# HOW TO KEEP FOR A WHILE WHAT YOU WANT TO KEEP FOR EVER

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## INTRODUCTION

*This article is the lecture notes for the museology course at Denmark's Library School, April 2005. Much of the content is more thoroughly treated in other articles on the author's website: www.padfield.org/tim/cfys/*

Preventive conservation seems to be a clearly understandable phrase, but it has two interpretations. One method of preventive conservation, very widely used in the past, was to varnish everything that came into the care of a museum, or dip it in molten wax. Nowadays we are not so proud of this legacy of greasy dark brown surfaces, concealing paintings, bronze, iron even wood, with a uniform patina. But we use a modern equivalent: a transparent acrylic resin, Acryloid B72, whose use on a Faberge diamond encrusted cigar case caused me to pronounce it a fake. Fortunately a colleague insisted on shining a uv lamp on the soft, easily scratched and optically dull stones. The characteristic blue green phosphorescence of diamond saved the priceless relic from the charity shop window.

Far more invasive techniques come under the heading of 'preventive' conservation. For example, heating archaeological iron to 800 degrees to volatilise the chloride which may or may not be present and may or may not lead to corrosion. The heating destroys the crystal structure which would reveal the way the object had been manufactured.

The alternative definition of preventive conservation is controlling the environment so it is not necessary to smear varnish over things.

I will look at the environmental agents of decay and describe how their damaging effect can be minimised, first in principle, then in practice. I will start with radiation.

## RADIATION

Figure 1 shows a gallery in the North Jutland Museum of Art near Aalborg. The nicest explanation is that Alvar Alto, the architect, used a solar transit model valid for the latitude of Helsinki, or maybe dusted off a project designed for the far north. Let me introduce some numbers. Direct sunlight indoors is about 80 thousand lux, don't worry about the unit just yet, I will return to that subject, remember the number and compare it with the generally agreed recommendations for paintings of sunbathing nudes: 200 lux.

Figure 1: A gallery in the North Jutland Art Museum, near Aalborg, Denmark.

At risk of pre-empting the wise words of the following speaker, I emphasise that this environment is not putting the painting at risk, it is ensuring accelerated damage. Light damages, proportionately to its intensity. There is no safe amount of light. The rate of damage depends on the materials. Some Fox-Talbot salt prints are kept so dark that there is even deep discussion of the ethics of exposing them to the brief flash of light needed to photograph them, so the copy can be displayed. A porcelain plate is probably immune to light damage.

The damage caused by light was quantified already by 1880. Particularly noteworthy isan investigation by Chevreuil undertaken on behalf of the Gobelins tapestry factory. A later report, from the

Figure 2: A gallery in Louisiana Modern Art Museum, Denmark.

Figure 3: The central court of the National Museum of Denmark, Copenhagen

Figure 4: How delicate colours were protected in olden times.

Figure 5: How the National Museum protects its art in modern times.

1920s by Russell and Abney documents the fading rate of watercolour pigments. Numerous reports from the early twentieth century document the deterioration of cellulosic textiles in light, then used for aircraft wings. Nevertheless, the Louisiana Museum of Modern Art (figure 2) has only just removed the paintings from this gallery

It still requires negotiating skill for the conservator to prevent the damage caused by the exhibition environment.

This exhibition (figure 3) in the entrance hall exposes a diverse collection of objects to direct sunlight, without even protection from ultraviolet radiation. This exhibition paired a curator and an immigrant, who patrolled the permanent exhibitions extracting an object for particular attention in this exhibition. This ceremony was repeated week after week, to build up a set of fifty exhibits. Note the carved ivory tusk jutting into the sunlight on the right side.

Indoor sunshine is nothing new, so one can ask, how did people protect their property in the days when it was generally known that sunlight is a potent destructive agent?

Here is a painting of the technique used in olden days (figure 4). I would be grateful if any art scholar could identify this picture for me, I have lost the record.

And how did the National Museum solve its problem in modern times?

It's good that the National Museum is aware of traditional protective measures (figure 5). It has few other resources in this particular place: The entrance hall was designed never to hold museum objects, only shop, restaurant, and poster exhibi-

Figure 6: The glare of sunlit objects behind the observer obscures the shaded object in the case.

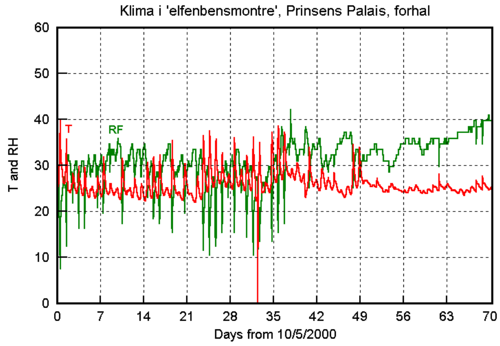


Figure 7: The climate within the showcase containing the carved ivory. The second half of the record is after the case had been moved and the blanket screening tradition established.

Figure 8: A cross section of an elephant tusk cracked through drying.

tions. It is ventilated but not air conditioned. Its praised airy lightness makes another difficulty.

Where is the exhibit? (figure 6) It is barely visible in the reflected glare from the items thought not to need protection. Notably a display pillar of postcards of Copenhagen and the little mermaid.

Even in a well designed exhibition, typically 60% of the light reaching the observer does not come from the object she is looking at but from reflections in the glass that increasingly is used to protect the object, from people. The eye and the brain are good at seeing through the glare, using hints like parallax, but exhibition designers prefer to use artistic intuition in a field where there is much they can learn from experimental psychology, as well as geometric optics, in maximising clarity of perception, and colour sensation, while minimising the light energy absorbed into the object.

Talking of light energy: when one is up towards 100,000 lux of direct sunlight, the heating effect of light becomes serious, particularly in a glass box. Here is the microclimate within the tusk box (figure 7). The left half shows the climate during the unprotected period. It was measured within an ivory coloured box, because measuring temperature caused by radiation is prone to error. The temperature reached above 35 degrees on sunny days. The effect on a black object would have been much greater, perhaps up to 60 degrees, as I will show in a moment. The relative humidity correspondingly drops below 10%. I explain relative humidity in detail later, but note now that ivory is formed within the body of a mammal where the relative humidity is close to 100%, so an excursion to 10% threatens serious physical damage through cracking.

Here (figure 8) is a section of a tusk taken from the store of a maker of reproduction baroque flutes after an unusually cold winter, with consequent low indoor relative humidity, ruined her entire stock of ivory. I return to this subject later. Here, I just want to emphasise the connectedness of all matters environmental.

Here is a more carefully researched exhibit (figure 9): a print framed behind glass, exposed first in Denmark's Open Air Museum in a typical interior

Figure 9: Experimental prints hanging on a wall in the Open Air Museum, Copenhagen

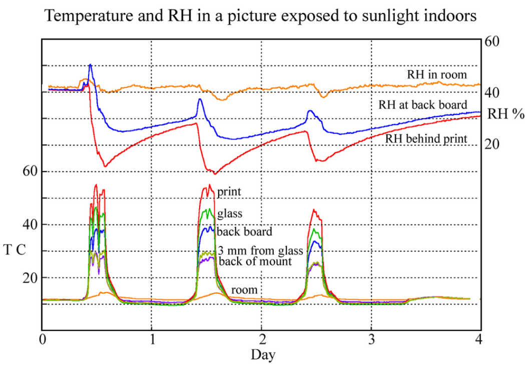


Figure 10: The climate measured within the pictures shown in 9. Three episodes of direct sunshine are shown.

scene and then moved to various other exhibition environments.

Here (figure 10) the picture has been exposed to sunlight, through a window, playing directly on the picture. In this rather complicated graph, concentrate on the central annotated pillar. During a 4 hour exposure to direct sunlight through a window, the picture got hotter than the glass in front of it, because it was a gloomy print with lots of black ink. This darker object reached over 50 degrees, in conditions similar to those experienced by the tusk in the foyer.

The oscillations of the relative humidity, the upper traces, is more difficult to interpret but I will show a final example of indirect damage by strong light where the explanation is much clearer.

The Apollo lunar expedition capsule (figure 11)

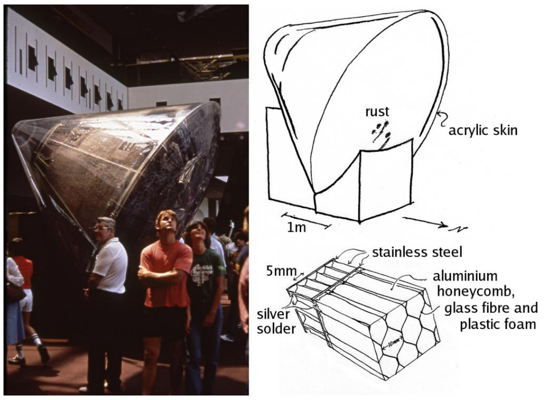


Figure 11: The Apollo 11 lunar capsule, in the central court of the National Air and Space Museum, Washington D.C.

came down in the Pacific ocean. Then it was awarded an honoured position in the central foyer of the National Air and Space Museum in Washington DC. There it began to rust, on the shady side. The explanation is that water vapour distilled from the furnishings of the crew compartment, illuminated by direct sunlight, to condense on the cooler surface of the heat shield. There the water migrated to the aluminium-steel junction deep within the heat shield, dissolved salt from the porous heat shield and generated a deep red corrosion product: ferric chloride.

The Russians made more sensible arrangements to ensure the durability of their spacecraft in retirement - they brought them down on land.

I return to the direct effect of light on museum objects. The best investigated type of light sensitive art is the natural dyes. Here (figure 12) are several of them, before and after exposure to light from a fluorescent tube. To give you an idea of the power of light, 50Million lux hours is the exposure received by an exhibit exposed at 50 lx, which is pretty dim light, for eight hours a day, for fifty years. This means that if you turn over the shaded side of an eighteenth century dyed dress in a museum exhibit, you will clearly notice the fading of the exposed side.

The yellow dyes (figure 13) are much less light resistant, which is why all tapestry foliage is blue. At the bottom of this figure is the reference set of dyes - the blue wool standards. The natural dyes nearly all fade faster than blue wool number 4.


Figure 12: The fading of several natural dyes in artificial light. The exposures of the three faded areas were 8, 36 and 91 million lux hours.

Exhibition designers naturally are frustrated at the conservators' specification of maximum 50 lux for coloured stuff. It is very difficult to make a startling exhibition at this light intensity, even using all the tricks to fool the eye into believing it is brighter. Here (figure 14) is the flamingo feather robe which stands at the entrance to the exhibition 'People of the World' in the National Museum. It is designed to entice visitors to enter the exhibition, so it has a spotlight on it. On the left is our attempt to quantify how much damage this will cause, how fast.

A feather taken from the zoo is flanked by three blue wool standards. This assembly was exposed behind glass to daylight for two months, in Brede. The feather is fading at about the rate of standard 4, which is quite good for a natural product. The colour is a carotene, which is not used for dyeing cloth, because there seems to be no easy way to make it stick.

The use of the standard defines the light sensitivity of the dye, regardless of whether the exposure is in Brede or in Morocco.

I have blithely used the unit lux, to describe the

Figure 13: The fading of natural dyes. At the bottom is the fading of the blue wool standards used to quantify dye fading in light.

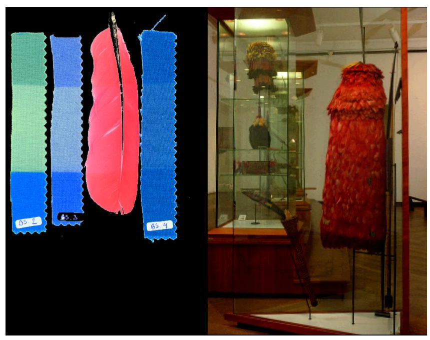

Figure 14: Testing the light fastness of flamingo feathers.

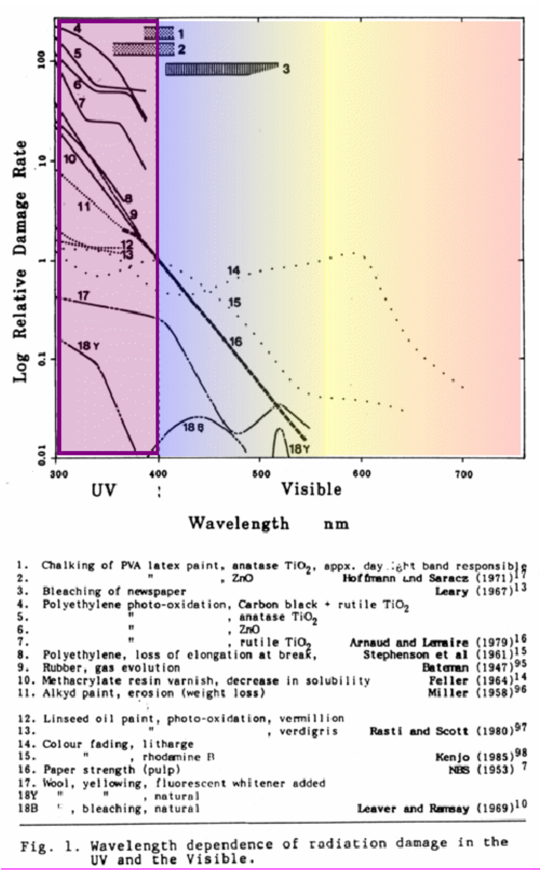


Figure 15: The effectiveness of different wavelengths in causing chemical decay.

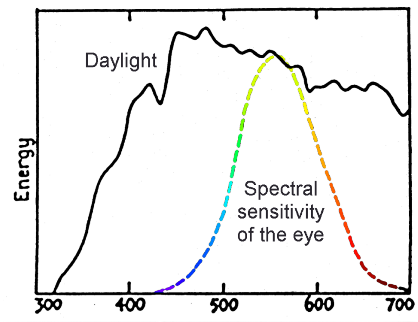


Figure 16: The spectral energy distribution of daylight and the spectral sensitivity of the human eye, which peaks at 550 nm., yellow-green light.

damage potential of light, without defining it.

We will approach the matter obliquely, but logically. Let us look first at how the museum object 'sees' radiation (figure 15).

In this compendium of published damage rates, collected by Stefan Michalski of the CCI, one can clearly see that ultraviolet radiation is by far the most toxic. Note that the vertical scale is logarithmic, damage increasing much faster at short wavelength.

However, radiation visible to us, called light, and therefore useful and unavoidable in museums, is not entirely harmless. The radiation we see as blue is the most harmful. Let us turn now to how the eye responds to radiation in this same region.

The eye mostly responds to yellow green radiation, at about 550nm wavelength. Office fluorescent lamps are designed to yield a lot of light at this wavelength. Only a little blue and red needs to be added to give the versatile human brain the illusion of white light. This light source is also rather good for preservation, being deficient in blue radiation. The purists would be appalled at this easy statement. The colour rendering is dreadful, they will say. That may be true for matching threads to repair a garment, but does it matter in a museum? no-one has really studied this thoroughly.

In figure 17 I sketch the competing factors. For best visibility, museum lighting should be rich in wavelength at the top of the yellow curve, for best conservation, light should be deficient in wavelength within the blue area.

How far can one go in reducing the blue component?

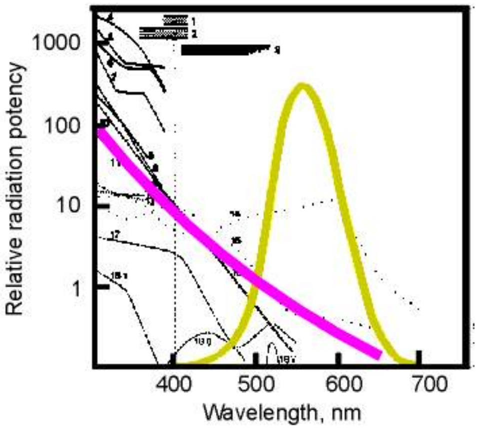


Figure 17: The spectral energy distribution for damage to objects contrasted with the spectral sensitivity of the eye.

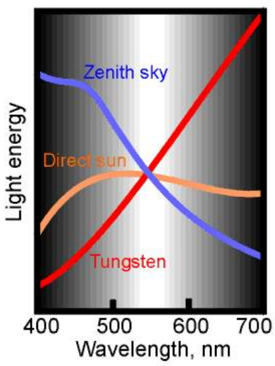


Figure 18: The spectral energy distribution of three light sources, adjusted to give the same visual brightness.

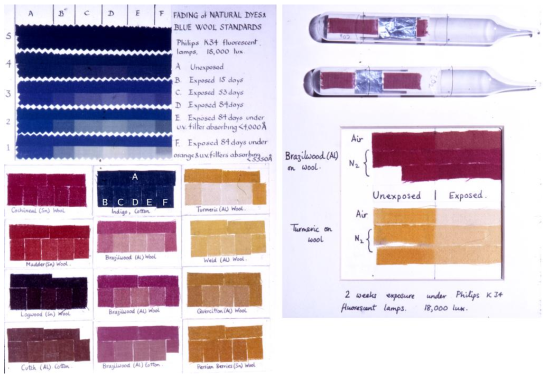


Figure 19: The influence of UV and orange filters, and encapsulation in an inert gas, on the rate of fading of dyes.

Figure 18 shows several traditionally acceptable light sources, arranged to give equal illumination of a grey object, as assessed by the human eye. The damage to objects will vary by a factor of 20 FOR THE SAME ILLUMINATION AS DEFINED BY THE LUX. Hey, I haven't told us yet what the lux is. It is the accumulated brightness of the background to this figure, more scientifically, the radiant energy arriving at the object, with energy at each wavelength multiplied by the height on the curve marked spectral energy sensitivity of the eye in figure 16. For more detail, consult my web pages. Instruments to measure lux were developed long ago, as photographic light meters. Instruments for measuring the spectral energy distribution of a light source have only recently become cheap and transportable. Conservators cling to the lux as the measure of photochemical damage rate. This is plain wrong, but a very durable tradition.

This discussion has turned rather abstract and diagrammatic, so here (figure 19) are some examples of the spectral sensitivity to fading of dyes.

On the left are a series of tests in which dyes have been exposed to filtered light. The lower middle square of each sample has been exposed to a fluorescent lamp designed to imitate north daylight, which is relatively rich in uv radiation. The next square has had the uv filtered out. There is a barely discernible degree of protection to brazilwood on wool, no protection of turmeric. The right hand lower square has been protected by an orange filter which excludes wavelengths shorter than 550nm,

Figure 20: The Museum of Modern Art Glass in the cistern under Soendermarken, Frederiksberg, Denmark.

Figure 21: A flash photo of the statue shown in figure 20, showing abundant mould growth on the plinth.

that means it allows through the half of the visual spectrum which causes least damage. This is very effective. The conclusion is, for these dyes, that uv filters provide little protection, it is the blue to yellow radiation that causes damage. So it seems that incandescent light, deficient in blue, is the most conservation friendly illumination. But of course it isn't so simple as that, because incandescent light has a strong heating effect.

## WATER IN AIR AND IN MATERIALS

The next environmental agent is water. This (figure 20) is the Museum of Modern Art Glass in the

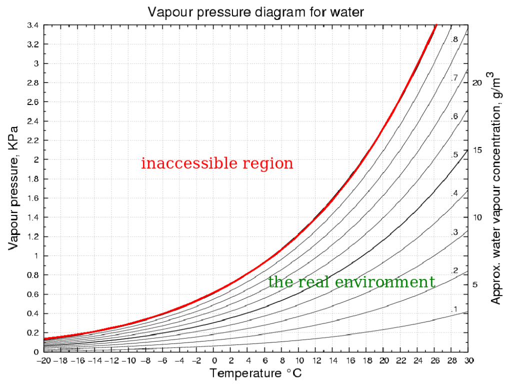


Figure 22: The vapour pressure diagram for water.

ancient cisterns under Søndermarken in Frederiksberg, a part of Copenhagen. The relative humidity is held reliably at 100% by the constant centimetre of water on the floor. The mould growth on the sandstone statues and on the compressed wood fibre plinths is abundant, but the pillars of the 150 year old construction are not mouldy.

I use the term relative humidity, which you have surely heard, but what is the accurate definition of relative humidity? Unlike the lux, the relative humidity, often shortened to RH, is an entirely appropriate unit for conservation discussion. It is important to understand it.

The formal definition is this: it is the water vapour concentration in space, expressed as a fraction of the maximum possible water vapour concentration. You know there is a limit, it shows as dew and fog. The RH is a ratio, so we can express the concentration in any units we like, the result of the ratio-ing will be the same. By tradition, mostly, we use the vapour pressure, which is the pressure exerted on the container, such as the walls of the Museum of Modern Glass Art, by the water molecules buzzing about, at about 400 m/s.

To come further with this very important aspect of preventive conservation, we have to understand relative humidity, and why this peculiar way of defining water vapour in space around museum objects is appropriate to conservation discussion.

The red curve in figure 22 marks the vapour pressure of water over a water surface, which is why I started with a view of the Frederiksberg cisterns. In most other places, most of the time, the space is not saturated. There is a deficit of water, so the

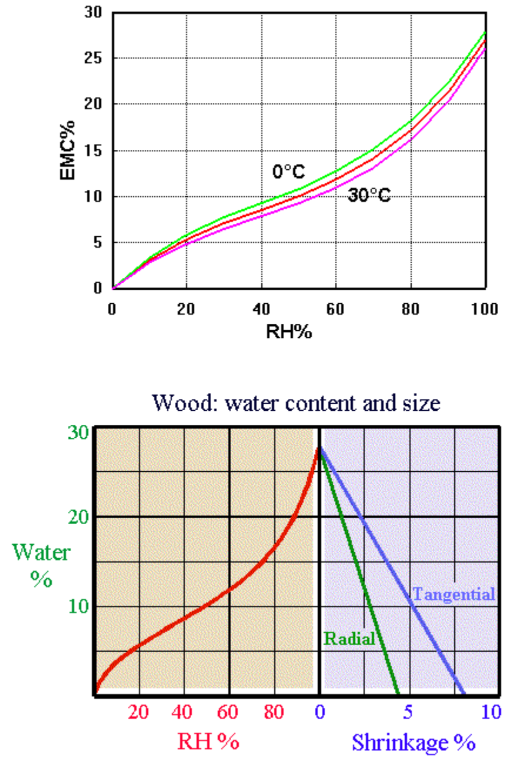


Figure 23: The water sorption of wood and the consequent change of dimensions.

Figure 24: The altar of Gierslev Church, Zealand, Denmark

actual situation is somewhere in the area marked ‘the real environment’. Typically, indoors, it will be about 20 degrees and about 6/10 saturated, which we commonly change to 60%.

Here is a very important point: the relative humidity as defined is this way is not a concentration - you can see that the 60% curve passes through many values of vapour pressure or of water vapour concentration, given on the right hand axis.

So why use this indirect measure of water abundance?

The previous figure and this one (figure 23) are all one needs to understand almost everything about water vapour in museums. The top diagram here shows that the water content of wood depends on the relative humidity, almost unaffected by temperature, increasing steeply with increasing RH. The lower diagram shows that the size of a piece of wood depends on the water content, also almost independent of temperature. So the size of a piece of wood depends on the relative humidity and only much less on the temperature.

Figure 24 shows the altar of Gierslev church in the middle of Zealand. It has an amusing conservation history. Early in the twentieth century the experts from the National Museum decided that the side picture on the altar was art so valuable that it should be removed to the National Museum for safe keeping. The picture on the front was judged in too bad a condition to bother about. In the intervening years the picture in the National Museum was first dunked in molten wax and then lost in the storage vaults. By the year 1998 the still decaying picture in the church was the piece in the best condition, so the National Museum tried again, bringing now the front picture in for treatment.

Mindful of the humid conditions in the church, the conservator wrapped the picture loosely in polyethylene and left it to come slowly to equilibrium with the 55% RH of the conservation workshop.

In spite of this precaution the paint rose up in tents, so emergency treatment had to be given, the conservator working in a steamy polyethylene tent kept moist with a pile of damp paper.

What had happened? We can guess that the painting was made in a workshop, at perhaps 70% RH, on oak panels seasoned to about the same relative humidity. When the young painting was installed in front of the stone altar, which rested on the ground without moisture barrier, the wood swelled as it came to equilibrium with the 98% RH at the surface of the stone. The water was unable to

Figure 25: The altar picture of Gierslev Church, during restoration.

Figure 26: A Japanese Lacquer box in the Freer Gallery, Washington D.C.

evaporate through the paint film. The paint hardened slowly over the swollen wood. When, centuries later, the now brittle paint experienced the shrinking of its support it did not conform but shortened by buckling.

Here (figure 26) is an example which looks the same, but with an opposite mechanism. Japanese lacquer is hardened by exposure to moisture, so the box is born in a moist atmosphere. When the environment dries out, both wood and lacquer shrink. In the grain direction of the wood the lacquer shrinks more than the wood and so opens cracks across the underlying grain.

These examples illustrate two important points. Damage through relative humidity change can happen within minutes of a change of the surrounding climate and the stress free relative humidity depends on the manufacturing history of the individual object.

For most organic materials, the manufacturing

Figure 27: A close-up of the box of figure 26, showing cracking across the longitudinal direction of the wood support.


Figure 28: Sponge bottle

RH was very high, often 100%, as with the ivory shown earlier. For industrial materials also, the RH at formation is high. Photographic film has the gelatin layer laid on as a water solution, which is why film naturally curls.

Some materials show an extreme reaction to humidity change, here are two examples: a sponge, and the seeds of a geranium plant, whose feathered tails twist four times round as the RH changes from 20% to 90% RH.

You can understand why conservators are much concerned with RH, as failures of stewardship can show almost instantly as catastrophic visible deterioration, in contrast to the slow attrition worked by light.

It is often said that RH change is ok if it is slow, so the material can adapt. This is a quarter truth. Slow change preserves objects from damage caused by drying, or wetting, of the exterior, before the interior has ‘noticed’ the change of ambient RH. Slow

Figure 29: The seed head of a geranium (window-box type). The feathery stalks twist around four times between RH limits 20% to 90%.

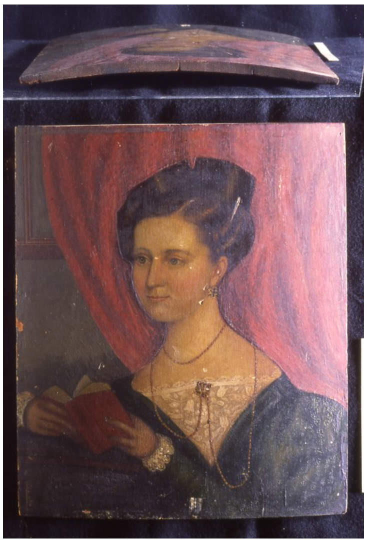

Figure 30: A protrait of Mrs Eliakim Esterbrook. The Museum of American History, Washington D.C.

change does not diminish the strain caused by material properties such as the differential shrinkage of wood in its three directions - radial, tangential and longitudinal.

Even slow change must be very slow. Here (figure 30) is an example of damage caused by the annual RH cycle on the United States Atlantic coast.

I introduce you to Mrs Eliakim Esterbrook, originally from Virginia but now a pensioner residing in the basement store of the Museum of American History in Washington DC. During her painted residence in the alternately humid hot and dry cool climate of indoor Virginia, she grew rather stout - as shown by the cross section in the tilted mirror

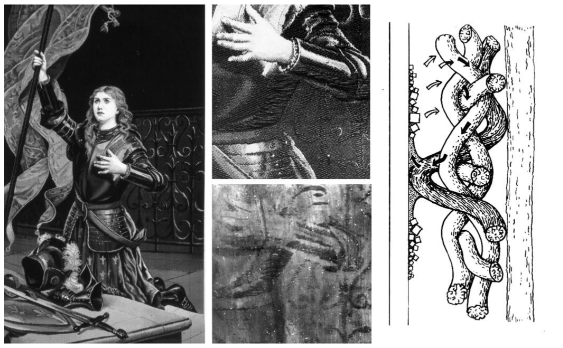

Figure 31: A Jacquard woven silk picture of Joan of Arc. Museum of American History, Washington D.C.

at the top. The phenomenon is caused by cycling RH. In summer the unpainted wood surface swells, but is restrained by the still dry interior wood, so the surface cells collapse. In winter the wood dries, again from the surface. The collapsed cells become stronger as they dry and shrink smaller than their original size, forcing the plank to bend. After many cycles the wood is markedly bowed, and the paint, which does not react to moisture nearly as much, begins to flake. You can see this phenomenon on nearly every piece of antique furniture. Mr Esterbrook was painted on both sides of the panel, and he is as straight as an old soldier.

There are subtler effects of relative humidity which make it a major obsession with conservators. I show one amusing example (figure 31). This is a woven picture, a sort of automatic tapestry made by the Jacquard process. This gives an uneven surface. The picture was pressed against glass in its frame. Over years the inner glass surface clouded over, but not where the picture touched it! The cloud was salt and the mechanism was a slow migration of the salt in solution in the silk cloth to the surface where it crystallised, due to minute differences in the behaviour of bulk salt and salt in a microporous substrate.

We saw the effect of salt on the Apollo capsule in the previous section. Salt is everywhere, particularly in Danish church wall paintings. The water absorbing and releasing properties of salt have a large and largely hidden influence on the durability of artifacts.

Nearly all the physical processes described here

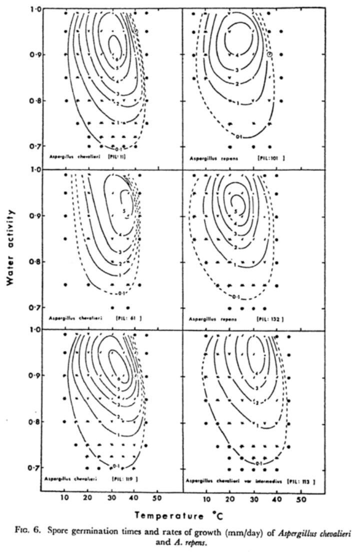


Figure 32: The optimal growth conditions for micro-organisms. Ayerst.

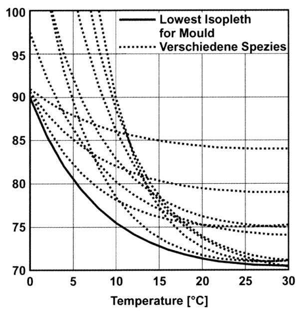


Figure 33: Limits for growth of micro-organisms. Martin Krus

Figure 34: Interior of the organ of Køge Church, Denmark, showing an unidentified mould growing in a moderate relative humidity

are less threatening at high RH. Materials are softer and so stresses are less. However, we cannot envelop collections in a beneficial cloud of steam, because mould growth happens on an only slightly slower time scale.

There is a classic paper by Ayerst, (figure 32) showing the optimum growth conditions for several microorganisms. Notice the reduced growth rate at low temperature and the higher RH needed for growth at low temperature. Martin Krus summarised these and many other results in the graph, figure 33.

Even this shows only a few organisms, and no growth below about 70%RH. When one extends the range of organisms to those that cannot be identified, or even easily cultured, the danger region extends down to 50% RH.

The organ of Køge church, south of Copenhagen, is afflicted with a fungal growth that has defied identification and which is capable of growing at a relative humidity around 60%.

Relative humidity and temperature are intertwined, as we have seen in the diagram of vapour pressure. Generally, conservators are less concerned about temperature variation, calculating that dimensional change is ten times less than hu-

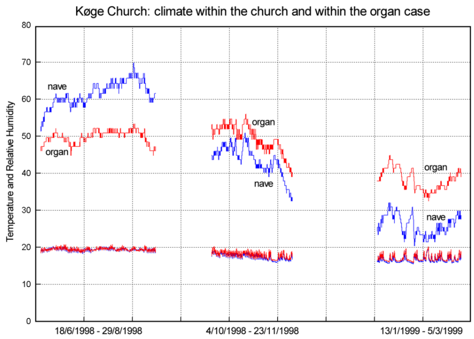


Figure 35: The climate measured in the organ shown in figure 34


Figure 36: The hazards of cold storage.

Figure 37: A mirror whose silver layer has flaked after disinfection by cooling to –30°C. National Museum of Denmark

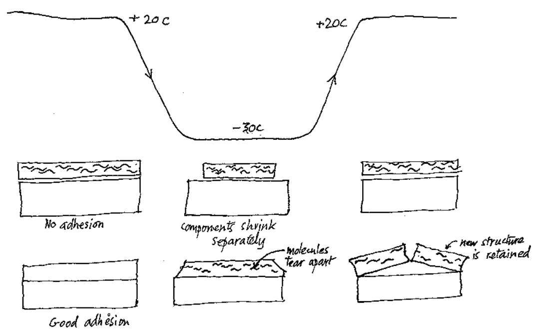


Figure 38: The proposed mechanism of flaking of the mirror in figure 37

midity generated change, for the normal indoor climate.

Stressfully low temperature is, however, used as a preservative, particularly in specialist stores, notably for furs and for film.

Low temperature is also used for economic reasons in country churches, where it appears to do no harm to the church furnishing. Only the churchgoers need conservation treatment here.

The sad remains of a wall painting are here (figure 39) sheltering in a niche in the cold wall while the congregation enjoys personally directed radiant heat. This works well in a secular society where hardly anyone goes to church. It is much easier to preserve artifacts without light and without people.

So far, I have talked mostly about the physical damage caused by the variation in water content of materials, as a consequence of variation of rela-

Figure 39: How the Brits keep warm in church.

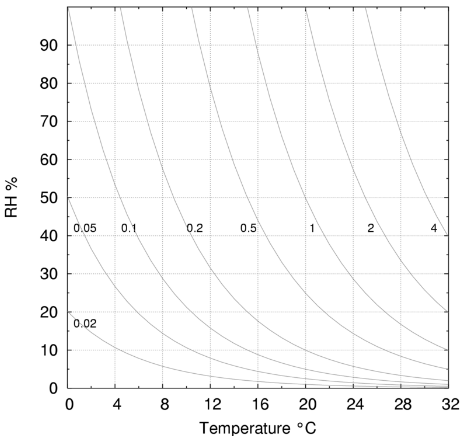


Figure 40: An array of lines of equal reaction rate for a typical hydrolysis reaction, such as the decomposition of cellulose acetate film base.

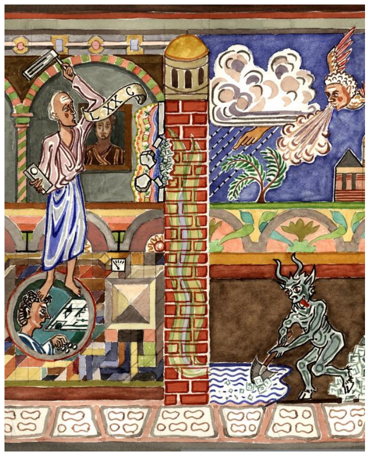

Figure 41: Garry Thomson, whose book 'The Museum Environment' has been a powerful influence on environmental standards in museums.

tive humidity in the surrounding space. I turn now to the chemical effects of temperature and relative humidity, where again there is a powerful synergy between the two influences.

The quantitative effect of temperature on the rate of a very common class of degradative reaction was explained by the Swedish chemist Svante Arrhenius in the late nineteenth century. The effect of relative humidity on the same reaction was also explained by Van't Hoff in his law of mass action, slightly earlier. I combine these two influences in this diagram (figure 40). Each line represents a constant reaction rate. This reaction rate can be achieved by a temperature of 28 degrees at 17% RH, or by a temperature of 16 degrees at 90%RH.

If one holds the RH constant, a horizontal line on the diagram, and lowers the temperature, the reaction rate will decrease, likewise at constant temperature, a higher RH will increase the reaction rate.

Where do we put the compromise temperature and relative humidity?

Curiously enough, the answer lies in a study of both chemistry and the technology of air conditioning. I return to the matter later.

# STANDARDS

The funny thing about museum standards is that everyone has his (usually) own standard, a hairs-

***Table 1*** *Suggested values for the optimal conservation of artworks for steady-state indoor climate conditions.*

| Artworks materials | UNI 10829 standard $\theta_0$ (°C) | $\Delta\theta_{max}$ (°C) | $u_\phi$ (%) | $\Delta u_{max}$ (%) | Decree of 10th may 2001 $\theta_0$ (°C) | $u_\phi$ (%) |
|---|---|---|---|---|---|---|
| *a) Organic materials/objects* | | | | | | |
| Paper, papier-mâché, paper artwork, tissue-paper, wallpaper, stamp collections, manuscripts, papyri, printings, cellulose materials | 18 - 22 | 1.5 | 40 - 55 | 6 | 15 - 24 | 50 - 60 |
| Fabric, veils, drapery, carpets, fabric tapestry, arras, silk, costumes, dresses, religious vestments, natural fibre materials, sisal, juta | 19 - 24 | 1.5 | 30 - 50 | 6 | - | 40 - 60 |
| Wax, anatomical waxes | <18 | N.R. | N.R. | N.R. | - | - |
| Herbaria and botanical collections | 21 - 23 | 1.5 | 45 - 55 | 2 | - | 40 - 60 |
| Entomological collections | 19 - 24 | 1.5 | 40 - 60 | 6 | - | - |
| Animals and anatomical organs preserved in formalin | 15 - 25 | - | N.R. | N.R. | - | - |
| Animals, dried anatomical organs, mummies | 21 - 23 | 1.5 | 20 - 35 | - | 19 - 24 | 40 - 60 |
| Furs, feathers, stuffed animals and birds | 4 - 10 | 1.5 | 30 - 50 | 5 | 15 - 21 | 45 - 60 |
| Water-colours, drawings, pastels | 19 - 24 | 1.5 | 45 - 60 | 2 | 19 - 24 | 50 - 60 |
| Ethnographic collections, masks, leather, leather clothes | 19 - 24 | 1.5 | 45 - 60 | 6 | - | 50 - 60 |
| Painting on canvas, [illegible] and canvas [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 19 - 24 | 35 - 50 |
| [illegible] miniatu[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Lacquer, inlaid, decora[illegible] furniture | [illegible] | [illegible] | [illegible] | [illegible] | 19 - 24 | 50 - 60 |
| Polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, wood musical instruments | 19 - 24 | 1.5 | 50 - 60 | 2 | 19 - 24 | 45 – 65 |
| Unpainted wood carvings, wickerwork, wood or bark panels | 19 - 24 | 1.5 | 45 - 60 | 2 | 19 - 24 | 40 - 65 |

Ethnographic collections, masks, 19 - 24
leather, leather clothes

Figure 42: A page from a listing of two Italian standards.

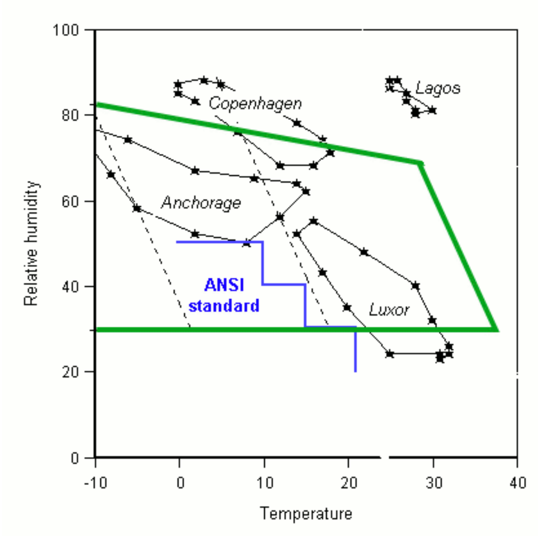


Figure 43: The ANSI standards for monochrome film and the monthly average climate in several places.

breadth different from everyone elses. Even official national standards have a breathtaking illogicality. Here (figure 42) are two Italian standards, carefully lined up on the same page. There is a mixture of material categories, which is fair enough, and human categories, for example 'ethnographic collections' which means the artifacts of a civilisation unenlightened by the European renaissance. Since our standards should be for prevention of damage caused by mechanisms unaffected by our evaluation of the cultural significance of the object there can be no scientific sense in such a standard.

There are scientifically based standards of course. The Image Permanence Institute of Rochester, New York State has done pioneering studies of the degradation of film. The ANSI standard for photographic collections, largely based on the IPI research, gives several choices (figure 43), and one wonders how are they arrived at?

The ANSI standard for monochrome film is the blue zigzag. The limits for acceptable storage are outlined in green, more about this later. Note that the zigzag limit steps neatly round the monthly average climates of almost anywhere. I have added a few disparate climates to show that one cannot export photos to be stored anywhere. So this standard forces air conditioning.

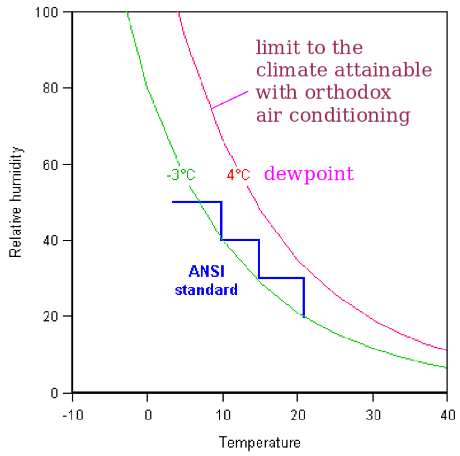


Figure 44: The ANSI standards and the limiting dew point for orthodox air conditioning.

Figure 45: “I have here the climate graphs which result from our group effort to build a museum”

But that is not all - it forces an unusual air conditioning. In this graph (figure 44) the same standard limit is accompanied by lines of constant dew point. These may be totally mysterious to you, so I will shortly explain. The point I want to make here is that the standard carefully skirts the region of temperature and relative humidity, to the right of the red curve, which can be enforced by the standard air conditioning installed in offices, supermarkets and cinemas, and in many museums.

At this point I want to introduce the bygherregruppe, the building committee, the group of wise people representing the interests of builder, engineer, owner and users of the building that is about to be erected. My experience of these groups, which should have the super human group intelligence that comes from mixing different professions, has not been happy. I identify the problem as the lack of enough shared education for synergy to happen. This whole session is about giving you the language, the jargon and the critical insights to make you a better contributor to these meetings, which will surely hit you at several times in your careers.

The result of shaky technical knowledge is that people fall back on standards and specifications, not as a desirable discipline to ensure quality control, but because they do not know enough of each others' specialities to hammer out a solution relevant to that particular project.

The standards we have in conservation are particularly unconvincing and the evidence that supports them is shaky and controversial. Conservators have not developed a professional concensus and obsessive individuals and institutes have freedom to impose demonstrably absurd standards.

I have described the standard for lighting, which is designed to protect against photochemical destruction of inanimate objects but instead uses a quantity only relevant to the photochemistry of the human eye. The situation is little better for temperature and relative humidity.

To contribute helpfully to the design of a museum or archive we have to grasp the principles of atmospheric physics and of air conditioning. It is not that difficult. Here is a crash course.

Air conditioning was invented in the hot humid climate of the southern United States, so I will start with how air is cooled and dehumidified.

Start at the blue cooling device in figure 46. In this convoluted tube a volatile liquid is evaporating. This causes the tube to cool below the air temperature, so air passing over it is cooled. Evaporative cooling is a frequent phenomenon: you know that running in wet clothes cools you down. The energy for evaporation is drawn from the cloth, which therefore cools below ambient. The liquid in the blue tube is not water, though in principle it could be. It is a volatile hydrocarbon or ammonia.

The room air passes over this coiled tube and cools. It is likely that water also will condense from the air.

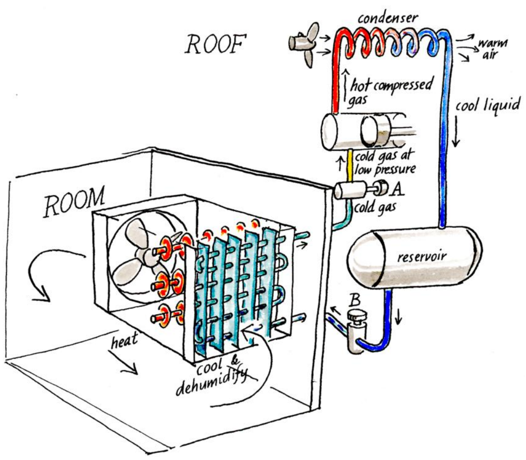


Figure 46: A simple air conditioning unit. See text for explanation.

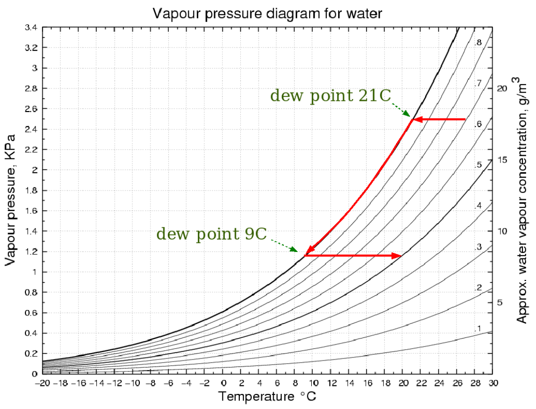


Figure 47: The state of air moving through the air conditioning unit.

You have seen this diagram before (figure 47), the diagram for water vapour. Consider the red line. We start with summer outdoor air at 27 degrees and 77%RH. Our target weather in the museum is 20 degrees and 50%RH. The air cools as it passes over the evaporating coils, moving to the left on the diagram. When it has cooled to 21 degrees, the air has reached the limit where water vapour will condense out. When I say that air has reached the limit I really mean that the water vapour in the air has reached its limit, the air has nothing to do with this process, being merely a carrier of water vapour round the building. The temperature at which condensation begins is called the dew point. It is a temperature but, as you can see, it also uniquely defines the water vapour content. So now we have three ways of defining the amount of water vapour in the space around us: vapour pressure, dew point, g/m$^3$. There are others! But make a note of the dewpoint - it will turn up later.

As the air cools further it moves down the limiting water vapour pressure curve. Finally, at 9C we have removed enough water from the air to give 50% RH at our final condition, but the air is much cooler than we want it, so it must be re-heated to the final 20C. The cooling system has therefore been used for two purposes: to cool the air, but also to dehumidify it. To dehumidify the air we have to over-cool it, then reheat it to the desired temperature.

This wastes energy, though not as much as you may think from the diagram, because engineers have cunning schemes for saving energy, which you, as a conservator, can safely leave to the more esoteric knowledge of the engineer, who will be using a slightly different diagram to this one.

Now we go back to the diagram (figure 46) where the air has reached the red reheat unit where it is heated nearly to room temperature, not quite, because in summer heat is coming through the walls to give the final puff to the desired room temperature.

That is the circuit for air conditioning: cool to the desired dew point, which fixes the final relative humidity, then reheat to the desired room temperature.

What are the limits to the flexibility of this system? The main limit is ice on the cooling device. If the surface of the cooling element is below freezing, the air will not get through. Then there has to be

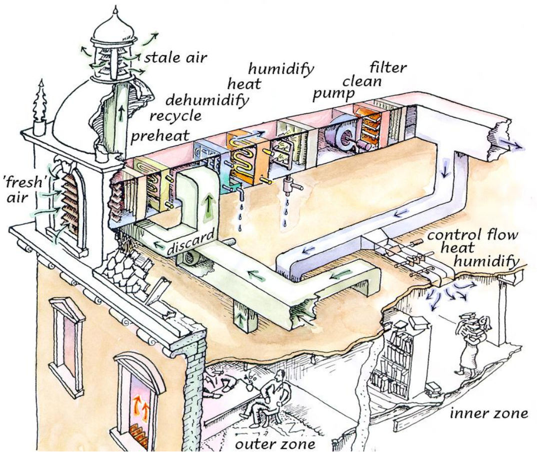


Figure 48: Typical air conditioning equipment for a large building.

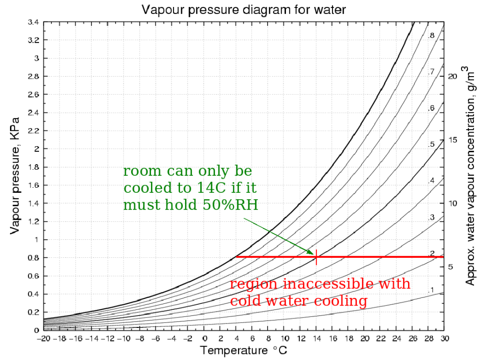


Figure 49: The limit for conventional air conditioning.

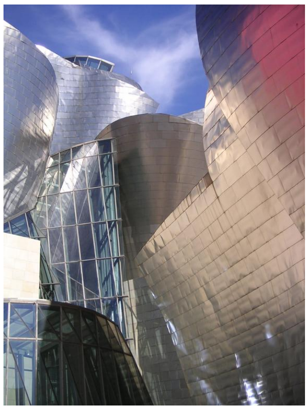

Figure 50: The Bilbao Guggenheim Museum, designed by Frank Gehry.

a defrost cycle, which seems simple but I won't further embarrass the National Museum by showing a climate record that demonstrates what happens when the cooler ices up for a month or two.

The air conditioner illustrated here is 'direct expansion' in the engineers' jargon. The vapour of the fluid evaporating in the tube is compressed, which reheats it, then cooled by passing it through a heat exchanger, usually on the roof, so it condenses and is held in a reservoir before returning to evaporate in the air conditioning unit. However, the fluid is expensive so in large installations, museum size, the cooling fluid is water, cooled to 4C by heat exchange with the expensive specialised fluid in a separate device.

So here, finally (figure 48) is the standard diagram for air conditioning in its full flowering - consuming about a quarter of the volume of the building and a large slice of its running costs.

Now we return (figure 49) to the familiar diagram, where I have marked the 4C dewpoint limit for this conventional air conditioning. One can establish a climate anywhere along the red line, or above it. For example 8C at 75%RH, or 18C at 40%RH, but one cannot make 8C at 40%RH.

This seems very simple, as I have explained it, I hope, but it is very commonly not known. The film archive in Bagsværd went into a months long coma because the knobs were turned to 10C and 40%RH, which was written on the dial, but was unattainable.

So now you can see why I am disappointed at the formulation of the IPI standard - why choose a range of possibilities, all of which require unusual air conditioning. Why not choose just one set of temperature and relative humidity, since all are equally demanding technically?

Enough of this criticism. After the break we will work on how to develop a sensible specification for designing exhibition and storage spaces, based on science rather than blind faith in the current gurus.

# MUSEUM DESIGN

The conservator has little power to compare with the star status accorded to architects. In the several books I have read, and exhibitions I have vis-

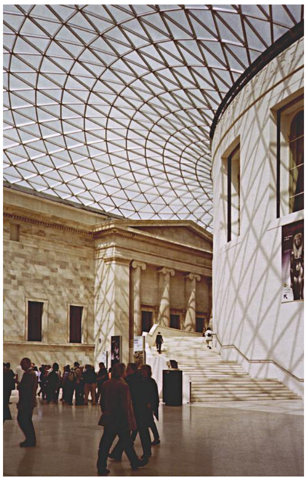

Figure 51: The courtyard of the British Museum, London. The roof was designed by Norman Foster

Figure 52: The Korean scholar's house in the British Museum.

ited, concerning the Guggenheim Bilbao museum, (figure 50) - none mention climate control. The roofing of the courtyard of the British Museum, (figure 51), caused the first installation of full air conditioning in the BM, in the Korean gallery. This is because open courtyards serve a purpose: to increase heat loss from a building during the vastly greater proportion of time the interior space is warmer than the exterior.

This lone air-conditioned gallery paradoxically includes a full size replica of a very different academic establishment - a Korean scholar's house (figure 52), exquisitely suited to the local climate - of Korea, not necessarily of the BM.

So we can hope that the tide will turn, from empty grandeur to subtly appropriate design. We can maybe take heart from local developments.

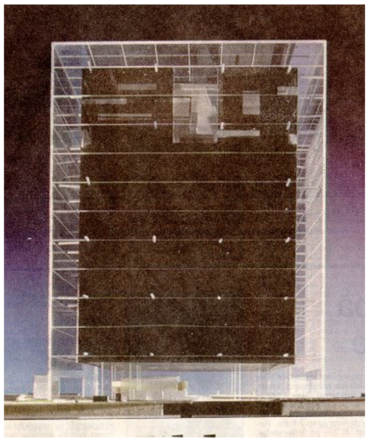

Figure 53: One of the entries in the competition for the State Archive of Denmark.

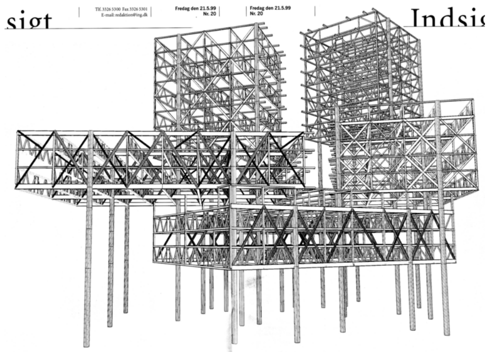

Figure 54: The winning design for the State Archive, under attack in the journal Ingeniøren for being weak on its legs.


Figure 55: Does measurement help?

The long running drama about the National Archives suggests that conservation is having a greater influence, though a recent enquiry to the project leader, about concepts of passive and low energy climate control got the response “We haven’t got so far yet.”

So here is our chance to exercise some influence on the hole under the rails, as it is currently planned.

# SETTING STANDARDS

Here (figure 55) is another definition of the phrase ‘passive climate control’. Preventive conservators are good at measuring, not so good at archiving the measurements and unwilling to assert the consequences of their measurements - that most of the trash localities offered for museum storage are not worth the very low price put on them.

Instead of assessing the barely acceptable, we should start from the beginning - what is the scientific ideal and how can we attain it.

Since we have already established that there is no single ideal for the diverse materials in our collection, we have to start somewhere.

Since we are in the library school, I take my starting point from Don Sebera, a chemist in the US National Archive, who invented the isoperm concept: a diagram in RH-temperature space where each line, those in the grey background (figure 56), connects points that give the same degradation rate.

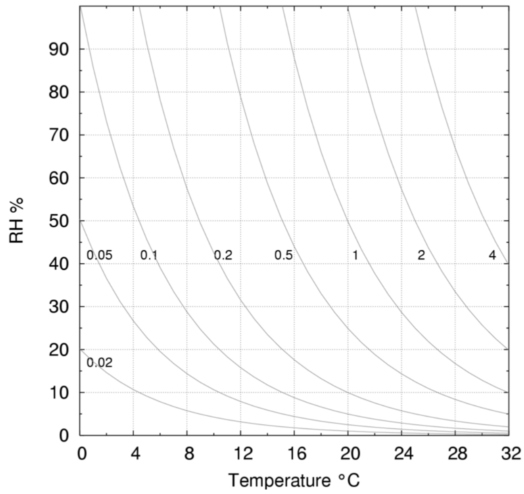


Figure 56: Lines of equal damage rate (isoperms) for hydrolysable materials.

He used the very common class of decay of organic materials through hydrolysis - the breaking of the polymer chain through addition of water. So far I have, for dramatic visual effect, shown water as a potent cause of physical stress but the relative humidity is also identical with the potential for chemical action by water, in the breaking of the cellulose molecular chains that form the raw material for books, for example.

As one would expect, tracing a line vertically, thus increasing the RH at constant temperature we pass towards faster reaction rates. Moving horizontally to higher temperature at constant RH also increases the reaction rate, quite dramatically considering that the temperature scale really begins at -273 degrees. This accelerating reaction rate was first quantified by Svante Arrhenius in the late nineteenth century and has been abundantly confirmed since, as a general guide to reaction rates of many kinds.

On these generic decomposition rate lines, I have superimposed (figure 57) a set of lines of constant dewpoint. Interpret these lines in this way - if your air conditioning runs at a particular cooling element temperature, then the room climate must be somewhere along the corresponding dew point line. The same applies incidentally to non-air conditioned rooms, here the dewpoint is that of the outside air. If that air is warmed for human com-

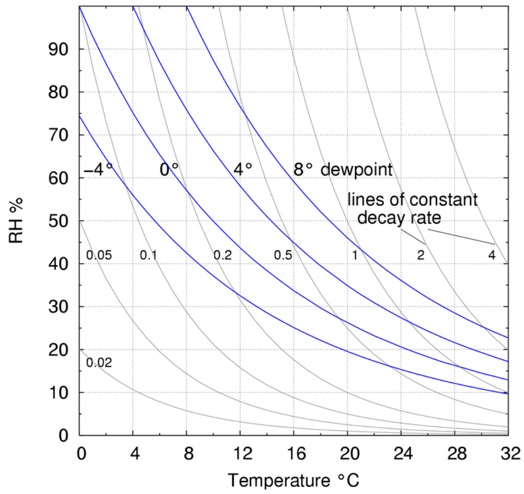


Figure 57: Isoperms with superimposed dewpoint curves.

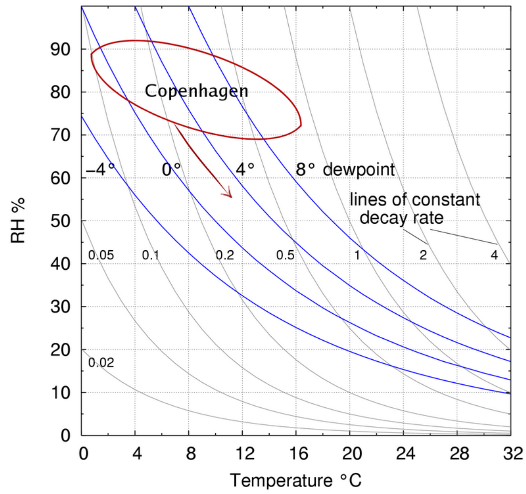


Figure 58: The previous figure with the monthly average course of the Copenhagen climate superimposed.

fort, the dew point stays the same, so again the room climate must be on one of the blue lines.

Now, here is an important point: the pattern of blue lines intersects the pattern of grey lines in such a way that warming the air, sliding down and to the right along any blue line, increases the rate of degradation of the material. The blue lines cross into faster reaction rates at they descend the diagram.

Put into simple English: it is better to have a cool archive at high RH than a dryer archive at a higher temperature. That is not so intuitive a result, and certainly does not show in the recommendations for library preservation, which aim for the lowest RH compatible with being able to handle the paper without it cracking. It is undeniable that low RH is good, but the wise people who set the standards seem not to have been familiar with the processes and costs of air conditioning technology.

Now the going gets a bit tougher: where is the Copenhagen climate in this picture? The oval in figure 58 marks the course of the monthly average temperature and RH in Copenhagen, outdoors.

Here is an interesting observation: this oval lies nicely centered on the 4C dewpoint line, which I explained was the limit for orthodox air conditioning. So half the year the Copenhagen air is better than air conditioned air for blowing into the archive. For the other half it is not catastrophically bad, so maybe we can keep monochrome film and other archivalia without air conditioning, if we bend the rules slightly, to account for regional peculiarities. Because the north Americans are insanely energetic, nearly all the standards, for anything, are basically American standards, lazily copied by the Europeans.

Here (figure 59) is the same diagram with added limits for high and low RH. Above the upper limit, taken from Martin Krus' diagram which I showed earlier, there is a risk of mould growth, below the lower line, which is much more vaguely grounded in experiment and observation, there is a risk of mechanical damage through shrinking stresses on laminated materials.

This has been a hard session for you, I fear. After the break we will take a tour of museum buildings to see if we can learn from them how we can build new.

# ALTERNATIVE CLIMATE CONTROL

Behind the lower range of narrow windows of the Alcazar fortress in Segovia, central Spain, is the military archive, a room between the massive outer wall and the limestone rock of the castle mount.

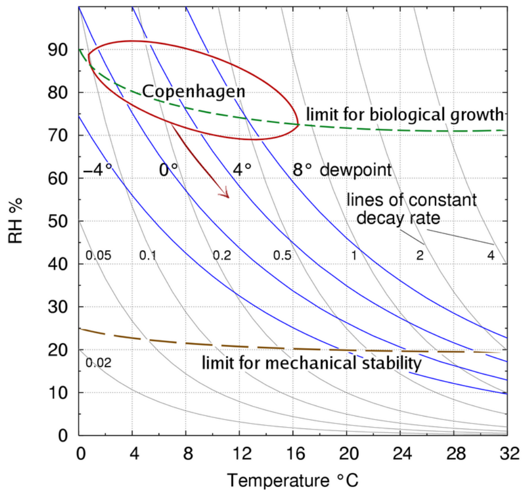


Figure 59: Limits for mould growth and for drying cracks are added to the previous figure.

Figure 60: The Alcazar: the citadel of Segovia, Spain

Figure 61: The military archive, The Alcazar.

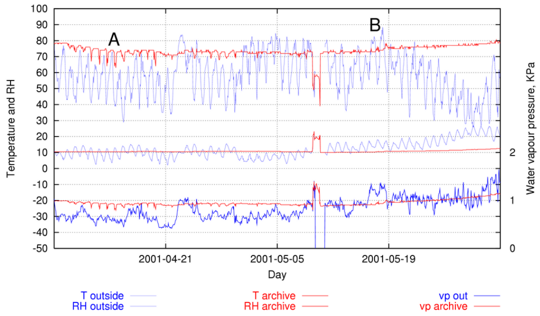


Figure 62: The climate within the archive. Note the influence of opening the windows at times marked A and B.

It is stuffed with bundles of paper wrapped in string. It has the ideal combination of thermal mass and hygroscopic material to buffer both temperature and RH. It has also another climate control resource: the curator.

Here (figure 62) is the climate over a period of a month in the spring. Notice the impressive constancy of the indoor RH, the top red trace, and temperature, the middle trace. The curator is responsible for the sharp blips in the record under the letter A. This is caused by opening the windows, which pushes the RH in the intended direction: downward from the rather high 80%RH. The buffering by the paper resists this. It pushes the RH back up as soon as the curator closes the windows and goes home to make dinner. But if you look closely, the RH doesn't quite recover its old value. The curator's action is beneficial.

Before you think I am being uncharacteristically kind to the museum employees, I hasten on to point B. Here, the curator is continuing her habit of opening the window, but now the Spanish summer is hastening forward and the outside air contains more water vapour than that inside, as shown by the lowest two traces on the graph. Now her action is driving up the RH.

This diagram therefore gives a warning and suggests a possibility. The habit of opening the window is not always beneficial, but maybe we can use cunningly timed ventilation to use the instant value of the outside water vapour concentration to climatise a museum with a computer and a fan, but not air conditioning.

Here (figure 63) is one of the new buildings of

Figure 63: The University of Copenhagen, Amager. The Arnemagnaean archive is behind the windowless area.

Figure 64: Interior view of the archive.

Copenhagen University, a collection of rectanguloid clones in travertine and glass, of equal thickness. The windowless area conceals the archive of the Arnemagnaean Institute - the collection of manuscripts concerning Iceland collected by Arne Magnus.

Inside, it is as exciting as any other archive and here, to further excite you, is the air conditioning equipment. It's pretty neat isn't it, compared with the others I have described?

Here (figure 66) is a section through the archive. It is a bomb-proof concrete box. Unlike the Rigsarkiv, it is guaranteed to fall to the ground uninjured if the supporting pillars collapse, though one wonders if it will resist the weight of the structure falling on top of it.

Anyway, outside the concrete structure is rather

Figure 65: The minimalistic air conditioning equipment.

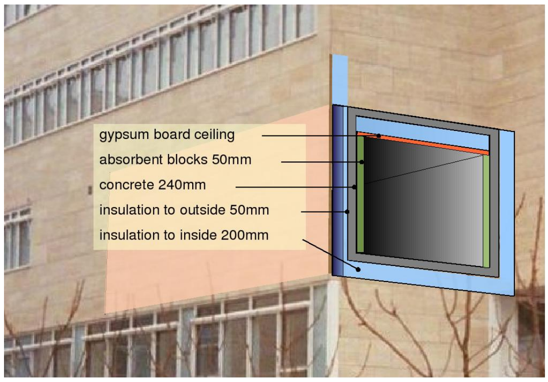


Figure 66: A section of the archive. Notice the thick insulation towards the interior and thin insulation to the outside!

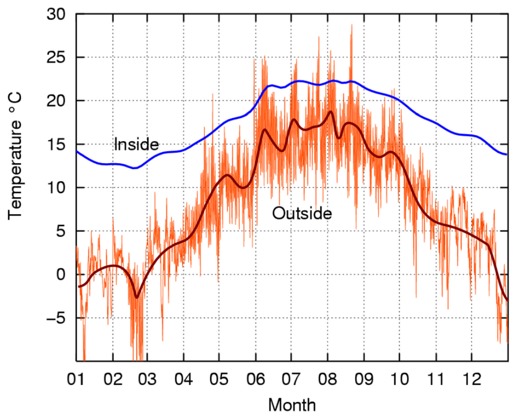


Figure 67: The predicted course of the temperature within the archive.

thin insulation to the outside and rather thick insulation to the inside. This apparently perverse thermal arrangement gives the archive a temperature cycle through the year that follows half way between the running average of the outside temperature and the nearly constant 20C of the inside.

This is a predictive computer model, courtesy of COWI, which shows in blue (figure 67) the expected inside temperature resulting from the orange outside temperature, which is a typical year's weather for Copenhagen, which never actually happened. The predicted indoor temperature hasn't actually happened either but the modelling had one useful result: we could use it to convince ourselves, and eventually the supervising architect, that the thin insulation towards the outside was actually thick, just like the rest of the building. It is not only military archive curators who work on autopilot. That was eventually put right.

Buildings nowadays are predicted: a lot is done with computer models. The predictions are seldom fulfilled, as many angry office workers can testify. Maybe this is why it is so difficult to get any actual figures for the indoor climate from the building management. In this case it is a monthly struggle to get the climate data we need to evaluate the effectiveness of our design, which is based on letting outside air in only when it will nudge the indoor climate towards the specified value.

This (figure 68) is a tricky graph. I show three months. For each month there is an expected temperature in the archive, derived from the previously

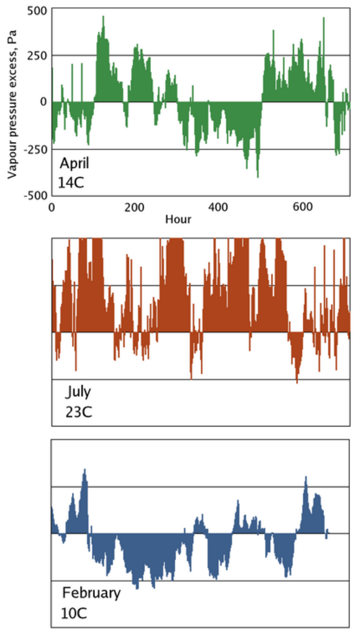


Figure 68: The air conditioning logic. When the solid area is below the line, outside air will dehumidify the interior.

shown computer model. The RH is defined to be 50%. From this defined value, plus the expected temperature for the month, I calculate the vapour pressure within the archive. This is compared with the outside vapour pressure during a year, which really did happen, in Copenhagen. When there is excess water vapour outside, the solid colour is above the horizontal line.

Whatever the actual RH in the archive, one can push it towards the desired value by pumping in outside air at some time in the month. This pumping will also change the temperature slightly, but not much because the archive is designed to adjust its temperature largely by the balance of heat coming through the outside and the inside walls.

Also, there must be considerable humidity inertia in the archive to allow it to survive three weeks of outside air of the wrong water vapour concentration.

You don't believe in computer models do you?

Here (figure 69) you may admire the actual results for a couple of months

At the very beginning of the graph you can see the 'Alcazar Curator' effect: two little bumps when

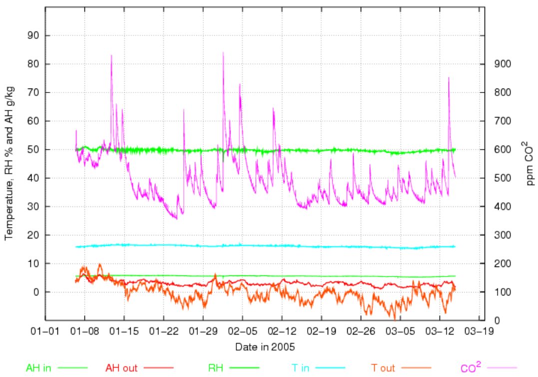


Figure 69: The climate measured within the archive. The carbon dioxide trace can be used to estimate the air exchange rate.

Figure 70: The state archive of Schleswig, Germany

the outside vapour pressure was higher than that inside, so the computer decided to pump in outside air. For the rest of the time there were no further chances, the two lower traces show that the outside water vapour pressure was nearly always too low to be helpful. That is because the inside temperature was higher than the modelled value, in spite of a rather cold period. Do we blame the programmer or the builder, or the weather? The moral is to design robust buildings where it doesn't matter if the predicted performance is not quite realised. The RH is so constant that we were in doubt about the accuracy of the sensor. By we, I include my colleague Poul Klenz Larsen, who has the most difficult part of the job - getting the data from the building manager.

Oh yes! The purple spikes. That is the $CO_2$ concentration, which reveals when people enter the archive. The decay of the spikes, particularly the ones on Friday afternoon, allow us to check the air exchange rate of the archive. It is about once per day.

The Arnemagnaean is a small archive, 10 x 4 metres, but inertia works also on a larger scale.

This (figure 70) is the regional archive in Schleswig and (figure 71) one year of climate record.

This archive was designed a bit differently: it was intended to be radiator heated to reduce the RH and a very advanced computer control heating system was installed, and never used. It's these models you see, you never can rely on them. My thanks to Lars Christoffersen of Birch and Krogboe

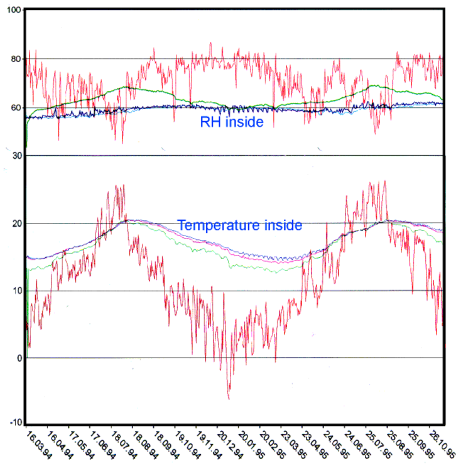


Figure 71: The climate in the Schleswig Archive.


Figure 72: Engineer MacIntyre first proposed using water absorbent humidity buffers in exhibition rooms.

Figure 73: The Friday Bar in the Copenhagen Agricultural College

for this climate record.

One should record a debt to the pioneers. The proposal to use water absorbent materials to maintain a more constant indoor relative humidity was first proposed in 1937 by Engineer MacIntyre, to protect the Mantegna pictures displayed in the Orangery of Hampton Court Palace; London. There is no evidence that his idea was ever implemented, and there is no trace of firehose in the ducts today, but his pioneer work is now coming to be mainstream, for storage and archiving.

For cultural heritage in other environments, there is still some way to go. This (figure 73) is the Friday bar in the agricultural college in Copenhagen. It was decorated by Storm P, who also designed the beer engine.

so why is the paint around the red devil flaking? For one thing it is not original, but look at the

Figure 74: A close up of the mural.

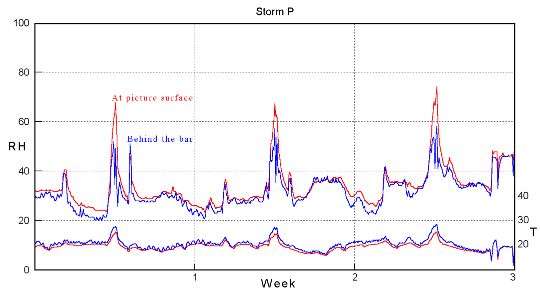


Figure 75: The climate in the bar. Note the surge in RH on Friday nights, and the smaller surge on Saturday, when the bar is cleaned.

climate: figure 75.

This shows the difference between an archive and a bar. One has no air change, the other has some air change, but not enough absorbent material, water absorbent I mean.

The violent peak in RH on friday evening is followed by a curious satellite peak about a day later. So remember - don't mop the archive floor.

My thanks to Poul Larsen for these climate measurements.

In archives and in lightly visited museums, air conditioning can be avoided, but in the popular museums where the crowd is as dense as in a cinema, engineers will claim that there is little alternative to this scene (figure 76).

Yet one hundred and fifty years ago the Arts and Industries Museum was built in Washington to house the wares left over from the Philadelphia International Exhibition. It was designed by a military engineer and the military have been the best conservators, over millenia, long before the concept of art conservation was born. His design was utilitarian neo-Romanesque: a single exhibition floor with skylights cunningly arranged to give even illumination and pairs of spires at the centre of the four

Figure 76: The modern museum sacrifices about a quarter of its volume and a large slice of its running costs to air conditioning.

Figure 77: The Arts and Industries Museum, Washington D.C.

Figure 78: Gundsømagle Church, 20km west of Copenhagen.

symmetrical facades, to act as convective chimneys to remove hot air and draw cool air in through the windows.

One could say that standards of care have become much more stringent, but on the other hand the use of showcases is now universal, to protect objects from a less respectful public, so maybe we can make the showcase into the primary care container, allowing the museum a more natural and variable climate.

## THE MICROCLIMATE IN CONTAINERS

This section, mostly about indoor air pollution, is omitted, because it is described in another article on this website:

www.padfield.org/tim/cfys/tis/tis.php

## HUMIDITY BUFFERING

This (figure 78) is the nave of Gundsømagle church in Zealand, Denmark. The walls are limewash over a local form of travertine - a porous limestone. The church is warmed to about 12C in winter, boosted rapidly to 24C for church services and for the organist to practice.

This gives us a laboratory for examining the effect of walls and furnishings on the interior climate.

During these sudden heating episodes we can assume that there is very little air exchange with the graveyard. So the church should behave like any other enclosed body of air prevented from exchanging water from its surroundings - it will move along a curve of constant dewpoint, as explained earlier. That is the blue line.

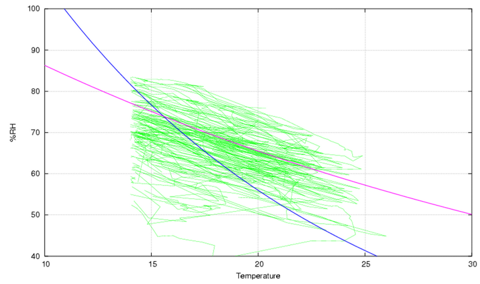


Figure 79: The trace of temperature and relative humidity during repeated episodes of heating and cooling the church.

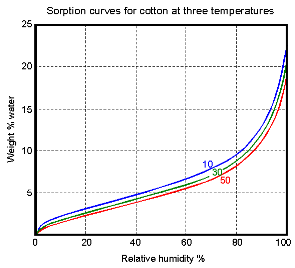


Figure 80: Water sorption of cotton with varying relative humidity.

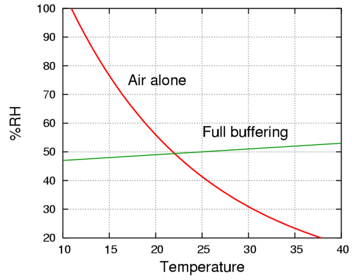


Figure 81: The different responses of an empty container and one filled with cotton.

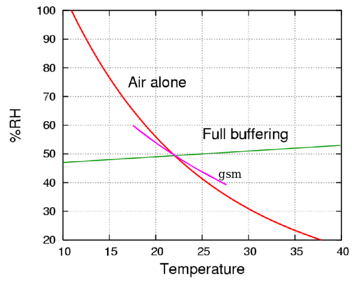


Figure 82: The climate record from Gundsømagle, superimposed on the previous figure.

In fact the air follows the purple line, as shown by the mass of squiggles (figure 79), each representing a heating and cooling episode, during an entire winter heating season.

The RH changes with temperature much less than one would expect. The air must be exchanging water vapour with the walls of the church. This process, however it occurs, is referred to as humidity buffering. It occurs to some extent in all buildings, but can be deliberately increased to enhance the dimensional stability of absorbent materials such as wood.

The explanation for buffering is quite simple: it depends on the insensitivity of the moisture content to temperature change. Here (figure 80) is the sorption curve for cotton, used as an example. Nearly all other materials have the same pattern of reaction to relative humidity.

If one takes a bundle of cotton in a close fitting plastic package and raises the temperature, from 10C to 30C, the moisture content must stay the same, because the package has a fixed water content, so the position on the graph moves horizontally to the 30C curve. This means that the RH in the interstitial spaces has risen from 50% to about 55%. Figure 81 displays the data in an alternative way.

If the same plastic box were filled with air, the RH would have fallen from 50% to 20%.

If the plastic box had just a little cotton, the result would be somewhere between the two lines.

Here is the squiggle from Gundsømagle Church superimposed on the diagram (figure 82)

It is not very impressive, but then limewash and porous limestone have much flatter sorption curves than cotton, that is they have much less capacity for water exchange with the surrounding space. Porosity is not enough.

That is humidity buffering against temperature change, which should not be necessary in a museum or archive. Then there is buffering against air change (figure 83). If the outside air has a different water content to the inside air, whatever its temperature, then the inside air will vary in RH as the outside air leaks in, either by accident or delib-

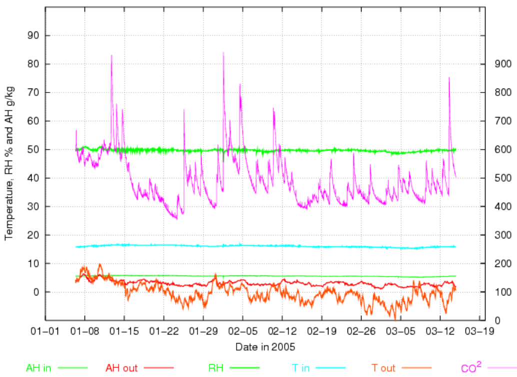


Figure 83: Humidity buffering against leakage, as shown by the lapse rate of the surges in carbon dioxide concentration when people visit the archive.

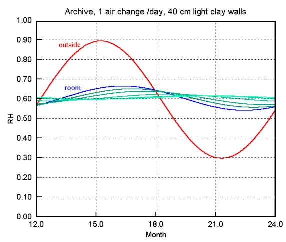


Figure 84: A computer simulation of the RH in an archive as the outside RH changes.

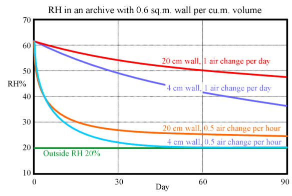


Figure 85: The influence of buffer thickness and air change on the RH within an archive.

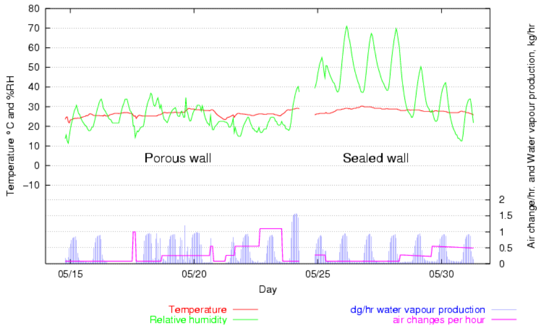


Figure 86: Humidity buffering by porous walls in a bedroom.

erately to prevent people suffering carbon dioxide narcosis.

Absorbent materials have vastly more exchangeable water in kg/m$^3$, than air. 100g of cotton contains the same water as 10m$^3$ of air. As the RH around it changes, cotton will absorb or release water to maintain the equilibrium as defined by the sorption curve.

That is very simple to calculate, if the air leak is very slow.

Here is the RH of the Arnemagnaean archive (figure 83 again. It is very stable indeed, buffered by the walls and the archive content. Compare this with the trace for carbon dioxide, which is scarcely buffered at all and therefore can be used to derive the air exchange rate, which is about once per day.

At the bottom: the green and red traces show that the outside air is consistently dryer than that inside, so buffering against air exchange is clearly working.

Here (figure 84) is the computer prediction of the result of leaking in air of the same temperature but a different RH (the red curve) at the rate of one air change per hour into a room with 1 m$^2$ of absorbent clay wall per m$^3$ of volume. The blue curve is the expected room RH and the paler green lines are the calculated RH at depth within the absorbent lining. The palest curve, at 40cm depth within the lining, shows hardly any change, so a thicker lining would not help. A thinner lining would be almost as effective.

This (figure 85) is a different presentation of the same room, assuming a constant low RH leaking into the room, which would be the consequence of cold outside air leaking into a heated room. You can see how various thicknesses of absorber buffer the change of RH, for two different leakage rate.

Notice that even with 0.5 air changes per hour, typical for a lived in room, the half time for moving to the final 20% RH is five days, instead of half an hour for a non-absorbent room!

Who believes in computer predictions? Here is a real experiment (figure 86). It is a bit messy in design but is quite persuasive. On the left half of the graph is the climate in a bedroom, whose two


Figure 87: All human activities inject water vapour into the air.

virtual occupants are chastely imitated by a gently bubbling kettle, injecting water vapour every night, as shown at the bottom. The air change is also varied from time to time.

On the right is the same situation but with the porous wall covered with polyethylene sheet.

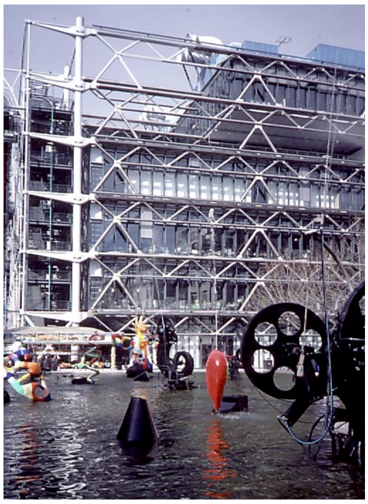

Figure 88: The Pompidou Centre, Paris. Designed by Renzo Piano and Richard Rogers.

## TRENDS IN MUSEUM DESIGN

These experiments in the building industry are more directed towards ameliorating the effect of human activity, which all add water vapour to the indoor climate, often in intense but intermittent bursts, between which natural ventilation can re-establish a healthy equilibrium.

But much the same applies to museums, which have crowds of heavy breathing guests for maybe six hours per day, followed by a long period of calm broken only by the lonely tramp of the guard.

So how have museum architects reacted to the possibility of low-tech moderation of the indoor climate? Really badly is the answer. The modern era in museum building can be dated from Renzo Piano and Richard Rogers' Pompidou centre in Paris. This thinly constructed building relies entirely on air conditioning to maintain its inner calm. It has already undergone one major reconstruction of the system since its opening in 1968. This is a classically four square building, in comparison with the bent paper models of Gehry.

Figure 89: Interior view of the Bilbao Guggenheim museum.

It is difficult to make such a structure with ther-

Figure 90:

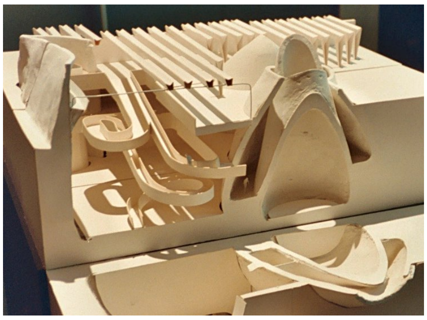

Figure 91: Model for Silkeborg Museum, Denmark, by Jorn Utzon.

Figure 92: The temporary exhibition of the Nydam boat, National Museum of Denmark

Figure 93: The Nydam boat, during a power cut.

mal and moisture buffer capacity. It is characteristic that the various architectural monographs about the Bilbao Guggenheim do not mention conservation aspects of the design at all.

When the fashion suddenly moved to outward tilting walls, the battle was lost: how can such a wall be made of heavy masonry and porous relatively weak materials? Fallout from these buildings will be cracking skulls in a few years but think what could have been.

This (figure 91) is a model of Jorn Utzon's design for Silkeborg museum. A lost work of genius - and inherently conservation friendly, being underground and with light trajectories that would never directly illuminate the collection.

So what do we get in modern times? Badminton court architecture (figure 92) . Here is the enclosure of the Nydam boat during its recent excursion to the National Museum.

And here is how it looked during a four hour power cut. You may think that the wires holding the canopy are a carefully considered emergency precaution but they are really there to hold up the apron that caught the drips from condensation on the underside of the uninsulated canopy. A serendipitous example of a reaction to an unforeseen phenomenon preventing an unanticipated disaster.

That is surely a good point to hand over to the master of risk management!