DEMYSTIFYING SILICA GEL

Steven Weintraub

ABSTRACT - It is important to understand how silica gels vary in performance in order to select the most cost-effective gel for a particular application. M_H, the hysteresis corrected buffering capacity of silica gel, is the critical variable for assessing silica gel efficiency. Calculating the correct quantity of silica gel allows for the cost-efficient selection of an appropriate amount of buffering material. If certain variables in the calculation are unknown, such as leakage rate or external RH conditions, general recommendations based on average display conditions have been provided, both for temporary exhibitions and for permanent displays. Finally, simple procedures for the use and maintenance of silica gel have been described. Passive humidity control within an exhibit case, when applied correctly, is a very simple and cost-efficient method of protecting museum collections from humidity induced damage.

1. INTRODUCTION

In 1959, silica gel was first recommended for use in museum applications as a buffering agent to control relative humidity (RH) in "closed packages" (Toishi 1959). Since that time, in spite of silica gel's use for museum exhibition case RH control throughout the world, there has been a great deal of mystery and confusion regarding the use of silica gel systems. The purpose of this article is to demystify and explain basic information about silica gel:

- How does silica gel function?
- What are the significant differences among silica gels used in museum applications?
- How much silica gel is required to control relative humidity in an exhibition case?
- How can silica gel be reconditioned?

2. WHAT IS SILICA GEL AND HOW DOES IT WORK?

2.1 EMC/RH ISOTHERM

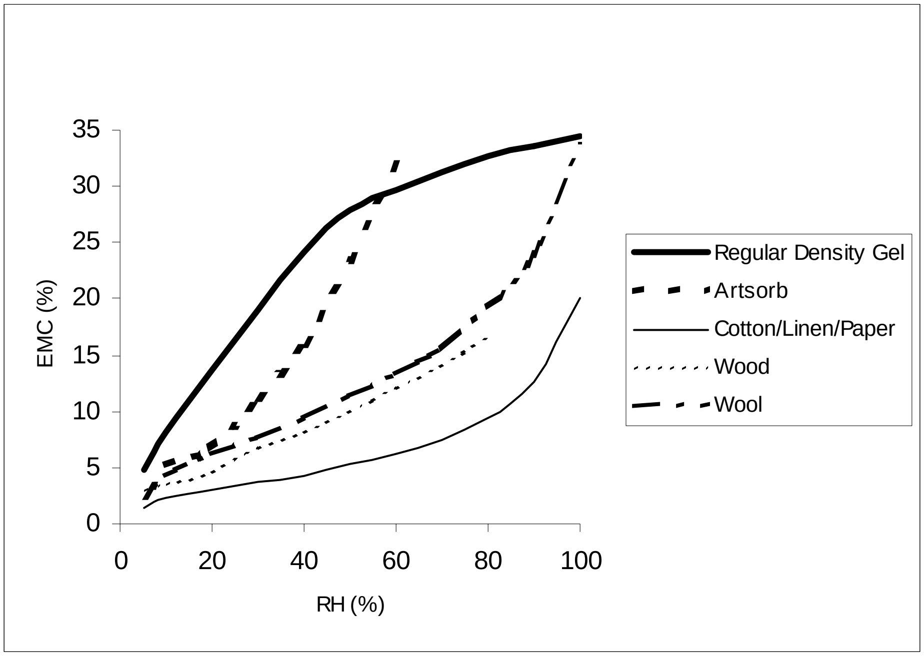
In order to understand how silica gel functions, it is critical to understand the concept of Equilibrium Moisture Content (EMC). Many materials contain moisture. The quantity of moisture in hygroscopic materials depends on the temperature and RH of the surrounding air. If the temperature or RH changes, the moisture content within the object will change so that it will come into equilibrium with the new condition of the surrounding air.

Moisture content is the weight of water in an object expressed as a percentage of its dry weight. The EMC is the moisture content of an object in equilibrium with a specified RH. For example, if a piece of paper weighing 100 grams at 0% RH increases to 105 grams at 50% RH, it now has 5 grams of moisture compared to its dry weight, resulting in a 5% EMC at 50% RH:

(105 g at 50% RH – 100 g at 0% RH)/100 g (dry weight) = 0.05 = 5% EMC

- To understand the moisture uptake characteristics of hygroscopic materials, a series of EMC values for the full range of RH conditions at a fixed temperature can be plotted. This is known as an EMC/RH isotherm (Fig. 1).

Figure 1. Equilibrium Moisture Content / Relative Humidity Isotherm



For organic materials, it is theoretically important to take temperature into account since it affects EMC. But, in actuality, a moderate change in temperature has a relatively small influence on EMC compared to a moderate change in RH (temperature has no effect on the EMC of silica gel within the normal range of museum use). Because hygroscopic objects are far less affected by temperature than RH in terms of impact on the moisture content and physical stability, RH is the principle focus of concern. And, since RH rather than the absolute moisture in air determines the moisture content of an object, we are concerned with RH rather than absolute humidity. [1]

2.2 BUFFERED CASES AND RH CONTROL

The interior of a relatively airtight exhibition case will provide some level of protection against fluctuating RH conditions outside the case. However, through gradual air leakage, the RH inside the case will slowly increase or decrease, depending on the condition of the outside RH. The rate of interior RH change depends on the amount of leakage. If the rate of air leakage is one air exchange per day, the RH within the case will equal the RH of the surrounding air within one day. [2] In reality, if there are a lot of hygroscopic materials within the case, the interior RH of a case with a leakage rate of one air exchange per day will barely change. The reason for this is the buffering effect of the hygroscopic materials within the case.

- As the exhibition case gains or loses humidity because of leakage, the hygroscopic materials within the case must gain or lose some moisture content in order to remain in equilibrium with the RH of the surrounding air. The water gained or lost by these materials offsets most of the expected change in RH within the case. In effect, these materials act as buffers to slow down the rate of change in RH within the exhibition case.

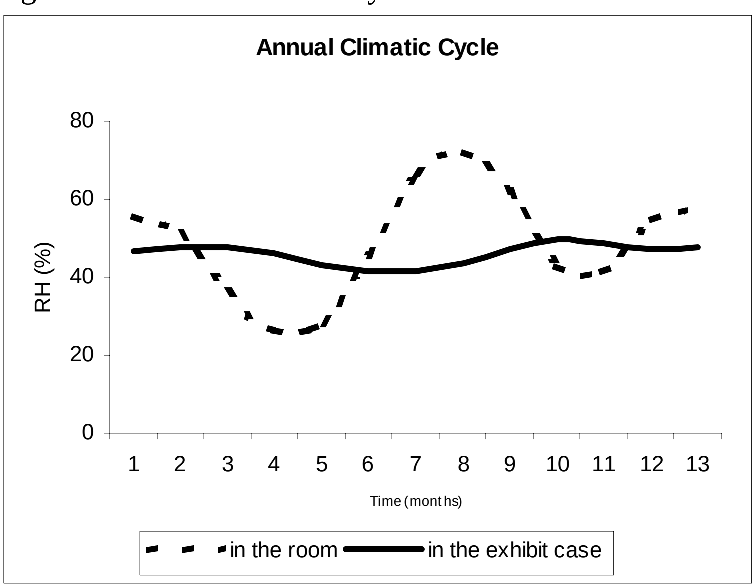
For example, a one meter case with an internal RH of 50%, an external RH of 25% and an air exchange rate of 1x per day will lose 5 grams of moisture in a day as the internal RH decreases from 50% to 25% RH (there are about 10 g/m³ at 50% RH and 5 g/m³ at 25% RH at 22.7ºC). However, if the case contains a great deal of hygroscopic materials, these materials will give off some of their moisture as the RH within the case falls in order to remain in equilibrium with the surrounding RH. As a consequence, the moisture given off by these materials offsets almost all of the 5 grams of moisture in air lost through leakage, so the RH in the case only falls by a fraction of a percent rather than by 25% RH over a single day.

2.3 BUFFERING CAPACITY AND RH CONTROL

As a result of the buffering effect of hygroscopic materials, the RH within an exhibition case will show only a very small daily fluctuation or a very slow change in RH over time compared to conditions outside the case (Fig. 2). However, the degree of internal fluctuation or change in RH within the case depends on the buffering capacity of all the hygroscopic materials within the case. If the case has a relatively small ratio of hygroscopic materials compared to the total case volume, the buffering capacity of the case will be limited compared to a case with a large amount of hygroscopic materials.

- In practical terms, this means that a case with a large amount of buffering capacity may take many months for the RH to decrease from 50% RH to 25% RH, whereas if there is very little buffering capacity, the decrease may occur over a period of days or weeks. In fact, for an exhibition case where the only hygroscopic material is the object itself, the object becomes the buffer. By introducing other buffering materials into the case, it is possible to significantly reduce the rate of change of moisture from the object itself, thereby reducing risk of RH induced damage. [3]

Figure 2. Annual Climatic Cycle



Since all hygroscopic materials provide some level of buffering capacity, why do museums use silica gel for this purpose rather than inexpensive, easily available organic materials like cotton? The primary reason is because of the much higher buffering efficiency of silica gel compared to organic materials. [4] Buffering capacity is based on the amount of moisture that a material will gain or lose within a specified range of RH. The buffering capacity of materials can be compared in a general way by looking at their EMC/RH isotherms (Fig. 1). From this graph, it is clear that the two illustrated silica gels have the capacity to adsorb much more moisture than natural materials such as wood, cotton or wool at the low to mid-RH range.

As a consequence of silica gel's high moisture capacity, far less silica gel is needed by weight to achieve a certain amount of buffering capacity compared to organic materials. In addition, because of the high density of silica gel (approximately 0.7 kilograms per liter or 44 pounds per cubic foot for a regular density grade), it takes up far less space in an exhibition case than an organic material with equivalent buffering capacity.

2.4 SILICA GEL – A BRIEF DESCRIPTION AND HISTORY

Silica gel is a chemically inert, non-toxic material composed of amorphous silicon dioxide. It has an internal network of interconnecting microscopic pores, yielding a typical surface area of 700-800 square meters per gram; or, stated another way, the internal surface area of a teaspoon full of silica gel is equivalent to a football field. Water molecules are adsorbed or desorbed by these micro-capillaries until vapor pressure equilibrium is achieved with the relative humidity of the surrounding air. Silica gel was patented in 1919 for use in the adsorption of vapors and gases in gas mask canisters during World War I. During World War II, it was commonly used as a dehydrating agent to protect military and pharmaceutical supplies, among a number of other applications. Its use as a buffering agent to control RH within the mid-range rather than as a desiccant is a unique to museum applications.

3. DIFFERENT TYPES OF SILICA GEL – DIFFERENT TYPES OF PERFORMANCE

3.1 DEFINING BUFFERING CAPACITY – THE VARIABLE M

The moisture adsorbing properties of silica gels are affected by factors such as capillary pore size or the inclusion of hygroscopic salts, resulting in a wide range of performance. [5] Therefore, it is important to compare the buffering capacity of different types of silica gels to determine which silica gel has the best performance for a specific application. Thomson (1977) described the "specific moisture reservoir" with the variable M.

- The moisture buffering capacity of a material is defined by its M value, which is the amount of water (in grams) that is gained or lost by 1 kilogram of silica gel for each 1% change in RH.

For example, if one kilogram of silica gel adsorbs 50 grams of moisture between 40-50% RH, M is calculated as follows [when calculating M from EMC values, multiply the EMC value by 10 to convert it to grams of water per kilogram of dry silica gel]:

$$M = 50 \text{ grams of moisture}/10\% \text{ RH} = 5$$

M varies because of the following factors:

- The point along the EMC/RH isotherm at which it is measured.
- The magnitude of the RH range used to determine M.
- Whether it is measured along the adsorption or desorption isotherm.
- The difference in M values derived from the adsorption and desorption isotherms (hysteresis), expressed by the variable M_H, described below.
- Whether M_H, the hysteresis compensated M value, was estimated or experimentally determined.

For example, within the range of 30-60%, the M value of regular density silica gel (RD gel) can vary from 6 to 1.25, depending on how it is calculated. [6] This large variation in M has major consequences, since the amount of silica gel required to buffer an exhibit case will vary inversely with M. In the above example, a case would require almost five times as much silica gel if M = 1.25 instead of M = 6.

3.2 DEFINING BUFFERING CAPACITY – THE VARIABLE M_H

To avoid confusion about the correct value of M, it is necessary to use a modified value, M_H, which accounts for variations in the value of M.

- M_H is the average amount of water (in grams) that is gained or lost by 1 kilogram of silica gel for each 1% change in RH. This is determined by repeatedly cycling silica gel between adsorption and desorption within a specific RH range until a constant value is measured. By taking hysteresis into account, M_H reflects actual buffering performance. [See Appendix 1 for a description of M and M_H calculations.]

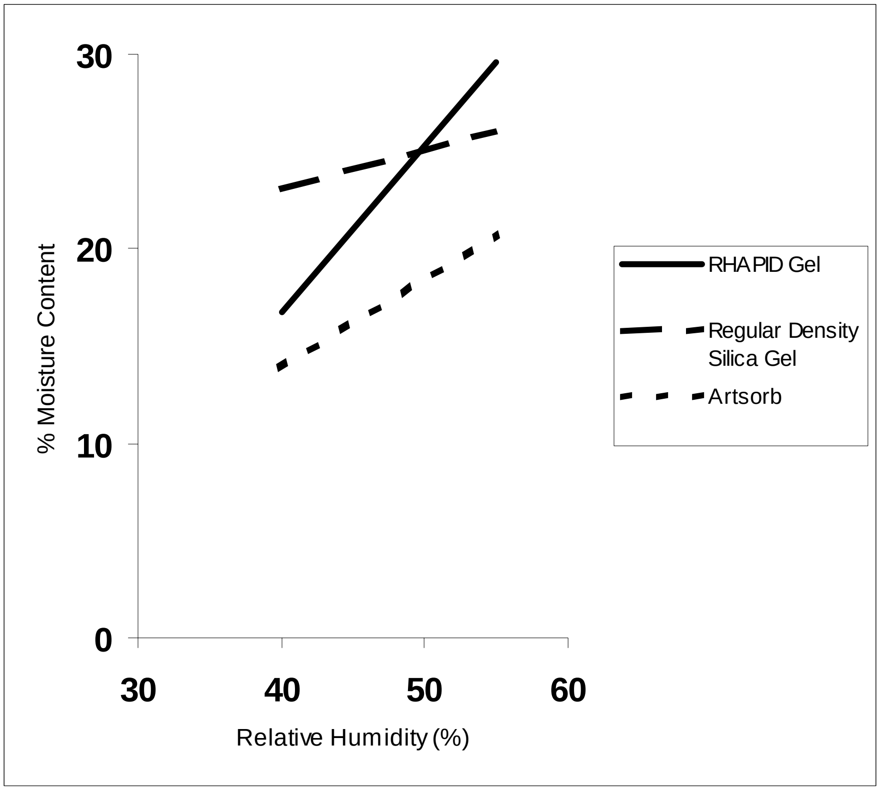
Three types of silica gel used in museum applications were tested to determine their M_H values in the range of 40-55% RH. [7]

Experimentally determined M_H between 40-55% RH

- RD gel = 2.0
- Art-Sorb = 4.5
- Rhapid Gel [8] = 8.7

Based on these results, RD gel is less than half as efficient as Art-Sorb, and Rhapid Gel is almost twice as efficient as Art-Sorb (Fig.3). These results are not surprising, based on the overall EMC/RH isotherms for these silica gels (Yu et al. 2001). RD gel has very good adsorption properties below 45% RH, but quickly flattens out in the higher RH range. It is very important to understand the implication of this behavior. It means that RD gel is a very effective buffer below 45% RH, but has very little buffering capacity above 45-50% RH. Art-Sorb has less buffering capacity than RD gel below 45% RH, but has a large buffering capacity above 60% RH. Its mid-level performance is between the other gels in the 40-55% RH region because this is the transition range at which it begins to improve its buffering performance. [9] Rhapid Gel has very large buffering capacity in this mid RH range because its peak adsorption and desorption capability is centered in this RH region.

Figure 3. Hysteresis Corrected EMC/RH Isotherm Between 40-55% RH



4. HOW MUCH SILICA GEL IS ENOUGH?

4.1 TOO MUCH OR TOO LITTLE?

The most frequent questions regarding silica gel are:

- How long will silica gel last?
- How much silica gel is required?

All silica gels have an infinite life in terms of the ability to adsorb or desorb moisture. Therefore, silica gel can be reconditioned and reused indefinitely.

Recommendations for the required amount of silica gel vary from 20 kg/m³ of RD silica gel (Thomson 1977) to 0.5 kg/m³ of Art-Sorb (Art-Sorb 2003). Why are these recommendations so different? The discrepancy is not based on comparison of buffering capacity, but rather on the formulas used for determining quantity.

Thomson determined that 20 kg/m³ of regular density silica gel was required in order to buffer the RH in an average case over a full year so that it would never require reconditioning. His goal was to create a self-correcting, maintenance-free case where the interior would be buffered against the low winter RH and high summer RH of the surrounding air (Fig. 2). [Appendix 2]

Although Art-Sorb does not publish the source for their recommendation of 0.5 - 1.0 kg/m³, it can be deduced from a published study by Miura (1981), referenced in earlier Art-Sorb product literature, and information referenced in the Lascaux website (Art-Sorb/Lascaux 2003). These references deal with the amount of silica gel required to offset changes in RH brought about by rapid changes in temperature, a short-term effect.

- If it is correct that Art-Sorb's recommendation of 0.5-1.0 kg/m³ is based on protection against short-term temperature effects, it is not appropriate as a basis for how much silica gel should be used within an exhibition case for protection against long-term leakage, which requires much more silica gel.

4.2 DETERMINING THE QUANTITY OF SILICA GEL

Estimating the amount of silica gel required to buffer or control RH within an exhibition case must take into account the varying condition of the display environment and the capacity of the buffering material. This can be calculated as follows:

1. Determine the total amount of moisture gained or lost by an exhibit case over a specified period of time.

2. Determine the amount of water that can be adsorbed or desorbed by a kilogram of silica gel within the anticipated RH range of the exhibit case.

3. The total amount of silica gel required is determined by dividing moisture gain or loss by available moisture capacity of silica gel.

These steps are encompassed by the following equation, developed by Weintraub and Tétreault (Tétreault 2003) [10]:

$$Q = (C_{eq}\ D)V(Nt)/(\ M_H\ F)$$

Where:

- Q = Kilograms of silica gel required.

- C_{eq} = Concentration of water vapor at saturation.
  [At 22.7º C (73ºF), a cubic meter of air holds 20 grams of water vapor at saturation]

- D = The differential between the external RH and RH within the exhibit case. External RH is based on the average maximum range of RH fluctuation within the room. For a temporary case, interior RH is based on the acceptable limit of the RH range within the case. For a permanent case, interior RH is based on the RH midpoint within the case. As an example:

  - For a temporary case where the internal RH range is 45-55% and the exterior range is approximately 35%-65% RH, D is the difference between the lowest internal and external RH values, 45% and 35%, or between the highest internal and external RH values, 55% and 65%. In either case, D = 10% or 0.1.

- For a permanent, maintenance-free case where the internal RH range is 45-55% and the exterior range is approximately 30%-70% RH, D is the difference between the RH midpoint within the case (50%) and the lowest or highest external RH values, 30%, or 70%. In either case, D = 20% or 0.2.

- V = The volume of the case, expressed in cubic meters.

- N = The number of air exchanges per day.
  [Thomson (1977) used a value of one air exchange per day for a typical moderately sealed exhibit case]

- t = The maximum number of days that the exhibit case should remain within an acceptable range of RH.
  [90 days for a typical temporary exhibition]

- M_H = The moisture buffering capacity of silica gel within the specific RH range of use, taking hysteresis into account.

- F = The acceptable maximum range of RH fluctuation within the exhibit case. [45-55% RH as a typical value for organic materials]

As an example, the amount of silica gel required for a permanent, maintenance-free case of one cubic meter, using regular density silica gel (M_H = 2) and utilizing the values described in brackets for the above variables, is:

$$Q = (C_{eq} D)V(Nt)/(M_H F)$$

$$Q = (20 \times 0.2) \times 1 \times (1 \times 90)/(2 \times 10) = 18 \text{ kilograms of silica gel}$$

- Since the relationship of all variables is arithmetic, it is easy to recalculate the amount of silica gel required based on a change in one or more variables.

4.3 QUANTITY OF SILICA GEL FOR A TEMPORARY EXHIBITION

For a short-term application such as a special exhibition that is 90 days in duration, a smaller quantity of silica gel can be used, compared to the requirement of a permanent exhibit. This assumes that the RH within the gallery space is usually moderate and rarely exceeds 35-65% (i.e. no more than 10% RH above or below the RH range within the case). If the acceptable exhibit case range is 45-55%, then the differential between internal and external RH is 10% and D = 0.1, and 9 kg/m³ of RD gel is required.

For an exhibit case located within a space with moderate RH control, the following amounts of silica gel are recommended based on their respective M_H values [8]:

Recommended quantity of silica gel for temporary exhibition cases in rooms with moderate to good climate control

- **RD gel:** **9 kg/m³** **or** **0.55 lb/ft³**
- **Art-Sorb** [11]**:** **4 kg/m³** **or** **0.25 lb/ft³**
- **Rhapid Gel** [12]**:** **2 kg/m³** **or** **0.125 lb/ft³**

4.4 QUANTITY OF SILICA GEL FOR MAINTENANCE-FREE EXHIBIT CASES

In addition to using the above equation to calculate the amount of silica gel required for short time periods, it can also be used to calculate the amount of gel required to buffer a case over an annual cycle, such as Thomson estimated through his "hygrometric half-time" calculation.

The concept of a self-correcting maintenance-free case requires that the acceptable RH range inside the case falls midway within the annual RH range outside the case. For example, if the room RH varies from 30% to 70% RH, the exhibit case interior midpoint RH will be 50% RH. In the summer, as the room RH rises, the internal RH will gradually rise to the upper limit of its acceptable RH range, for example, 55% RH. In the autumn through winter as the room RH drops, the internal RH gradually drops back to the 50% RH midpoint and eventually to the lower limit of its acceptable range at 45% RH. In the spring through summer, the RH rises to a maximum of 55% RH and the sequence of RH self-correction continues ad infinitum.

Each period in which the humidity rises or falls above or below the RH midpoint is approximately 90 days. Therefore, the case requires a buffering capacity of 90 days. By using a value of t = 90 days and a D value based on the RH midpoint, the above equation can be used to calculate the amount of silica gel required for a maintenance-free case. In the leakage example above where t = 90, assumptions similar to Thomson's were used regarding air exchange rate (N=1), M_H value (M_H=2 for RD gel), and the RH range inside and outside the case (D=0.2). This yielded a result of 18 kilograms, similar to the value of 18.75 kg determined with Thomson's half-time formula.

Recommended quantity of silica gel for maintenance-free exhibit cases

- **RD gel:** **18 kg/m³** **or** **1.1 lb/ft³**
- **Art-Sorb** [11]**:** **8 kg/m³** **or** **0.5 lb/ft³**
- **Rhapid Gel** [12]**:** **4 kg/m³** **or** **0.25 lb/ft³**

4.5 MARGIN OF SAFETY

In reality, the rate of leakage and the actual amount of moisture gained or lost by an exhibit case is a more complex process than is taken into account either by the above equation, or by Thomson's half-time equation (Michalski, 1994). Both Thomson's hygrometric half-time equation and the silica gel quantification equation, described above, err on the side of putting in more silica gel than is actually required under specified conditions. This is because of the simplifying assumptions used to define the leakage rate. The excess gel provides an extra margin of protection. The recommended quantity also compensates for the fact that the total amount of silica gel in the case does not act instantly, especially if it is located in trays with a depth greater than a few beads.

4.6 CASE LEAKAGE

The most difficult and speculative part of the silica gel equation is the rate of leakage. At present, there is no simple inexpensive standard method for calculating leakage for museum exhibit cases. Unless this value can be quantified, an assumption of one air exchange per day is typically used. As the leakage rate increases, there is a proportional increase in the amount of silica gel required to control case RH. At a point, if the leakage rate is very high (above 2 air exchanges per day), so much silica gel would be required that passive RH buffering is no longer a viable alternative. For cases with a high leakage rate, it is essential to reduce the rate of leakage, or consider an alternative approach such as the use of an active RH control system.

4.7 RATE OF RESPONSE

There is no significant difference between the rate of response of different types of silica gels during adsorption or desorption (Figs. 4, 5). The location and distribution of the silica gel are the critical factors that determine rate of response. In a space where there is no air movement, it takes approximately one day for a single layer of silica gel to fully adjust to a new RH level within a moderate range (10-20% change in RH). If silica gel is placed in a tray approximately 2.5 cm (1 inch) deep with gel, it will take much longer for the full amount of gel to equilibrate to a 10-20% RH change (approximately one month). Therefore, it is important to maximize the surface area of the gel relative to its total volume.

It is important to allow for a maximum zone of air exchange between the silica gel and the space that it is supposed to condition. If the silica gel is located in a space below the visible portion of the case, the air exchange is limited to a small slot or set of holes. Therefore, the silica gel may not effectively offset changes in RH within the display area, either from a rapid changes in temperature, or from a rapid rate of leakage. A future publication will discuss the question of air exchange and silica gel location.

Figure 4. Hours to Reach Equilibrium when RH is Changed from 40% to 55%

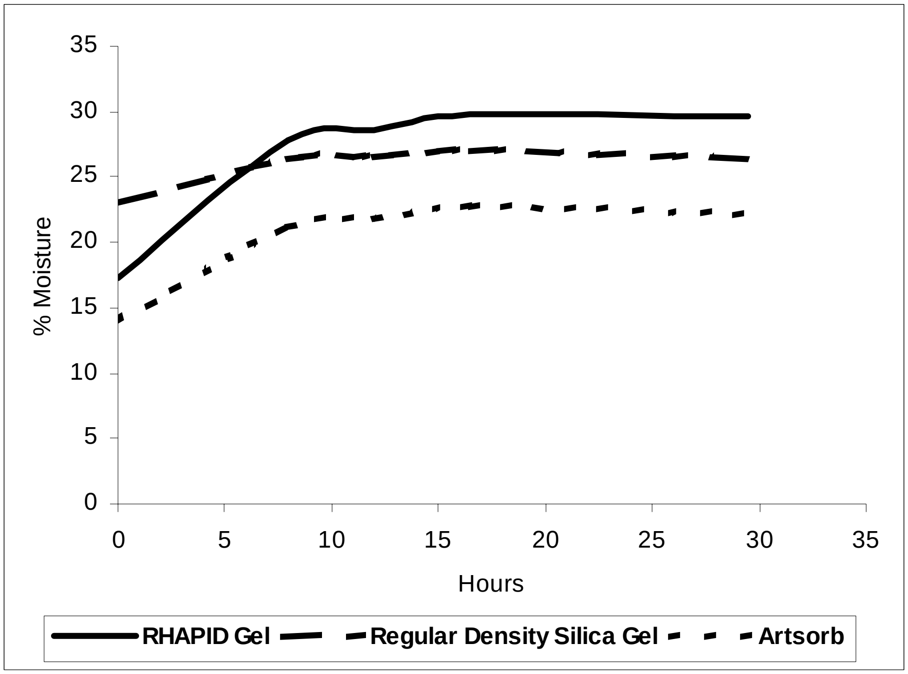
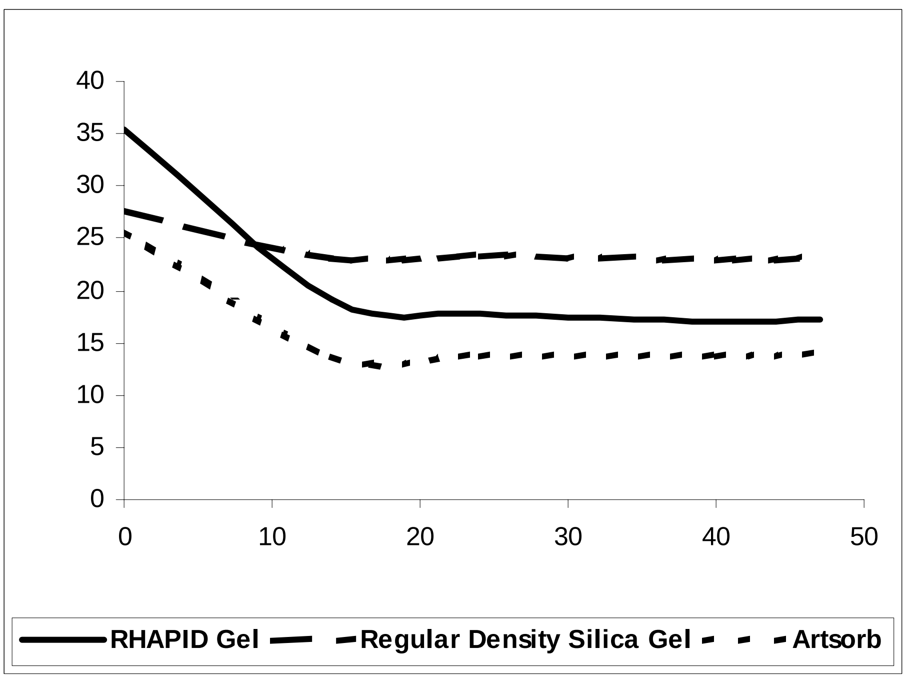


Figure 5. Hours to Reach Equilibrium when RH is Changed from 55% to 40%



5. METHODS FOR RECONDITIONING SILICA GEL

5.1 CONDITIONING SILICA GEL OUTSIDE THE EXHIBIT CASE

5.1.A REMOVING MOISTURE

The most efficient method of removing moisture is with heat. Although silica gel has a very high melting temperature (1600º C), it will lose its chemically bound water and hygroscopic properties if heated above 300º C. In addition, there is a new class of indicator gels, incorporating organic dyes that are heat sensitive and their color indicating dye will be effected above 125-150º C (Goldberg and Weintraub 2001). Therefore, it is not recommended that indicating silica gel be heated above 120º C and regular gel be heated above 200º C. The principle impact of a lower heat of regeneration is that a longer time is required to dry the gel and there is less potential for the degradation of silica gel properties.

In a conventional oven, the time of regeneration varies from minutes to hours, depending on temperature and the thickness of the gel. Although silica gel can be dried in a microwave oven, it is difficult to determine the temperature inside the gel. Also, since metal cannot be used in a microwave oven, only glass, ceramic or microwave safe plastic with a high melting temperature should be used to hold the gel, since the individual beads can become very hot.

5.1.B ADDING MOISTURE

The simplest method for conditioning silica gel is to place it in a room or environmental chamber set to the desired RH level. The best method of confirming that the silica gel is at the correct RH is by measuring the RH of a sample batch of gel. This is done by placing the sample gel in a sealed container or plastic bag with a hygrometer (use a large amount of gel relative to the surrounding air), and allow a day for the RH within the bag to stabilize with the gel mixture. Although an approximate RH value can be calculated based on weight, this method is not recommended because of its margin of error.

- Methods of speeding up conditioning time:
  - Spread the gel as thin as possible.
  - Use a fan to circulate air around the gel.
  - Periodically mix the gel layers to improve uniformity.
- For a single layer of bead, allow at least 4 days if the gel is initially dry, and longer if spread as a thicker layer.
- Silica gel can be conditioned to a higher RH than the desired level, either to speed up the conditioning process or because of the inability to control RH. If so, it is important to allow 2-3 day for the moisture to equilibrate within and between the gel beads, especially if beads with different moisture contents are mixed together.
- The direct addition of water through mist spraying or immersion is not recommended, since the high heat of decrepitation causes silica gel beads to crack and fragment. Although silica gel retains its hygroscopic properties, the overall response time of silica gel in a tray will slow down because of denser packing from the mix of large beads and smaller fragments.

5.2 METHODS FOR CONDITIONING SILICA GEL WITHOUT REMOVING IT FROM THE EXHIBIT CASE

Silica gel in cases can be reconditioned by adding water or appropriately conditioned silica gel to the case. This method is very effective if the silica gel is spread into a very thin layer, or has a very fast response time, such as is achieved with Rhapid Gel. Otherwise, only the upper layer of silica gel will be conditioned and there is a risk that the RH within the case will rise or fall too quickly, without adequately conditioning the full bulk of silica gel.

Increasing or decreasing surface area can control the rate of water evaporation. If there is concern about placing water directly in a case, or if a fast rate of evaporation is desired, a saturated humidifier wicking pad, preferably one treated with an antimicrobial agent, can be used. Generally, water will evaporate more rapidly in this manner because of the extended surface area of the wicking pad compared to a dish of water.

The initial speed at which dry gel removes excess moisture is very fast. It is important to limit the surface area of dry gel to prevent the case RH from dropping too quickly. This is because the speed at which dry gel adsorbs moisture is faster than the rate at which silica gel desorbs moisture.

If silica gel is conditioned in place, the rate at which the RH rises or falls within the case must be carefully monitored in order to determine if the rate is acceptable and when the water or dry gel that was placed in the case to condition the main supply of silica gel must be removed.

It is possible to calculate how much moisture must be added or removed to recondition silica gel in place (Lafontaine 1984, Weintraub 1991). It is important to take into account the impact of other hygroscopic materials inside the case. With experience, adjusting the amount of water or dry gel required may be required to compensate for other hygroscopic materials.

5.2.A CALCULATE THE AMOUNT OF WATER REQUIRED TO INCREASE RH:

Multiply the % increase in RH required, the M_H value of the silica gel, and the weight of silica gel within the case.

For example, if the goal is to raise RH from 45% to 55% in a case containing 2 kilograms of silica gel with an M_H of 9, 180 grams of water is required:

$$10\% \text{ RH} \times 9\ (M_H) \times 2 \text{ kg} = 180 \text{ grams of water}$$

5.2.B CALCULATE THE AMOUNT OF DRY SILICA GEL REQUIRED TO DECREASE RH:

- <u>Step 1</u> - Determine how much moisture must be removed by multiplying the % decrease in RH required by the M_H value of the silica and the total amount of silica gel within the case.

- <u>Step 2</u> - Establish the EMC adsorption value for the dry gel at the desired RH set-point and multiply this value by 10, to convert the value to the amount of moisture that can be removed per kilogram of dry gel.

- Step 3 - Divide the amount of water to be removed (Step 1) by the amount of water that can be removed by a kilogram of dry gel (Step 2). The result is the total amount required to recondition the silica gel in place.

  For example, the goal is to lower RH from 55% to 45% in a case containing 2 kilograms of Rhapid Gel (M_H = 9). If the dry gel is a regular density silica gel (EMC = 25% at 45% RH), the amount of dry gel required is 0.72 kilograms:

  1) 10% RH x 9 (M_H) x 2 kg = 180 grams of water
  2) 25% EMC x 10 = 250 g of moisture per kg of silica gel at 45% RH
  3) 180g/250 g = 0.72 kilograms

6. CONCLUSION

Passive buffering of RH within the exhibition case is an important risk management tool. A well-sealed exhibition case containing hygroscopic materials will have some capacity to stabilize RH within the case. The inclusion of silica gel will enhance this effect. Silica gel can serve as a low-maintenance method of RH control to compensate for poor RH control within the room. Alternatively, it can provide inexpensive, passive back-up when a mechanical RH control system malfunctions. Unfortunately, a lack of clear and correct information regarding how silica gel should be used and maintained has limited its use. The above discussion provides a comprehensible baseline of information on the proper and effective use of silica gel.

It is important to understand how silica gels vary in performance in order to select the most cost-effective gel for a particular application. M_H, the hysteresis corrected buffering capacity of silica gel, is the critical variable for assessing silica gel efficiency. Calculating the correct quantity of silica gel allows for the cost-efficient selection of an appropriate amount of buffering material. If certain variables in the calculation are unknown, such as leakage rate or external RH conditions, general recommendations based on average display conditions have been provided, both for temporary exhibitions and for permanent displays. Finally, simple procedures for the use and maintenance of silica gel have been described. Passive humidity control within an exhibit case, when applied correctly, is a very simple and cost-efficient method of protecting museum collections from humidity induced damage.

ACKNOWLEDGMENTS

The author wishes to thank the following people for their helpful comments and input: Fenella G. France, PhD., Jean Tétreault, and Merv Richard.

ENDNOTES

1. It is possible to plot an EMC/absolute humidity isotherm, since there is a direct correlation between absolute humidity and moisture content. However, a small change in temperature will result in a much larger shift in the EMC/absolute humidity curve compared with the shift that takes place with the EMC/RH curve.

With regard to temperature and humidity control, a moderate change in temperature may not have a major, direct impact on EMC, but it will have a major influence on RH, which in turn, does have a significant impact on EMC (1º C temperature change will result in an approximately 3% change in RH at a fixed absolute humidity within the general range of 20º C and 50% RH).

2. The air exchange rate refers to the amount of time required for a complete exchange of air between an enclosed space and the surrounding air. In reality, leakage is a complicated process, and a complete exchange of air does not really take place. Air exchange is more accurately described by a half-life decay rate, typically used to explain such phenomenon as nuclear decay (discussed by Thomson, in his 1977 article on hygrometric half-time). Although less accurate, the concept of an air exchange rate is used as a standard for expressing the rate of leakage.

3. Some conservators have expressed concern that the presence of silica gel will increase rather than decrease the change in moisture content within an object in a sealed case when there is a temperature induced change in RH (Sozzani 1997). This line of reasoning does not consider the impact of case leakage, which is the primary purpose for using silica gel.

For a situation where room RH is different from case RH, any case leakage will result in a change in an object’s moisture content. The presence of an adequate amount of silica gel will greatly slow down the change in the object’s moisture content. Compared to the risk of a large change in moisture content from leakage, the rather small change in moisture content due to temperature effects in a case containing silica gel presents minimum risk to the object and therefore is not significant.

4. A further advantage regarding the use of silica gel rather than organic materials as a humidity buffer is that silica gel is inert and does not have any inherent volatile components.

5. According to the Art-Sorb Material Safety Data Sheet (Art-Sorb/Waller 2003), Art-Sorb contains lithium chloride. Most silica gels are principally composed of silicon dioxide, with the addition of other modifiers such as aluminum to slightly alter adsorption characteristics for specific applications. Art-Sorb is the only silica gel known to contain a soluble salt component.

6. These M values were derived from data published by Yu et al. (2001). Both M values were based on the desorption isotherm. An M value of 6 was calculated between 46% and 34% RH. An M value of 1.25 was calculated between 62% and 46% RH.

7. The three silica gels tested are:

- Regular density silica gel, referred to as RD gel in this article. Regular density silica gel is the most common type of silica gel and is available from any source that sells silica gel. Because of its capacity for high moisture uptake in the low RH range, it is a very effective desiccant.

- Art-Sorb, from Fuji Silysia Chemical LTD, is a silica gel utilized in museum applications. Information is available through the Art-Sorb website (www.art-sorb.com).

- Rhapid Gel and Arten Gel, from Art Preservation Services, are silica gels specially developed and manufactured for museum applications. Arten Gel is available as an 8-mesh bead (approximately 2 mm diameter). Rhapid Gel is only available in sheet form. Information is available through the Art Preservation Services website (www.apsnyc.com).

  Since Yu et al. (2001) used Arten Gel in their study, all references to Arten Gel performance in this publication are based on values from the Yu publication. Rhapid Gel values were based on research carried out by Art Preservation Services, using Rhapid Gel in bead form (prior to its inclusion in a sheet matrix).

  Arten Gel and Rhapid Gel have similar EMC values at the low to mid RH range. Above 50-55% RH, Rhapid Gel has slightly higher EMC values, which improves its performance in the upper RH range.

8. In order to simplify calculations for determining silica gel quantities, Rhapid Gel's M_H is rounded off from 8.7 to 9.0 in the subsequent sections.

9. At 50% and 60% RH, there is a large discrepancy in the M values for Art-Sorb reported by Yu et al. (2001) compared to the values listed in the Art-Sorb website. The reason is based on the manner in which the values are listed. Instead of equating M values to the lower part of the RH range from which the value was calculated, it would be more correct to show the M value at an intermediate RH, or at the higher end of the RH range from which it was derived. Using the higher RH value as the basis for the M value, the value of M becomes 4 instead of 9 at 50% RH, and 9 instead of 19 at 60% RH. This approach results in M values that are in good agreement with the M values determined by Yu et al., and provides a more correct estimate of buffering capacity at the specified relative humidity.

10. Weintraub and Tétreault (Tétreault 2003) developed the equation for determining silica gel quantity, building on Thomson's hygrometric half-time formula, and a method described by Perkins (1987) for calculating the number of Gore-tex tiles required to control RH in a standard exhibit case.

11. In addition to beads, Art-Sorb is available in sheet form, containing 400 grams of Art-Sorb per m^2 (0.08 pounds per 1 ft^2). Approximately 10-20 m^2 of Art-Sorb sheet is required to condition 1.0 m^3 of case volume.

Based on their previous standard sheet size of 50 x 50 cm (20 inch x 20 inch), Art-Sorb recommended 5 sheets per m^3 (using the formula of 0.5 kg/m^3). This recommendation is not correct if the purpose for using Art-Sorb sheet is to protect against leakage. In fact, 40-80 Art-Sorb sheets are required per m^3 (or 80-160 sheets, based on the modified sheet size of 25 x 50 cm currently sold in the U.S.).

12. Rhapid Gel is only available in sheet form, containing 750 grams of Rhapid Gel per m^2 (0.15 pounds per 1 ft^2). Approximately 2.5-5 m^2 of Rhapid Gel sheet is required to condition 1.0 m^3 of case volume.

In applications where silica gel bead is required for low to mid-RH range applications, Arten Bead is available and can be used as a substitute for Rhapid Gel sheet, utilizing the same 2-4 kg/m^3 recommendation due to their similar M_H values.

APPENDIX 1

1. ESTABLISHING A VALUE FOR M

Yu et al. (2001) evaluated the efficiency of three different types of silica gel, regular density silica gel (RD gel), Art-Sorb, and Arten Gel, used to control RH in exhibition cases, by comparing their M values at different RH levels. [7] According to their experimental results, M was different for each of the gels tested, and varied for a single gel type, depending on the point along the EMC/RH isotherm where it was measured. For example, within the range of 33-60% RH, they found the following variations:

M at various points along the adsorption isotherm

- RD gel = 6 (at 33% RH) down to 3 (at 60% RH)
- Art-Sorb = 3 (at 33% RH) up to 10 (at 60% RH)
- Arten Gel = constant at 7 (between 33-60% RH)

The confusion about varying M values can be avoided by calculating M within the specific RH range of use. Utilizing experimentally determined values from Yu et al., the average M value for the three tested gels within the adsorption range of 33-60% RH is:

M based on the adsorption isotherm between 30-60% RH

- RD gel = 4.5
- Art-Sorb = 4.1
- Arten Gel = 6.3

- Because M varies based on the range of RH within which it is used, it is important to take into account the actual RH range of interest when determining the buffering capacity or M value of a particular silica gel. [8]

2. HYSTERESIS AND M_H

In addition to differences in M depending on the RH range of use, M also changes depending on whether the silica gel is adsorbing or desorbing. For example, when M is calculated for the three gels utilizing values from Yu's desorption range of 62-34% RH, the M values are:

M based on the desorption isotherm between 30-60% RH

- RD gel = 3.1
- Art-Sorb = 5.8
- Arten Gel = 7.4

Differences between the adsorption and desorption M values are due to hysteresis, which occurs when the EMC/RH isotherm for adsorption and desorption are not the same (Fig. 6). In order to account for hysteresis, it is necessary to repeatedly cycle silica gel through the RH range of interest until the moisture content at the top and bottom of the RH range become constant and repeatable (Fig. 7). However, if it is not possible to experimentally determine the M value within a specific RH range, it can be approximated from the silica gel EMC/RH isotherms for adsorption and desorption.

Figure 6. Hysteresis EMC/RH Isotherm for Regular Density Silica

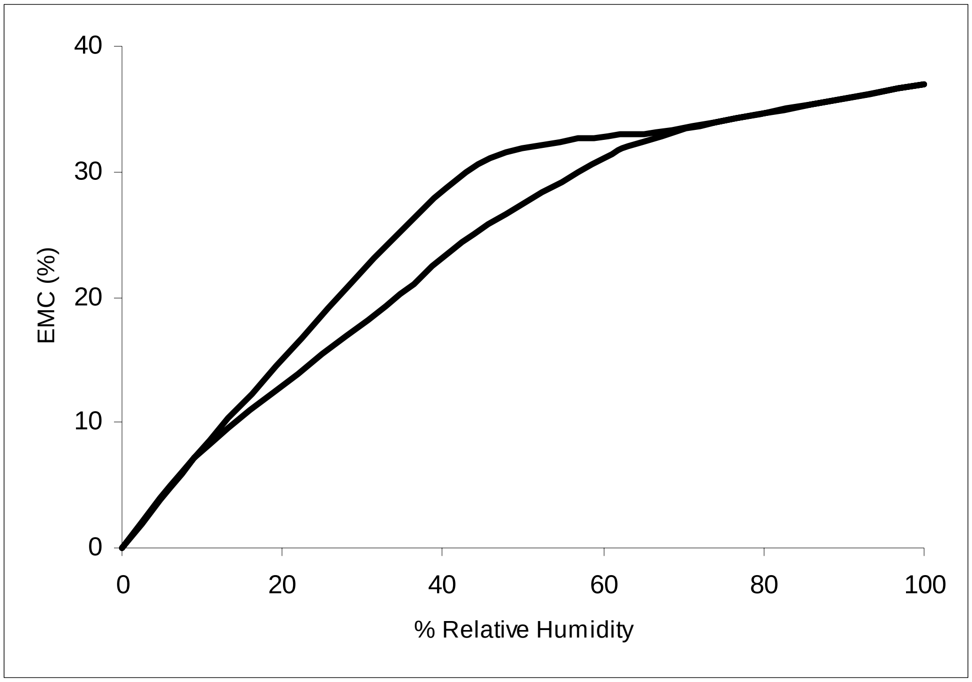
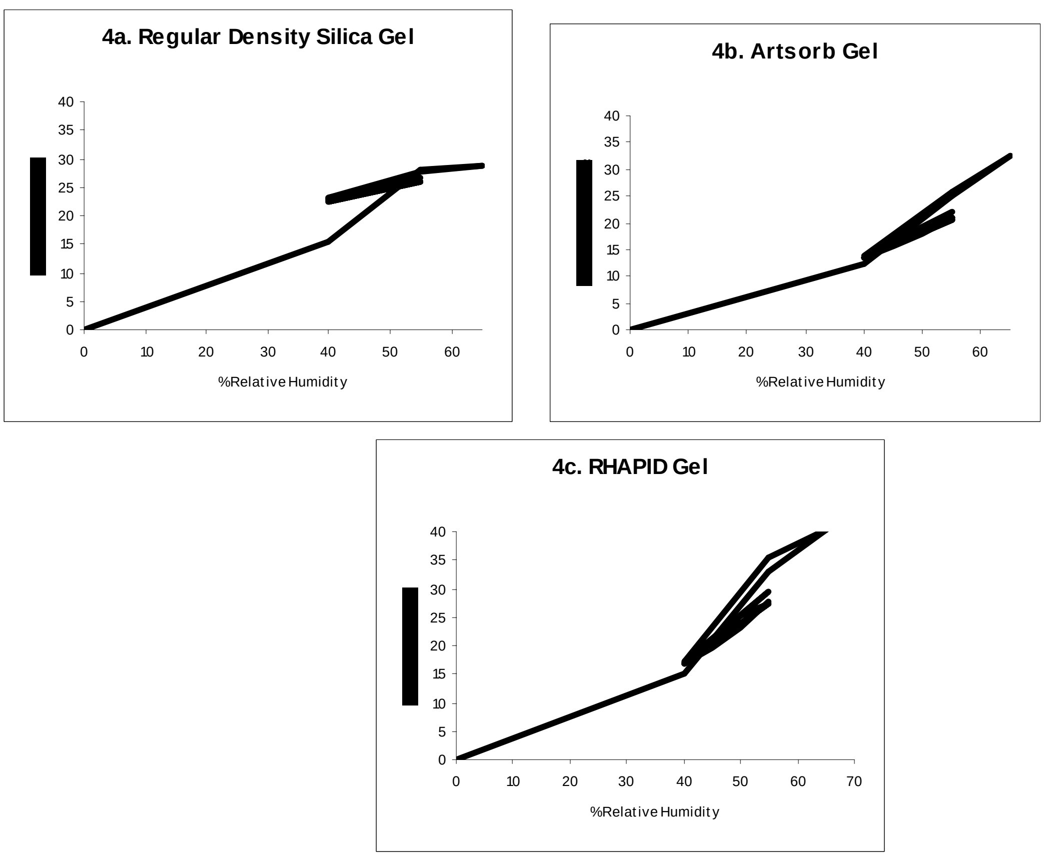
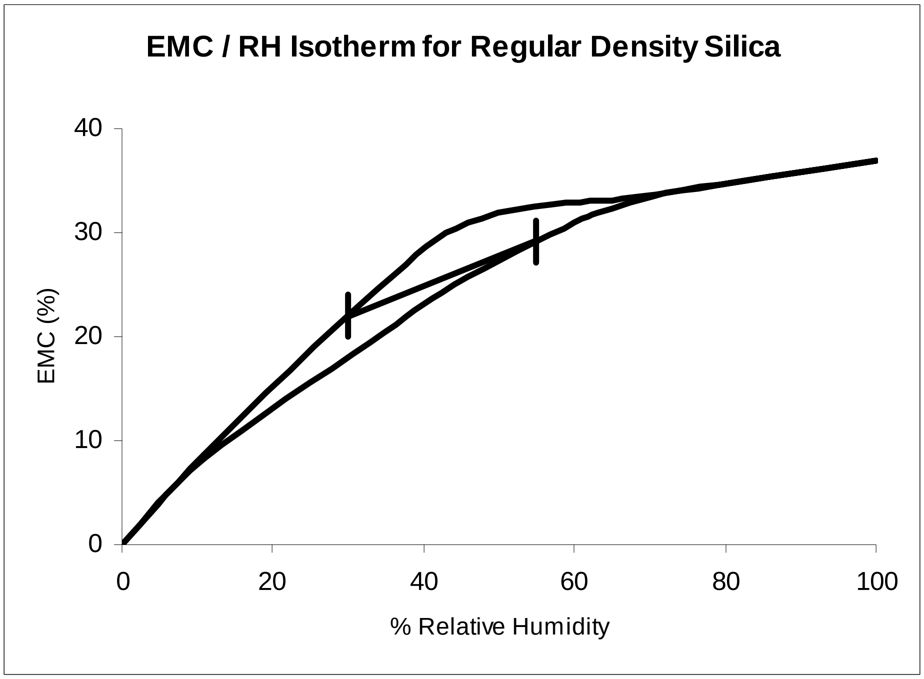


Figure 7. Hysteresis Cycle Between 40-55% RH



For the RH range of use, the EMC for the highest RH value is taken from the adsorption curve and the EMC for the lowest RH value is taken from the desorption curve. The new hysteresis-corrected M value is referred to here as M_H (Fig. 8). This method of approximation works reasonably well over a large RH range (25% or greater) but decreases in accuracy as the RH range becomes smaller.

Figure 8. Hysteresis EMC/RH Isotherm for Regular Density Silica



The M_H values for the three gels evaluated by Yu, utilizing this method of approximation between 30-60% RH yield the following results:

Derived approximation of M_H between 30-60% RH

- RD gel = 2.8
- Art-Sorb = 3.7
- Arten Gel = 5.7

M_H provides a more realistic picture of the true buffering capacity of different types of silica gels within a specified RH range of use (Weintraub 1981). According to the above numbers, RD gel is about 25% less efficient than Art-Sorb, and Arten Gel is about 50% more efficient than Art-Sorb.

3. BUFFERING CAPACITY WITHIN THE ACTUAL RH RANGE OF USE

The most accurate method of determining the actual buffering capacity of a silica gel in a specific range of use is to test it after cycling the silica gel within the RH range of use, as described above. A very typical RH range of 40-55% or narrower is used by museums for organic materials. Therefore, Art Preservation Services performed tests on the three silica gel types in the study by Yu et al. within this narrower range. Tests were performed on Rhapid Gel, comparable in performance to Arten Gel at the low to mid RH range, but with improved capacity in the upper RH range (see Endnote 7). The three gels were cycled at least four times between 40% and 55% RH, until the values stabilized and remained constant in subsequent runs (Figs. 3, 7). Based on these experiments, the following M_H values were measured:

Experimentally determined M_H between 40-55% RH

- RD gel = 2.0
- Art-Sorb = 4.5
- Rhapid Gel = 8.7

Based on their respective M_H values between 40-55% RH, a case would require 1.0 kilograms of Rhapid Gel, 1.9 kilograms of Art-Sorb or 4.3 kilograms of RD gel for comparable buffering performance.

APPENDIX 2

HYGROMETRIC HALF-TIME

Thomson (1977) formulated a method for determining how much silica gel was required to stabilize RH throughout an entire year. He took into account that the leakage rate would permit enough moisture to enter an exhibit case during the summer to offset the loss of moisture that occurred during the winter. As a result, the extreme RH seasons would balance each other out.

Thomson assumed a leakage rate of one air exchange per day (N). Then, he took into account that leakage actually occurs gradually throughout time at an exponential rate (similar to the half-life decay rate of radioactive materials), rather than arithmetically as a single air exchange. Thus, he called the concept "hygrometric half-time". He used the following equation:

$$B = TN/4M \qquad B=18.75\ kg/m^3 = (150x1)/(4x2)$$

Where:

- B is the total amount of silica gel required per cubic meter of case volume.
- T is the number of days above or below the target RH (150 days).
- N is the number of air exchanges per day (1 air exchange for a typical case).
- M is the moisture buffering capacity of silica gel (M=2 for RD gel).
- 4 is based on the mathematically derived constant, 4.760, that is used to calculate the half-life rate of a material.

Based on the above values, Thomson calculated a value of 18.75 kilograms, which he rounded off to 20 kg/m^3 of case volume. In the above equation, if a silica gel with a higher M value were used, the total amount of silica gel required would be reduced. In fact, in Thomson's first edition of The Museum Environment (1978), he used an M value of 3, resulting in a recommendation of 12.5 kg/m^3. However, in his original Studies in Conservation article (1977) and in the 2^{nd} edition of The Museum Environment (1986) he used an M value of 2.

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AUTHOR'S ADDRESS

Steven Weintraub, Art Preservation Services, 315 East 89 Street, New York City, NY, 10128 (sw@apsnyc.org).

Article published in:
Object Specialty Group Postprints (vol. 9), 2002.
Washington, D.C.: American Institute for Conservation.