4-0 HUMIDITY

> ***"…most people assume that temperature is more important than relative humidity in its effect on objects. This is completely untrue. In fact the most important thing about temperature and its effect on collections is its effect on relative humidity levels."***
>
> ***– Barbara Appelbaum*** [1]

There is a tremendous amount of information available on relative humidity (RH) and its effects on museum collections. Excessive RH can cause direct damage to art and artifacts, particularly organic materials that begin to break down when moisture contents are too high. Corrosion from air pollutants and the acids within materials increases with RH.[2] So does the growth of fungi, bacteria and yeast. The Getty Institute describes the RH levels suited for the growth of the following organisms.[3]

Relative Humidity %	Organism
90	**Normal bacteria**
88	**Common yeasts**
80	**Common fungi**
75	**Halophic bacteria**
65	**Xerophilic fungi**
60 (minimum)	**Saccharomyces rouxii yeast**

Figure 4-1. RH levels suitable for growth of various bacteria.

Even in extreme anoxic environments (less than 0.1% oxygen) samples exposed to a RH of 70% showed high bacterial growth. That growth did not stop until the RH was lowered to the 33-40% range.[4]

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[1] Barbara Appelbaum, p. 25.

[2] Barbara Appelbaum, p. 39.

[3] Shin Maekawa, ed. , Oxygen-Free Museum Cases, Research in Conservation (Los Angeles: The Getty Conservation Institute, 1998), p. 21-23.

[4] Shin Maekawa, p. 23.

The “ideal” RH varies with the composition of the materials in a collection. There is no single perfect RH for all materials. A museum must examine the materials in its individual collections to determine the range of RH that is safe for these materials. It must then factor in the difficulty and cost of achieving these relative humidities. This is where the ability to establish individual case environments can be a tremendous help.

Relative humidities of 50% to 55% are commonly accepted as being ideal for collections. This RH is almost certainly too high for most collections in most of the United States. These numbers come particularly from Garry Thomson who did his research in England; where high humidity, rising damp, mildew and mold are major problems. In effect, they represent the minimum reduction in RH necessary for preservation in damp climates. In the United States, this research should be seen as establishing 50% to 55% RH as the maximum allowable RH rather than an ideal for which to strive. As Barbara Appelbaum correctly points out:

> “The museum literature has put us all off on the subject, because most of the work on museum environmental control has been carried out in a climate very different from that of most of the United States. Garry Thomson, who is largely responsible for making the museum community worldwide aware of the importance of environmental control in preservation of collections, carried out much of his research in a country where the outdoor RH ranges from 70% to 90% all year round.”[5]

This 50% to 55% as a maximum is still too high for some organic materials. Parchment materials may be subject to biodeterioration at these levels. Parchments and leathers are also subject to gelatination at relative humidity levels above 40%.[6] Metals, particularly iron, require low RH (lower than 50%) to prevent corrosion.

But low RH causes drying and brittleness in organic materials. Shin Maekawa at the Getty Institute found that 25% RH was the lowest relative humidity that could be tolerated by Egyptian mummies without causing large stresses in the material. He suggested an ideal RH for skin objects of 30%.[7]

It would seem from the research that a safe RH for general collections is around 30-35%. Many materials are safe through a much wider range of RH; provided, of course, that this RH is constantly maintained. Because of the stresses created when artifacts absorb and release water, changes in humidity surrounding collections should be made very, very slowly.

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[5] Barbara Appelbaum, pp. 32-33.

[6] Shin Maekawa, p. 10.

[7] Shin Maekawa, p. 10.

4-1 Cycles in Humidity

As Barbara Appelbaum points out, the greatest dangers to museum collections may be from the physical stresses created by changes in RH. As the equilibrium moisture content of an object changes, it expands or contracts.[8]

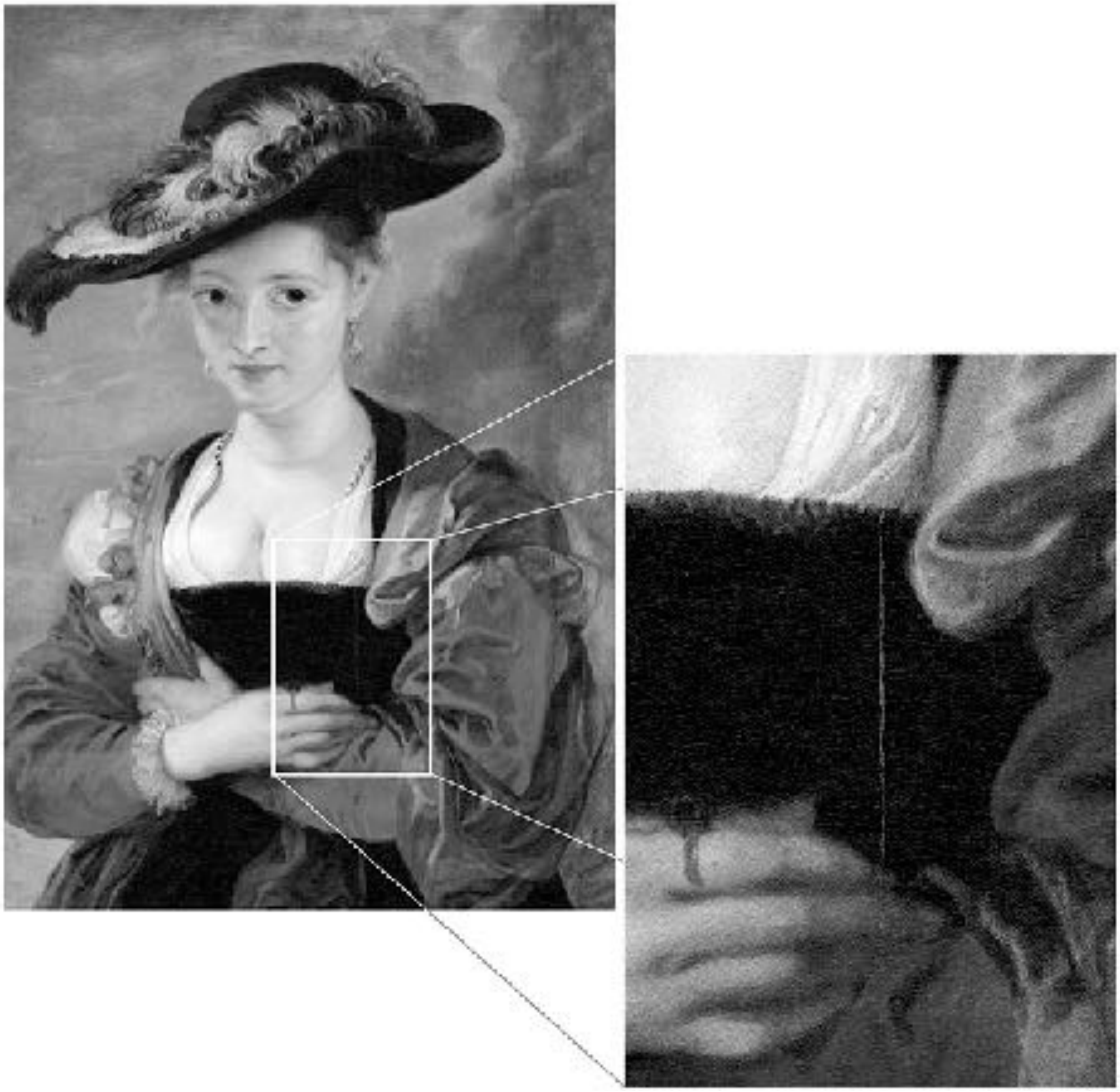

Figure 4-2. ***Portrait of Susanna Lunden neé Fourment*** **(c. 1620-25) by Peter Paul Rubens, Oil on oak panel.**

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[8] Equlibrium moisture content is the point where the water content in an object stabilizes in a particular RH environment. Each time the RH changes, objects slowly come to a new point of equilibrium. The time required is determined by the temperature, the air movement around an object and density of the object.

Because of this, RH stability may be of more importance than maintaining any particular RH level.[9]

As with the thermal expansion cycles described in the last section, these movements can create structural damage within the object or separations between layers of materials with different expansion rates. While rigid inorganic materials seem most susceptible to damage from surface heating, cycles in RH are most likely to damage more porous organic materials.

Figure 4-2 shows an example, *Portrait of Susanna* by Peter Paul Rubens[10], of the sort of damage that can be done by cycles in temperature and RH. The Rubens painting was painted on a panel made of several planks of oak. The detail shows the crack developing between two sections of wood. The coefficient of expansion of the glue joint is different than that of the wood creating stress and eventually damage.

As we consider the dangers of cycles in humidity, it is important for us to understand the relationship between temperature and relative humidity. Figure 4-3 shows a hygrometric chart. It is used with a whirling hygrometer (sling

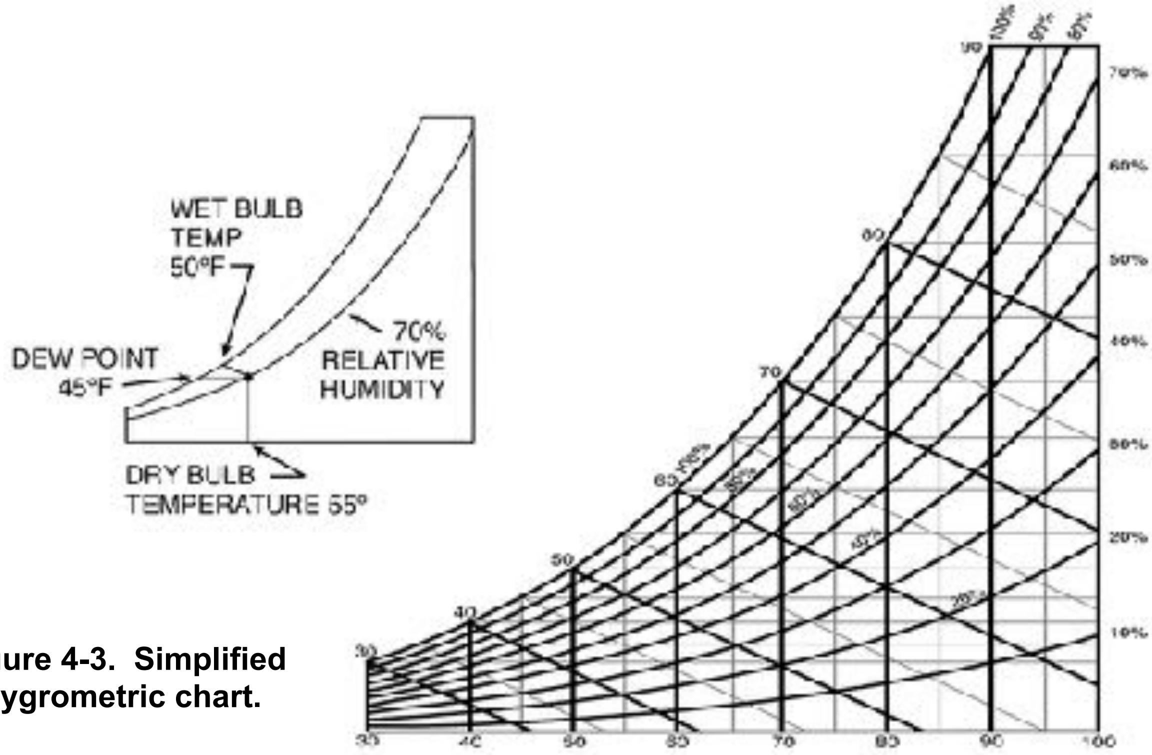

Figure 4-3. Simplified hygrometric chart.

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[9] Barbara Appelbaum goes so far as to write, "If you are asked what level of humidity you require for your collection, the answer should be 'Whatever level can be maintained without fail, 24 hours a day, twelve months per year." She states that changes in RH should be limited to 2% a day and 5% total over the period of a month. Barbara Appelbaum. p. 34-35

[10] Original photograph in Techniques of the Great Masters of Art, (Hong Kong: QED Publishing, 1985), p. 57. Modification and enlargement by author.

psychrometer) to measure relative humidity by comparing the temperatures of two thermometers, one of which has its bulb incased in a wet sock. The relative humidity controls the evaporation from this sock controlling the temperature drop of the wet thermometer. Measuring the difference between the two temperatures show us the relative humidity.

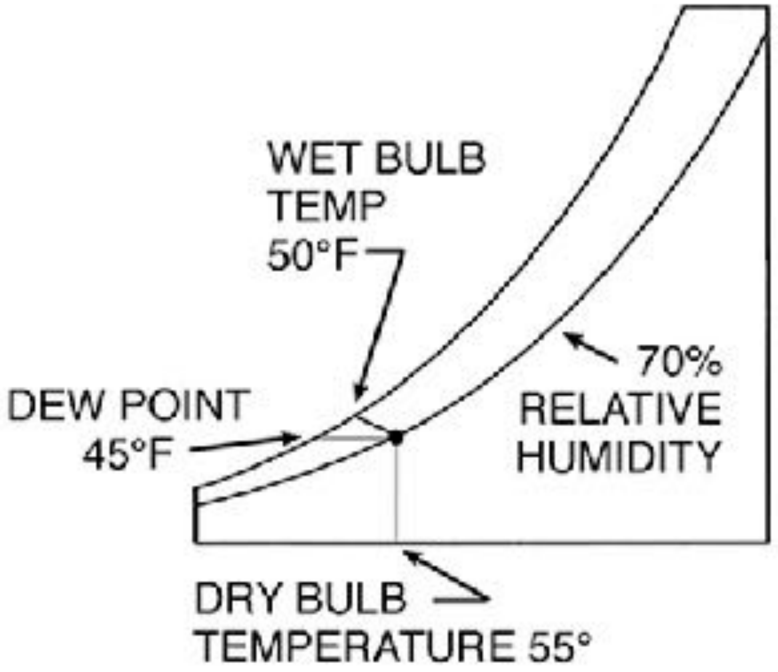

Figure 4-4. Simplified hygrometric chart shows relationships of temperature, relative humidity and dew point.[11]

The hygrometric chart also shows us the relationship between temperature and relative humidity. Figure 4-5 shows an enlarged area of this chart. You can see that raising the temperature only 10°F from 70°F to 80°F lowers the relative humidity from 50% to 35%.

While a 10°F cycle in case temperature may not seem terribly significant, a 15% change in relative humidity can be devastating. This is especially true when the temperature change causing the cycle is driven by conventional lighting and repeated daily. The RH shifts over and over again.

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[11] Chart graphics and artwork by author.

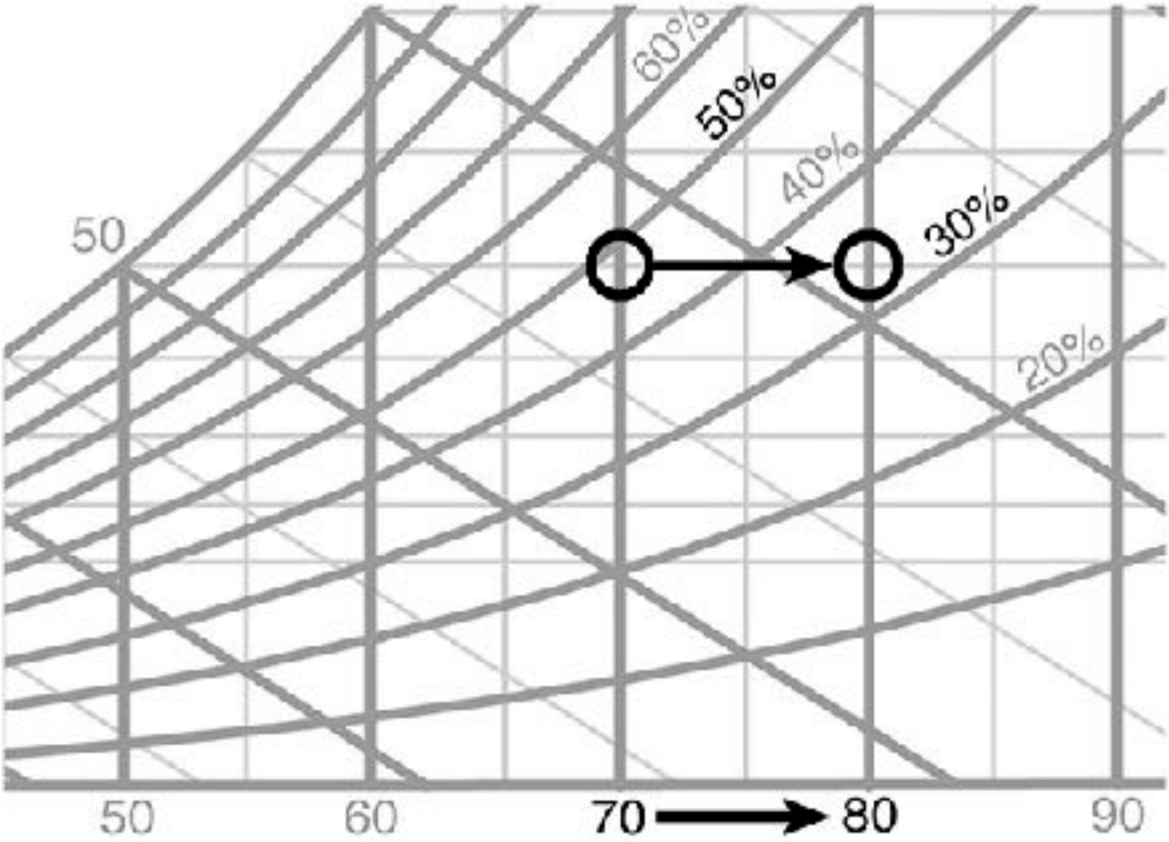

Figure 4-5. Small temperature changes create very serious changes in relative humidity.[12]

Again, note how the hygrometric chart shows a 10°F cycle in case temperature creates a 15% change in relative humidity. This change is a cycle driven by conventional lighting. It happens every day..

A 10°F temperature change was exactly what was measured in library cases equipped with internal fluorescent lamps described earlier. Objects in those cases were not only exposed to the stresses of daily temperature cycles. The temperature cycles would have resulted in large swings in RH within the cases.

The use of incandescent lighting in these cases would have greatly increased these IR induced cycles. The temperature and humidity work together. Total case breathing would be small, because although the temperature variations were large, the complete cycle was repeated only once each day.

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[12] Graphics by author.

4-2 Additional Factors Involving RH

There are some additional factors to consider when examining the effects of temperature induced RH variations. The first is the idea that thermal expansion in an artifact may be offset by the contraction resulting from a lowered RH. The two processes do operate in opposite directions. It is impossible however to say that they operate in equal opposite directions or that the time required to react to heating is the same as that required to react to a lowered RH.

It would seem most likely that an artifact would expand initially from the radiant heating and then contract slowly from drying throughout the time it was lit. When the lighting is turned off, the object would contract as it cooled and then expand slowly as the RH increased through the dark period. The effect of the opposite processes could well double the number of expansion and contraction cycles rather than limit them. This is supposition, but it is sound supposition. Each artifact and kind of material would have to be examined individually for response to these conditions.

A second factor involves the natural RH buffering of artifacts and case materials themselves. Materials at equilibrium moisture content contain a much larger amount of water than the atmosphere around them. At 60% RH, wood at equilibrium averages 10% water by weight.

At 40% RH, this drops to 8%. (Woods tested were poplar, ash, oak, chestnut, and fig from one-year-old to thirty-seven-hundred-years-old.)[13] This is a 32% RH drop from slightly under hydrated to very dry.

Adding a single gram of water to a cubic meter of air at 72°F will raise its RH 5%. In a case with a volume of one cubic meter, a kilogram of wood conditioned to an RH of 60% would loose only 3 of its 100 grams of water to offset the RH shift caused by the 10°F temperature shift described above.[14] Wood and other organic artifacts and wooden case materials can by themselves buffer temperature induced cycles in RH.

There is, however, no evidence that this buffering would occur in time with the initial cycles and as described above, the repeated loss and gain of 3% of it's water content might well cause structural damage to the wood or other artifact acting as a buffer.

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[13] Charles Selwitz and Shin Maekawa, Inert Gases in the Control of Museum Insect Pests, Research in Conservation (Los Angeles: The Getty Conservation Institute, 1998), p. 31, citing Richard D. Buck, "A note on the effect of age on the hygroscopic behavior of wood," Studies in Conservation, 1:39-40.

[14] This line of reasoning was proposed by Charles Selwitz and Shin Maekawa citing Richard D. Buck in the reference above.

4-3 Building or Gallery Defenses Against Improper RH

When we think about temperature changes creating changes in relative humidity, we cannot overlook the effects of heating and air conditioning systems. Most of these systems operate by radically altering the temperature of a small volume of air and then mixing it with the air in our environment to produce smaller changes in that environment. We have already pointed out that a 10°F rise in temperature can result in a 15% drop in RH. The simple fact is that without humidifying equipment, heating dries the air.

Air-conditioning can also dry the air. The air that passes over the cooling elements of an air-conditioning system drops well below the dew point. The dew point is the temperature where water vapor condenses out of the air. Most air-conditioning systems handle this condensation with a drain.

Anyone who has ever parked a car after driving it with the air conditioner on and returned to find a puddle of water under the car has seen this in action. As a matter of fact, all mechanical dehumidification equipment operates this way. Because the temperature change within the air conditioning system is so large, you can experience major changes in RH with very small changes in room temperature. Barbara Appelbaum found that fluctuations of just one degree in room temperature with a window air conditioner resulted in swings of up to 15% in relative humidity within that room.[15] Cooling the air can be just as dangerous to your collections as heating.

There are several major problems to be considered in museums with building wide humidity control systems. The first is the very serious damage that can be done by any sort of a malfunction. Consider the condensation problems of a building conditioned to 40% RH at 70°F cooling to 30°F during an ice storm induced power failure. Picture what might be possible and have an emergency plan.

A second serious problem involves the cycles inherent in mechanical systems. Barbara Appelbaum describes them well:

> A simple feedback system governs machinery. When the temperature hits one level, the machinery turns on, and when it hits another set level, the machinery turns off again. Temperature variations produce even wider RH variations, and each cycle can be under an hour. Unless every object in such an environment is containerized to buffer the short term changes, this environment would be very hard on objects.[16]

Building-wide controls can be very difficult to stabilize and adjust.

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[15] Barbara Appelbaum, p. 37.

[16] Barbara Appelbaum, P. 36.

> In some of the best cases, proper controls require from one to two years of constant tinkering by a local firm after the building is complete before the system functions properly.[17]
>
> People who do this repeatedly say that at least a year, one full change of seasons, is needed with all mechanical systems in full use before it is safe to move objects in."[18]

Appelbaum also relates that building wide systems are also fairly labor intensive, creating ongoing costs for a museum.

> It is generally considered that at least one full-time staff member will be needed for routine maintenance, in addition to a contract with an outside firm for repairs.[19]

While technology may have improved, each of these things should be addressed by a museum considering building wide controls. You must answer these questions. What are the temperature and resultant RH cycles going to be? What time is necessary to stabilize the system? What resources are going to be required to maintain the system? And finally, what are the consequences of equipment failure?

4-4 Case Defenses

It seems prudent then to focus attention on case level controls even when building-wide controls are in place. Cases can produce a very efficient buffer of gallery temperature and RH cycles. Cases equipped with RH buffers can also provide protection for materials when there is mechanical failure in building-wide systems. As an added benefit, cases provide local environments where individual artifacts can be maintained outside of the "average" conditions necessary for the collection as a whole.

As mentioned above, case materials and artifacts themselves can often act as RH buffers. Materials hold a great deal more total volume of water than the air surrounding them. This is of little value if the air around an object is infinite and repeatedly changing. Casework greatly limits the volume of air surrounding an artifact. This in itself will reduce normal RH cycles. Then the use of RH buffering materials described below can just about eliminate RH cycles.

4-5 Silica Gel RH Controls

Silica gel is a porous, granular, chemically-inert, form of amorphous silica. You might simply picture silica gel as small glass beads with many tiny cracks

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[17] Barbara Appelbaum, p. 52.

[18] Barbara Appelbaum, p. 55.

[19] Barbara Appelbaum, p. 53.

that trap water. Silica gel is usually sold in bulk weights or pre-packaged into porous packets or containers. Normal silica gel can absorb roughly 40% of its weight in water. Special silica gels that are less dense and hold several times more water than regular silica gel are available too. Each user will have to determine if the higher costs of these special silica gels are justified.

Where there is relatively high humidity in the environment and poor case sealing, or extensive case breathing; silica gel can be used as a dryer. Silica gel is commonly used as a storage agent or packing material for things that require or can tolerate very dry conditions. Dry silica gel is placed into a case or package to absorb moisture and reduce RH. In cases with poor seals or were there is excessive case breathing, the silica gel is replaced when it becomes saturated. It requires very careful monitoring and repeated maintenance to preserve a stable RH in such uses.

4-6 Silica Gel RH Buffers

Because a material like silica gel can hold a large amount of water compared to the amount held in a particular volume of air, silica gel is an extremely effective RH buffer in enclosed spaces like exhibit cases. The use of silica gel to control or buffer humidity requires the free exchange of moisture between the air in the case and the silica gel. Rapid buffering is more dependent on the surface area of the gel than volume. In determining the amount of silica gel required in a case the really critical factors are the surface area of the gel exposed and the integrity of the case sealing.

Actual experiments at NoUVIR have demonstrated a nearly one-to-one relationship between the saturation of normal silica gel and the saturation (RH) of the air exposed to it. In the test a number of 100 gram samples of dry silica gel were hydrated to specific percentages by weight. They were then sealed into containers with roughly an even volume of air to that of the silica gel. Over the next few days the air in the containers was tested for RH using several different RH testing devices.

Each sample contained 100 grams of silica gel. The test assumed that the silica gel would be able to absorb 40% of it's weight in water (manufacturers specifications). The sample, calculated to be fully saturated, absorbed the entire 40 grams of water with out leaving any visible unabsorbed water in the container. This silica gel sample did remain visibly damp and clumped together. The results are listed on the following page in Figure 4-5.

WATER HOLDING CHARACTERISTICS OF SILICA GEL AND AIR

Sample #	Water added (by weight)	% Saturation (calculated)	RH of adjacent air (measured ± 5%)
1	0 grams	0%	2-11%*
2	8 grams	20%	22%
3	16 grams	40%	38%
4	24 grams	60%	62%
5	32 grams	80%	88%
6	40 grams	100%	92-98%*

(* Some inaccuracy is to be expected at the extreme ranges of any meter.)

Figure 4-6. Saturation of standard silica gel and adjacent air in a sealed container.

These results demonstrate that silica gel has no greater or lesser affinity for water than does air. Silica gel with a particular % saturation of water will surrender water to the surrounding air should the RH drop below, and will absorb water should the RH rise above, that percentage of saturation. As silica gel is roughly 16,000 times as dense as air, a very small amount of silica gel will buffer a large amount of air. (Fifty grams of normal silica gel, roughly 62.5 cc, will hold as much water as 1 cubic meter of air at 72°F.)

In hermetically-sealed cases (or normally-sealed cases where pressure differential is eliminated), without fans or mechanical means of circulation, all of the moisture exchange between the case air and the silica gel will be the result of Brownian motion. Moisture will diffuse through the case air and the silica gel buffer. In these kinds of passive systems, the amount of surface area exposed in the silica gel and the amount of open area between the case interior and the gel location becomes the critical factors.

While we are looking at temperature, RH cycles and diffusion through case air, we might note that placing temperature and humidity sensors into case corners or behind objects (where they are in dead air spaces and shaded from case lighting) will almost certainly limit their effectiveness. In still air there will be a gradient of temperature and humidity from an irradiated surface to the corners of a case. Under lighting containing significant IR, the air in a case will have less change, and will experience that change more slowly, than the objects in the case. Air in the corners of the case will in the same way change less, and change more slowly, than air near the objects. Sensors must be adjacent to objects and illuminated in the same way as the objects for accurate temperature and humidity measurements.

4-7 Silica Gel Effectiveness

As mentioned in the section above, at common room temperatures a gram of water represents a 5% change in the RH of a cubic meter of air. Since standard silica gel is able to absorb and hold 40% of its weight in water, it should be fairly easy to calculate the amount of silica gel required for a particular case volume. The formula is:

$$S = V \cdot 0.5\,\Delta RH$$

Where: S is the weight of silica gel in grams.

V is the case volume in cubic meters.

ΔRH is the maximum percentage change in RH you expect to buffer against.

The constant .5 adjusts for the water content of both the silica gel and room temperature air.

Under ideal conditions, buffering a one cubic meter case expected to undergo a 10°F temperature variation (15% change in RH) would require 7.5 grams of silica gel (enough to absorb or release 3 grams of water). Because such buffering is almost never under perfect conditions, you should always add a cushion.

These numbers are very different from those usually recommended. A leading supplier of an enhanced silica gel for museum use recommends 1-2 pounds of silica gel per cubic meter. (They advertise "over 5 times the moisture buffering capacity of regular density silica gel.) As a pound is a little over 453 grams, 2 pounds of regular silica gel would be able to absorb and release 362 grams of water. That is about 18 times the weight of water required to completely saturate a cubic meter of air at 80°F. Of course these recommendations are from a firm interested in selling silica gel. They might be expected to be high.

Barbara Appelbaum, who has done a tremendous amount of study of RH, recommends silica equal to 2% of a case's volume. Her reasoning is as follows:

> …since too much silica gel cannot cause problems, and 2% seems to have worked in the past, we will continue to recommend it.[20]

In a one cubic meter case (35.3 cubic feet) this would end up somewhere around 30 pounds of dry silica gel and hold roughly 270 times the amount of

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[20] Barbara Appelbaum, p. 44.

water required to completely saturate the air in the case. Toby Raphael provides a “rule of thumb” of 1/4 to 1/2 of a pound per cubic foot.[21] This would require 8 to 17 pounds of silica gel for a one cubic meter case.

The tremendous range of recommendations is due to the huge variation in the effectiveness of case designs incorporating silica gel as a buffer. Real practical numbers for an effectively designed case will be somewhere closer to the ideal number of 7.5 grams per cubic meter than to Appelbaum’s 30 pounds.

Again, the key is the efficiency of the design. A sealed case with a desiccant chamber in the base and just a couple of holes into the exhibit space is terribly inefficient. Air tends to stratify and will not move easily between compartments in a sealed case. A second factor is that air will only penetrate a short way into a layer of silica gel in a tray. Only the silica gel on the surface of a tray is really effective. The most efficient way to use silica gel is to move case air through the silica. We will examine a very effective way of doing exactly this in the section describing the NoUVIR AIR-SAFE™ system.

4-8 Silica Gel Dangers

Color indicator gels are available that change color when saturated. The most common of these indicator silica gels is treated with colbalt chloride. Cobalt chloride gel is dark blue when dry and changes color to pink as it is saturated. Tests with measured saturations similar to those already described are shown in Figure 4-6.

COLOR RESPONSES OF COBALT CHLORIDE INDICATOR SILICA GEL

% Saturation	RH of adjacent air	Color
0%	2-11%*	Dark Blue
20%	22%	Deep Purple
40%	38%	Pale Violet
60%	62%	Pink/Violet traces
80%	88%	Bright pink
100%	92-98%*	Bright Pink (Damp)

(* Some inaccuracy is to be expected at the extreme ranges of any meter.)

Figure 4-7. Colors of standard cobalt chloride indicator silica gel at various saturations.

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[21] Toby Raphael, p. 2-4.

Color indicator silica gel is not regulated or considered a hazardous material in the United States. British Chemical Regulations do classify colbalt chloride silica gels as hazardous materials and as potential carcinogens (by inhalation).[22] There is currently no indication that the U.S. will follow British regulations.

Colbalt chloride comprises less than 1% of color indicator silica gel by weight and is fixed into the structure of the gel. Silica dust by itself is an inhalation hazard and a minor irritant (like glass wool). Standard safety practice requires the use of gloves, safety glasses and a dust mask. People following such practices should have no fears about using cobalt chloride indicator silica gel. Of course, pre-packaged silica gels will have no user risks of either dust or colbalt chloride inhalation.

4-9 Reusing Silica Gel

Toby Raphael recommends hydrating silica gel with distilled water.[23] This is to avoid introducing impurities into the case environment. Initial hydration is not, however, the only opportunity to pollute our buffer materials. While we will examine humidity cycles and their ability to concentrate pollutants in materials in the next section as we deal with pollution, it is necessary to introduce the subject here.

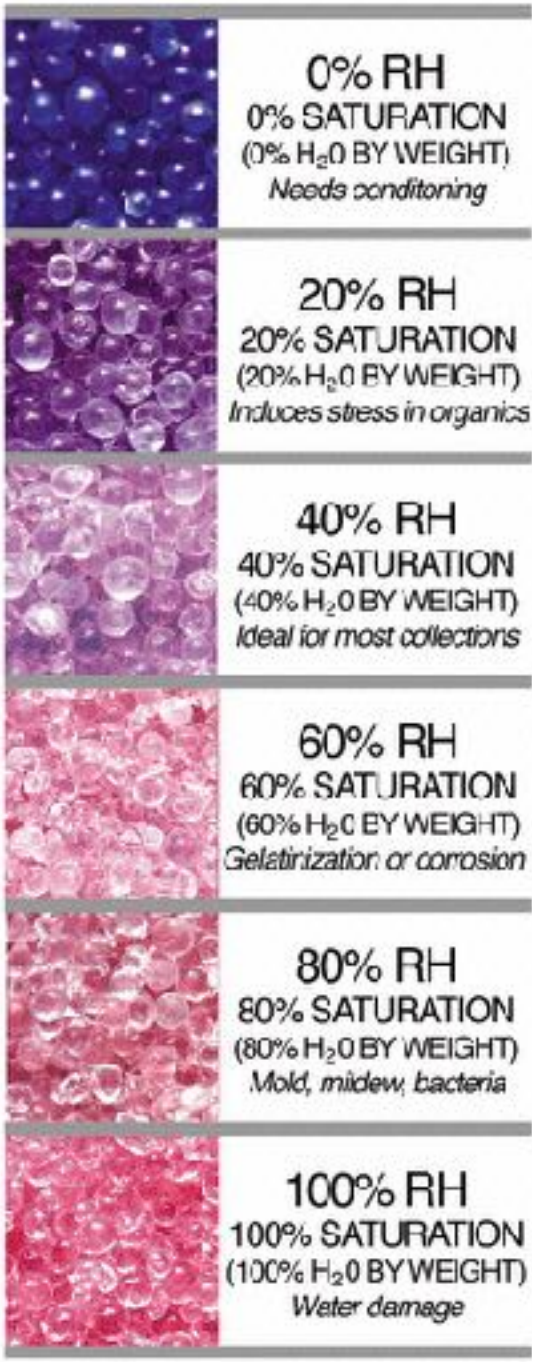

Figure 4-8. Colors of silica gel.

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[22] Lisa Goldberg and Steven Weintraub, "Regulations Change for Cobalt Indicating Silica Gel," AIC News, January 2001, p.14.

[23] Toby Raphael, p. 2-6.

Many materials are present in the air beside water vapor. Many of these materials become attached mechanically or chemically to water molecules in the air. Outdoors this causes the acid in acid rain.

The same processes occur indoors. Pollutants, dusts, acid gasses, cleaning solvents, saliva and other materials are in the air. These materials are absorbed into silica gel along with water vapor. Repeated cycles of absorption and drying involved in RH buffering tend to concentrate these pollutants within the gel.

Moderate heating to dry silica gel for reuse will cook out water, but is insufficient to neutralize the chemicals, toxins and pollutants absorbed with the water. Drying silica gel for reuse is the equivalent of simply running your sweat socks through the dryer every evening. It just doesn't deal with the whole problem. In the same way, drying silica gel for reuse simply concentrates pollutants within the gel.

Although it is has been a common practice, you should not reuse silica gel. When purchased in bulk silica gel is relatively inexpensive. Most museums are using far more silica gel than required for their needs. Efficient case design and efficient use of silica gel will more than offset the costs of regular replacement. As with some of the other things we have looked at in the museum, each problem is related to and impacts other dangers. There is more involved in the use of silica gel than simple humidity control.

4-10 Humidity Summary

Relative Humidity must be controlled within a museum environment. While each individual artifact has an ideal RH, published materials indicate that a RH of 30-35% is probably the best range for a museum environment. Cycles in RH are dangerous and induce structural changes and stress. Maintaining a stable RH may be more important than the particular RH selected (within reasonable limits). Very gradual shifts in RH (over seasons) are not as dangerous as rapid changes. The most radical shifts in RH are temperature induced and driven by the IR in conventional lighting. Cases, materials, even artifacts themselves buffer RH changes. Eliminating temperature cycles and planned RH control or buffering are vital. Silica gel is an extremely effective buffering material. But, silica gel must be handled correctly and used efficiently. It should not be recycled.