9]). They are common pollutants, often emitted from wood and wood-based materials.

Sulfur dioxide (Figure 2e), which occurs in the atmosphere, has a lower affinity for water (lower Henry coefficient (Table 2 in [9])), but approximately half of the pollutant is still absorbed by the salt solution.

The Henry coefficient of the outdoor pollutant nitrogen dioxide is lower than 1 (0.30), indicating that, in equilibrium, the concentration in the gas phase is higher than that in pure water. However, some absorption was evident in the salt solution at higher concentrations.

Hydrogen sulfide (e.g., from rotting biomaterial or anaerobic finds) is not very polar and has a low Henry coefficient for pure water (Table 2 in [9]). Therefore, only slight absorption is expected (Figure 2g).

The experimental setup did not work for carbonyl sulfide (COS) (e.g., emitted from degrading wool), as the measured concentrations exceeded those supplied, despite successful sensor training for COS in the absence of a solution. This effect has also been observed with magnesium nitrate [9] and might be due to the hydrolysis of COS, producing H_2S, for which the sensors were not trained in this experiment:

$$COS + H_2O \rightarrow CO_2 + H_2S$$

The sensor training did not work for hydrogen chloride (e.g., from the degradation of PVC) because large fluctuations occurred between the measuring cycles. However, the static experiment (see above) proved the ready absorption of HCl by the solution. Ozone (O_3) and nitrogen monoxide (NO) need not to be tested because of their relatively short half-life time indoors.

After installation three decades ago, pollution in some Coburg glass display cases was measured using glass sensors from Fraunhofer ISC. Compared with measurements in other European glass displays, Leissner concluded in 1996 (p. 83 in [27], see also [11]): 'The Freie Vitrine at the Glass Gallery in Coburg made from glass and stainless steel equipped with a salt solution to maintain humidity at 40% [sic] exhibited the best environmental performance according to glass sensor measurements and pollution analysis.' The reason for this, which was not further investigated at the time, is now evident: salt solutions absorb pollutants!

3.3. Quantifying Glass Disease

3.3.1. Alkali Ions

Glass degradation by ion exchange deposits alkali ions on the glass surface. This led to the idea of quantifying glass disease by swabbing the glass surface and measuring the amount of ions using ion chromatography (IC, [10]). Thickett and Ling [25] used IC to investigate the deterioration of weeping glass under controlled relative humidity. The measurement protocol [28] was used to swab the Coburg glasses (Figure 3, Table 3) and measure the ion surface concentrations to calculate the annual release (Table 4).

Figure 3. Hollow baluster goblet with Diana (a.S.00312, detail), S3 in Table 2. © Kunstsammlungen der Veste Coburg.

Table 3. Samples swabbed from Coburg glasses.

No.	Object/ Inv.-No	Showcase No. (Since 2018)	Treatment	Condition	Description	Sampling Location
S1	a.S.00385	26	16 November 2016	crizzling	Goblet with hollow baluster depicting the month of November in the shape of a dwarf. After Jacques Callot, 2nd half of the 17th century, Nuremberg	Cuppa exterior: surface tapered (V-shape)
S2	a.S.00386	26	16 November 2016	crizzling	Goblet with hollow baluster depicting the month of July in the shape of a dwarf. After Jacques Callot, 2nd half of the 17th century, Nuremberg	Cuppa exterior: surface tapered (V-shape)

Table 3. *Cont.*

No.	Object/ Inv.-No	Showcase No. (Since 2018)	Treatment	Condition	Description	Sampling Location
S3	a.S.00312	26	16 November 2016	crizzling	Hollow baluster goblet with the hunting goddess Diana and the hunter Actaeon, Nuremberg, around 1680 Colourless glass, matt cut, diamond cut	Cuppa exterior: surface tapered (V-shape)
S4	a.S.00304	26	16 November 2016	crizzling, matte areas on the surface	Goblet for the wedding of Duke Friedrich I of Saxe-Gotha and Altenburg and Margravine Christiane of Baden, Hermann Schwinger (?), 1681	Cuppa exterior: surface tapered (V-shape)
S5	a.S.00622	26	17 November 2016	crizzling, matte areas on the surface	Double tumbler with symbols of attack and defence, Georg Schwanhardt the Elder, Nuremberg, mid-17th century	Top and side of spherical surface (O-shape)
S6	a.S.00621	26	no cleaning for 20 years	strong crizzling, cracks already going through the glass, fragments (glued)	Tumbler with a portrait of King Gustav II Adolf of Sweden (1594–1632) Georg Schwanhardt the Elder (1601–1667), Nuremberg, around 1632	Cuppa exterior (upside-down): surface tapered (A-shape)
S7	glass tableau top	26	probably 2018	-	-	
S8	glass tableau bottom	26	probably 2018	-	-	
S9	showcase glass, vertical	26	probably 2018	-	-	
S10	HA.0035	01	1 November 2016	matte areas on the surface	Rippenbecher/Beaker, Venice, 2nd half of 15th century	Cuppa exterior: surface tapered (V-shape)
S11	HA.0089	02	9 November 2016	cuppa with matte surface	Goblet glass on a ribbed stem with wings, six-pointed bowl, Venice, 17th century	Cuppa exterior: surface tapered (V-shape)
12	HA.0029	02	26 October 2016	no visible decay	Kelchglas/Goblet, Hall/Tirol or Innsbruck, 1570–1590	Cuppa exterior: surface tapered (VtoH-shape)
13	HA.0484	02	26 October 2016	matte areas on the surface	Kelchglas/Goblet, Hall/Tirol or France, 2nd half of 16th century	Cuppa exterior: surface tapered (V-shape)

Table 4. Annual release of ions on Coburg glasses [µg/(cm^2·year)] (bd = below detection limit).

No.	Sodium	Potassium	Chloride	Nitrate	Sulfate	Formate
S1	0.014	0.168	0.011	0.028	0.024	0.058
S2	0.003	0.121	bd	0.006	0.009	0.054
S3	0.009	0.209	0.003	0.011	0.016	0.080
S4	0.410	0.018	bd	0.008	0.015	0.252
S5	0.375	0.023	0.005	0.003	0.016	0.302
S6	1.264	0.030	0.028	0.008	0.051	1.88
S7	0.048	0.002	bd	0.004	0.013	0.020
S8	0.074	0.003	bd	0.007	0.007	0.060
S9	0.046	0.002	bd	0.004	0.005	0.020
S10	0.065	0.011	bd	0.013	0.012	0.027
S11	0.041	0.003	bd	0.007	0.006	bd
S12	0.231	0.014	0.014	0.007	0.025	0.014
S13	0.120	0.005	bd	0.013	0.011	0.020

Other hitherto unreported measurements at English Heritage found glasses with a combined alkali content below 0.3 µg/(cm^2·year) (yellow line in Figure 4) to be stable

(visually judged). All but two of the Coburg samples, whether soda or potash glass, fall within this region and can be considered stable. Unstable glasses have a combined alkali content of over 0.4 μg/(cm^2·year) (red line in Figure 4). More data will be added when available to better determine this threshold.

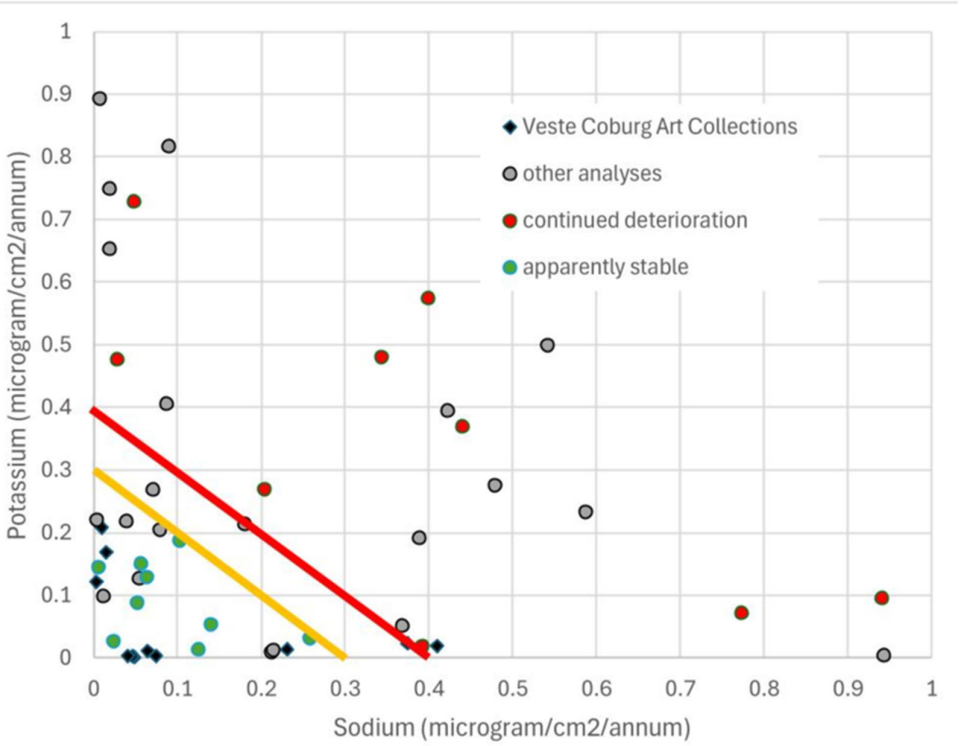


Figure 4. Comparison of annual alkali surface deposition on Coburg glasses and other glasses.

All values were not corrected for the contribution of dust. This is relevant especially for sodium, less so for potassium, and may vary with the position of the swabbed areas (horizontal or vertical) and in the case. The samples from the construction glass display case itself (S7–S9) allow a rough estimate of approximately 0.05–0.08 μg/(cm^2·year). If such a value is deduced, S4 and S5 move from the red line much closer to the yellow line and the stability field.

S6 from the tumbler with a portrait of King Gustav I Adolf of Sweden was not included in this evaluation because the time of the last cleaning was unknown. Due to severe deterioration, conservators have not attempted to clean it for at least the last 20 years. The numbers in Table 4 were calculated with a minimum of 20 years as the maximum-annual-release value. The last cleaning could have occurred much before the display change to magnesium chloride, and the ions would mainly be due to the previous non-climatised situation.

Overall, the measurements confirm the visual evaluation that glass disease has been stopped for over three decades by using magnesium chloride in display cases.

3.3.2. Formate

Formate ($HCOO^-$) is a common ion on glass. This may originate from formic acid or from the Cannizzaro reaction of the ubiquitous air pollutant formaldehyde in an alkaline medium:

$$Na^+OH^- + 2H_2CO \rightarrow Na^+HCOO^- + CH_3OH\uparrow$$

Thickett and Ling [25] were indeed able to detect the accompanying volatile methanol (CH_3OH). The fact that formates are found as metal corrosion products when in contact with glass (but not elsewhere on such objects, [29]) also points to the role of alkaline glass films and formaldehyde as sources. Formic acid attacks metals everywhere.

Formate on glass surfaces is coupled to alkali ions, such as sodium or potassium formate. S4 and S5 with the highest sodium release also have the highest formate value (S6 not considered, see above). Therefore, the effect of the reduced alkali release due to low humidity can hardly be separated from that of the formic acid or formaldehyde absorption in the solution.

3.3.3. Other Anions

A saturated solution of magnesium chloride emits traces of HCl (11 ppb at 25 °C [30]). If the solutions absorb acid pollutants, they will be acidified, and HCl emission will increase.

In an accelerated Oddy-type corrosion test, metal coupons were exposed for 4 weeks at 60 °C; the RH controlled by $MgCl_2$ is only 29.3% at this temperature. The copper coupon darkened (Raman: cuprite, Cu_2O). It was even speculated that this trace source of acid might be beneficial. It could neutralise some of the alkalinity on the glass surface and thus counteract the cleavage of Si-O bonds by OH^- [30].

Our measurements show that dust (S7–S9) does not contribute to the chloride values. No enlarged deposition of chloride on glass was found due to the solution. These values are lower than those found in the British Museum in a maritime environment (Figure 1 in [25]). Nevertheless, as a precaution, magnesium chloride solutions should not be used to display acid-sensitive materials.

The values for sulfate and nitrate are also low compared to the data from the British Museum (Figure 1 in [25]). However, the atmospheric concentrations of the precursor pollutants SO_2 and NO_2 are much higher there than on top of the rural hill in Coburg. Nevertheless, some absorption in the solutions appears plausible in light of our gas measurements.

4. Conclusions

For over three decades, saturated magnesium chloride solutions have stood the test of time in Coburg for the display of ‘sick’ glasses. The glasses are in a stable condition: the solutions not only provide a constant RH of 33% in tight cases, but they also absorb some pollutants, including those known for their corrosivity to glass. No expensive equipment or steady supply of electricity is required, which makes this passive method fail-safe. A handbook on the practical application of salt solutions, collecting experiences from 30 conservators worldwide participating in a community science project (2023–2024), is available online [22].

As discussed for magnesium nitrate [9], salt solutions require much less time for maintenance than silica gels. The latter must be reconditioned frequently because of its lower water capacity and fluctuating equilibrium RH, depending on the water content.

Saving money, energy, and conservator’s time—a sustainable solution to dry the tears of ‘weeping’ glass!

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Abbreviations

The following abbreviations are used in this manuscript:

DBU	Deutsche Bundesstiftung Umwelt
DRH	Deliquescence relative humidity
IC	Ion chromatography
IIC	International Institute for Conservation
RH	Relative humidity
TCO	Temperature cycled operation
XRF	X-ray fluorescence
% *w*/*w*	Percentage by mass

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