CLIMATE CONTROL IN LIBRARIES AND ARCHIVES

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ABSTRACT

The climate maintained within a library is the result of a compromise between the climatic needs of the readers and the staff, the climatic needs of the structure of the building, the need to minimize the deterioration rate of the collection, and the maintenance demands and running costs of mechanical air-conditioning. Passive climate control by careful design of storage containers and by slowing down the heat and moisture transfer through walls allows simpler air-handling systems that are less troublesome, less costly to run, and less dangerous if they fail. Orthodox air-conditioning systems can produce air at a dew point of about 5° C, allowing the building to be held at 18° C and about 42 percent relative humidity (RH). A lower temperature can only be obtained by allowing the relative humidity to rise, or vice versa. A lower dew point can be obtained by drying the air with a silica gel desiccant system after the initial dehydration with a cooling coil. Bound books are liable to physical damage below about 35 percent RH, however, and people feel cold below about 18° C. Therefore, colder or dryer conditions are only suitable for carefully insulated storage vaults, in which only a minimum amount of air need be circulated. The relative humidity in vaults should be maintained slightly below that in the reading room so the moisture content of the book does not change when it is warmed for the reader. A stable relative humidity is desirable, but the value can be chosen, within the limits of 40-62 percent, to take account of peculiarities of the local climate and of the building. Buildings which are humidified in winter may be damaged by condensation and freezing of water in the walls. Sudden changes of relative humidity can be entirely prevented by enclosing books in close-fitting, nearly airtight containers, which are safe if there is no permanent temperature gradient from one side to the other and no sudden temperature drop around them. The small danger of locally generated air pollution can be minimized by sealing interior wooden surfaces and by incorporating alkaline buffered paper into boxes and shelf liners.

Introduction

Cool air of moderate and stable relative humidity is good for books. This happy state is attained by a combination of a congenial local climate, a suitably constructed building envelope, good internal layout, mechanical air-conditioning, and passive climate control through well-designed containers for the books and documents. This article is an attempt to bring together the concerns of the architect, the air-conditioning engineer, the paper chemist, the conservator, and the librarian so that each can understand the difficulties facing the others as they try to achieve a good climate for conservation. I will not try to define the ideal climate for storage of documents. Tight specifications, laid down without regard for the problems of a particular building, in a particular climate, and with particular limitations in local skills, are a major cause of eventual dissatisfaction with the results.

This article begins with a description of mechanical control systems for indoor climate; continues with a description of the needs of the collection and how the characteristics of equipment and of the building structure set limits to the climate that can be imposed; and concludes with an account of the role of passive climate control.

Relative Humidity and Dew Point

One of the difficulties that people have with discussions on climate control is understanding the concept of relative humidity and why it is, for preservation people, the significant measure of atmospheric moisture (1). For air-conditioning engineers the important parameter is the dew point of the air, because this sets limits on the climate that can be attained with orthodox methods (2).

Given a room full of air, at a comfortable 20° C, with a piece of paper in it, we can add water vapor to the air and watch what happens to the paper. Without any water vapor the paper will be rather stiff and brittle. As the amount of water vapor increases, the paper becomes softer and larger. Eventually we find that we can add no more water vapor to the air: It immediately condenses out on the walls if we try. Turning to the paper, we see that it has become very flabby. If we measure the water content of the air at this time, we find that the most we can add is 0.015 grams per gram of dry air. This quantity is 2.4 percent of water vapor by volume. The typical water content of air at this temperature (20° C) in everyday, outdoor life is about two-thirds of this value. Rather than quote the absolute value of the water content, we say that the relative humidity is 67 percent. The relative humidity (RH) expresses the atmospheric water content as a percentage of the maximum possible water content at that temperature. It is a ratio, not a concentration.

The convenience of using, and thinking in terms of, relative humidity only becomes apparent when we consider the situation at a different temperature. At a room temperature of 10° C, for example, the maximum amount of water vapor in the air will be 1.2 percent, just half the amount that could be accepted by the air at 20° C. If we now turn to the paper, however, we find that it is just as limp as it was at the higher temperature, with the higher value of atmospheric water vapor. The paper would, however, be quite crisp in air at 20° C with 1.2 percent of water vapor. Thus the paper responds mainly to the value of the relative humidity rather than to the value of the moisture content. Actually, this is not surprising: The paper is responding to the potential for action of the water rather than to its absolute amount (3). To put it another way, the wateriness of the air depends on how close it is to saturation rather than on how much water it contains.

After saying this, I must now point out that the moisture content of paper, and therefore its stiffness and dimensions, is not exactly dependent on the relative humidity alone. There is a small temperature dependence which can usually be neglected in buildings held at a normal comfortable temperature. This effect needs to be considered in studies of the influence on paper of cold storage and of heat sterilization processes.

The 1.2 percent of water vapor that only half saturates the air at 20° C completely saturates the air at 10° C. This particular batch of air, whatever its actual temperature, has a "dew point" temperature of 10° C. If it is cooled below 10° C, water will condense out.

The Technology of Climate Control

The simplest way to control the climate in a building is to distribute air from a central conditioning plant through ducts to the individual rooms. An air-distribution system allows control of dust, pollution, and humidity as well as temperature regulation, all within the same system.

Let us build up a typical air-conditioning system (Figure 1) piece by piece (4). A fan blows air through a duct into the room. Upstream from the fan there is a heating coil

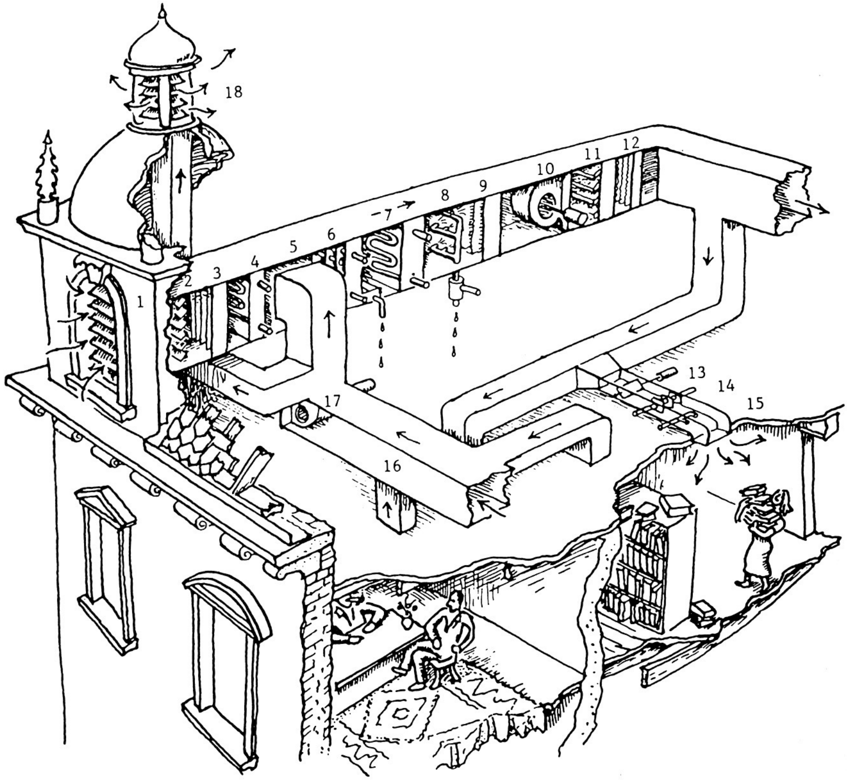

Fig. 1. Diagram of an air-conditioning system

1. Outside air inlet
2. Damper
3. Coarse filter
4. Pre-heat coil
5. Recycled air entry
6. Cooling coil
7. Re-heat coil
8. Steam humidifier
9. Medium filter
10. Fan
11. Pollutant filter
12. Fine filter
13. Damper
14. Re-heat coil
15. Steam humidifier
16. Return air duct
17. Return air fan
18. Exhaust

to give winter warmth. In summer the air will need to be cooled. The same coil could be used, circulating a refrigerant through it. For reasons that will become clear, it is customary to provide a separate cooling coil upstream from the heating coil. These two coils provide for the temperature control of the room. A temperature sensor in the room sends signals to the control system, which adjusts the flow rate of hot water or of coolant to the coils. Humidity is controlled by spraying water or steam into the air stream, or by allowing air to pass through a wet mesh. This procedure allows us to increase the relative humidity of the room air, up to a point. To dry the incoming air we can use the cooling coil to condense water from the air, which may then need to be reheated. Thus separate coils are used for heating and for cooling: Sometimes both are in operation at the same time. Dust filters are usually put in the air stream to protect the equipment as well as the room. Filters for gaseous pollutants are better placed downstream of the equipment to catch pollutants given off by the humidification equipment. The air pumped through this series of devices is a mixture of recycled room air with some outside air. The outside air serves three purposes: It pressurizes the building, it keeps the oxygen and carbon dioxide and odor contents within comfortable limits, and it sometimes contributes to fuel economy.

Such a simple system is excellent for a single room with a naturally uniform internal climate. A dimly lit, unoccupied book stack deep within a building, and with no unusual sources of heat in adjacent rooms, could be very accurately controlled by such an arrangement. The air would be distributed throughout the room by branch ducts so that every part would be flushed by air of uniform temperature and relative humidity.

Most buildings are more difficult to control because of the uneven distribution of sources of heat in different rooms. These heat sources may also vary from time to time. Sun shines through the windows intermittently, and cooking is mostly a daytime activity. A system that delivers uniform air to all these rooms will fail to provide adequate comfort to the occupants or safe conditions for the collections. This situation can be dealt with in several ways. I will describe one solution which could be applied to control the climate in a particular research library or archive. This is only an example; it must be emphasized that each building should be treated as an entire system and should not be governed by a set of arbitrarily imposed standards and methods.

Buildings lose heat only from their perimeters. They gain heat throughout the interior, from lights and from the activities of people, their computers and their coffee pots. A perimeter heating system, using hot water circulating through radiators, will cope with the winter heat loss through walls and windows. The interior of the building will then only need cooling. The cooling needs of the various rooms will differ, but none will need heating, except on starting up the system. A library needs continuous air-conditioning, so restarts will only result from occasional mishaps.

The air-conditioning ducts therefore carry an air stream that is always cooler than the required room temperature. Each room has a valve in its branch duct that lets into the room just enough of this air to maintain the room at the correct temperature. The air temperature in the duct is held at a value that will just serve to cool the room with the greatest cooling need. Other rooms take less air. Uniformity of temperature in a room demands a moderate air circulation so it is necessary to have some minimum air input. A small heating coil in the duct near the air inlet will allow a flow of air without over-cooling the room. This is wasteful of energy, but some waste is inevitable in close control of building climate.

The relative humidity is controlled by holding the moisture content of the air in the duct at a value that gives the correct relative humidity when the air has warmed to the correct room temperature. The relative humidity is therefore not independently controlled from room to room as is the temperature. Each room is merely flooded with air of the correct moisture content. The moisture content of the air can be boosted by putting a small steam injector in the local duct. This addition allows very close control of relative humidity but brings some hazards, which will be mentioned later.

Putting dryer air into the room cannot compensate for sources of humidity such as people and boiling kettles. A dehumidifier in the local duct would make a rather complicated system. A free-standing dehumidifier within the room is preferable. A consequence of this characteristic of air-conditioning systems is that it is important to prevent leakage of outside air into the building. The system will cope with the heat gain or loss caused by leakage, but it is less efficient at preventing changes of relative humidity. For this reason, and to avoid drawing in dust and pollutants, it is customary to design air-conditioning systems so that the interior is at a slightly higher pressure than that outside. This brings other troubles which will be discussed later.

The climate in a room can be controlled in many other ways. All use the same basic devices. One commonly used system does not vary the air volume pumped into the room, but has a heating coil in each branch duct to bring the air to a suitable temperature. A variant on this is to have a parallel duct carrying warmer air, which is mixed in varying proportion with the cold air to supply each room. These methods are rather wasteful of fuel.

Air Pollution

Filtration to remove particles is relatively easy and noncontroversial. For libraries one should aim for nearly total removal of dust. Several filters are needed. The first is a coarse filter to remove large lumps. The last is a very fine filter capable of removing nearly all dust over 1 micron in size. This filter presents a considerable resistance to air flow, and a correspondingly powerful pump is needed to drive the air through it. An alternative filtration method is the electrostatic precipitator, which removes dust particles by first charging them by passage through a strong electric field and then catching them on oppositely charged plates. Electrostatic precipitators tend to produce large agglomerations of particles, which eventually get caught up in the air stream. A conventional fiber filter is therefore put downstream to intercept these large particles. These devices have been criticized for generating ozone, but the rate of production of this dangerous pollutant seems to depend very much on the design of the device. This gas can also be removed, however, by a pollutant absorber downstream of the precipitator.

Gaseous pollutants are not customarily removed by air-conditioning equipment except in specialized buildings. For libraries the best choice seems to be active carbon filters. This material is inflammable, and an alternative is active alumina impregnated with potassium permanganate. This impregnant is needed to ensure complete removal of the very damaging pollutant sulphur dioxide (6, 10). The air is passed over granular beds of the absorbent. There seems to be some uncertainty over the performance in real life of pollutant absorbers, particularly for oxides of nitrogen.

Some pollutants are generated by the air-conditioning equipment. Chemicals are used in the humid parts of the equipment, such as drain pans for humidifiers, to prevent algal growth. Steam humidifiers are free of this problem, but chemicals are customarily added to the steam pipes to inhibit corrosion. The best solution at present seems to be to use high pressure steam to generate steam from purified water brought through plastic tubes to stainless steel heat exchangers. Electrical boiling of pure water is an expensive alternative.

Monitoring of pollutant concentrations demands more elaborate equipment than that needed for measuring temperature and humidity. Indeed, the efficiency of pollutant absorption by freshly installed active carbon can lead to such small concentrations in the air that only the most costly equipment and skilled operators can produce reliable data.

Controls and Calibration

There is a decisive move towards electronic sensing of the climate. A computer program decides what action is needed to keep each room at a constant climate and to minimize fuel consumption. The various valves and shutters are usually operated pneumatically.

Inaccurate sensors spoil the entire operation. Temperature sensors are quite reliable. They are usually devices whose electrical resistance varies with temperature. Relative humidity sensors are less reliable because their calibration drifts slowly, and all types are affected by contamination from airborne dust and pollutants (5). Recently, a dew point sensor has become available for air-conditioning applications. This device is a small metal mirror, which is automatically cooled to a temperature that just causes condensation. This humidity sensor is the most accurate available. The cold moist surface is even more prone to contamination than are the other types of sensor. It is, however, easy to clean.

A record of the interior climate can be obtained from the sensors used to control the system, but it is much better to use an independent network of sensors placed well away from the system sensors. If a bubbling coffee warmer is placed right under the system sensor, the climate in the rest of that room will become cool and dry as the system responds to the incorrect climatic data.

The clockwork hygrothermograph is still the best monitoring system for small institutions with less than 10 air-conditioned spaces. Above this size electronic systems are cheaper, and their data can be presented and recorded in a more informative way.

It is also vital to have intermittent checks on the system with hand-operated, calibrated sensors. Accurate electronic thermometers are available, which are quicker to respond than liquid-in-glass thermometers. Some have alternate sensor heads to allow measurement of surface temperatures as well as air temperatures. The psychrometer, or wet and dry bulb thermometer, is still the best hand-operated device for measuring relative humidity. Other electronic relative humidity indicators use sensors that are not so easily cleaned, and they are not to be relied upon for checking the system performance.

Climate for Books and Their Readers

After this very brief account of air-conditioning systems, I will turn to the climatic needs of the collections and describe how the choice of equipment and its mode of operation can best be adapted to the needs of a library. Several values are recommended for the climate that should be imposed in libraries (7). These are based on some reliable research on the rate of aging of paper. We can say with considerable confidence that the durability of a single sheet of paper is vastly improved if it is kept cool and dry. The degree of coolness and dryness that can be imposed to the benefit of the document apparently has no limits. On the other hand, readers don't like being cold, and a low relative humidity makes paper brittle and warps laminated materials. Therefore, no absolutely best condition for paper can be obtained in the everyday world. The building climate which is specified, and may be attained, will be a compromise based on the interplay of numerous factors whose relative importance will vary from library to library.

Temperature

Coolness greatly extends the life of paper (8). The ability of people to endure a cool reading room is limited, however. This limit seems to be about 21° C in the United States, but apparently Europeans are hardier, and temperatures down to 18° C are acceptable. In tropical climates people may find 21° C rather cool for sitting and reading. For good conservation, one should strive for the lowest possible air temperature. A moderately high relative humidity and still air allow the lowest comfortable air temperature. Discreet use of radiant heaters allows a further reduction in air temperature, but books also absorb the radiant heat, and so there will be some local lowering of the relative humidity. There is a natural limit to the temperature that can be imposed in a building by orthodox air-conditioning. This limit is set by the lowest dew point that can be obtained. The minimum value is around freezing, because below this the cooling coil will become obstructed by ice. If a relative humidity of 50 percent is specified, for example, the minimum room temperature will be about 10° C.

Air of lower dew point can be obtained by adding an absorption dehumidification stage to the air-conditioning system. Two methods are available. One method, which uses a lithium chloride solution to absorb water vapor, is not recommended because failure can be catastrophic. If the air stream becomes contaminated with lithium chloride for any reason, the salt will deposit as a liquid film on the collection. This deposit can be removed only by washing each document in water. The other method is to pass the air through granular silica gel, which takes up water by physical adsorption. The exhausted silica gel is regenerated by warming it in an air stream of low relative humidity. This method is reliable. The only danger comes from the tendency of silica gel to disintegrate into dust as it repeatedly wets and dries, particularly if the water absorption stage is allowed to go too far by a malfunction of the control system. More durable silica gel is becoming available, but it is advisable to have a dust filter downstream of the dehumidifier.

The latter system is, of course, more expensive and more complicated than the usual air-conditioning for peoples' comfort, but it can work reliably and allows storage at low temperature. There is again a natural temperature break, which is set by the temperature at which water will condense from the warm air of the inhabited parts of the building as it cools against the walls of the cold area. Let us assume that the office and reading areas are at 20° C and 50 percent relative humidity. This air has a dew point of 9° C. A cool storage vault that is below this temperature will have to have airtight insulation to prevent condensation, a construction that requires refrigerator technology and is quite expensive on a large scale. The other solution is to have a building that is a system of boxes within boxes, each one cooler than the one outside it. Such a building design is quite practical, and indeed a system of concentric zones for different purposes is sometimes the only solution to condensation problems which can afflict the outer wall of the building, as we shall see later.

It seems that cooling paper below freezing causes no physical disruption by ice formation if the paper was at equilibrium with a moderate relative humidity at normal room temperature. The evidence comes from experiments on the nature of water in wood fibers rather than from empirical experiments on repeated freezing and thawing of paper (12).

The technology of cold storage differs considerably from normal air-conditioning practice. Usually much less outside air is drawn in, because people do not work within. For museum use, a free-standing pollution absorber is needed within the enclosure.

The retrieval and re-storing of documents that are normally kept rather cold demands an inconvenient ritual. Thermal equilibration must be achieved without significant migration of water through the paper. The book must therefore be put into an airtight container before removal from cold storage and allowed to equilibrate to the higher temperature of the reading room before it is removed from the container, a process that takes about an hour. The danger is greater during re-entry into the cold chamber. Water may distill from the warm book and condense on the cold sides of the airtight container. This water can then dribble down and migrate into the paper, causing staining. The temporary transfer container should therefore have a water absorbent lining, and cooling must be gradual.

Relative Humidity

We have reliable evidence that a low relative humidity retards the deterioration of paper (8). A low relative humidity also makes paper brittle. This brittle state is not harmful if the paper is not handled in this condition and the stiffening effect is completely reversible. Embrittlement of an irreversible kind is characteristic of chemical degradation of paper by oxidation or hydrolysis. Because the two effects are similar to the hand, the two phenomena are confused, and people talk about desiccated paper when they are in fact talking about decayed paper of near normal water content.

There is really not much scope for aiding the preservation of paper by imposing a low relative humidity. A sheet of paper may be dried without catastrophic effect, but books react differently. They are made of different materials laminated together. As the relative humidity is lowered, these materials change their physical properties in different ways. Paper and leather will shrink and stiffen. Paper will shrink differently in different directions. Cloth, on the other hand, will expand in area as the relative humidity diminishes. Glue becomes extremely hard and brittle as it dries. These materials working against one another cause book covers to warp. These effects are not yet documented by reliable published data. Apparently a relative humidity below about 35 percent is rather risky. The upper limit for good conservation is set by the danger of mold growth at about 70 percent RH. Within this range the deterioration rate of paper seems to vary by a factor of between 2 and 4. The damage done by handling dry and stiff, rather than damp and pliable, paper is very difficult to quantify. At high relative humidity the various materials continue to expand at different rates, but they are much more forgiving to each other and will creep and deform to reduce the stresses caused by movement. I believe that within the limits of 40-60 percent relative humidity the choice should be controlled by the local climate and by the nature of the outer wall of the building, as I will explain later. It is better to have a constant relative humidity within this range than to strive towards an ideal relative humidity which can only be obtained in some seasons of the year.

Different parts of the building can have different levels of relative humidity. Buildings that are vulnerable to winter condensation should have offices around the perimeter in which a low relative humidity, down to 25 percent perhaps, is maintained in winter, with the collection confined to an inner region with higher relative humidity. It is not advisable to move books from air at one relative humidity to another environment that is more than 5 percent different in relative humidity because changing the equilibrium moisture content of a book is a very slow affair indeed. It takes weeks, rather than the hours needed for temperature equilibrium. If books have to be subjected to sudden changes of relative humidity because of the way the library operates, it is much better to have a rather high general level, around 60 percent, because climate changes at high relative humidity are much less traumatic for the book.

I strongly recommend a uniform relative humidity throughout the stack and reading area. The natural tendency of the air-conditioning system, as of the outside world from hour to hour, is to operate at a constant dew point. This means that in a single duct system every room must be at the same temperature to be at the same relative humidity, unless special provision is made by installing a secondary humidifier in the branch duct leading to a room. This allows a room to be at a higher temperature. Such local humidifiers are often inserted because the specification calls for very tight limits on relative humidity variation. These devices, so close to the room, can cause rapid oscillation of relative humidity about the set value, which is surely as harmful as an occasional slower wandering from the specified value. Such a local humidifier can cause trouble in another way: If the room humidistat calls for more humidity, the steam injector in the duct will add moisture. The dew point of the room air will increase and may exceed the temperature of the duct, which is carrying cool air. Condensation on the outer surface of the duct will drip into the room.

It is important that the curator understand the consequences of setting close tolerances on the climatic variation allowed. A less onerous specification, combined with some of the passive climate control methods discussed later, may well give a more reliable total system.

As a postscript to these separate discussions on the effects of temperature and of relative humidity, a comparison of the preservative effects of low temperature on the one hand and of low relative humidity on the other is of interest. The dew point attainable in a building is dependent on the technology of the device used to cool the air. Once a design dew point has been defined, one has a certain freedom in the choice of temperature, or of relative humidity, but not of both independently. For example, air at a temperature of 22° C and 33 percent RH has the same 5° C dew point as air at 12° C and 62 percent RH. The damage done by the high temperature of the first set of conditions is offset by the preservative effect of the low relative humidity. It seems from the slender evidence available that the low temperature-high relative humidity alternative gives better preservation (8).

People have a great tolerance for low relative humidity with little tolerance for low temperature, while books have a great tolerance for low temperature with little tolerance for low relative humidity. For a design dew point of 5° C a good compromise would be a room temperature of 18° C with a relative humidity near 42 percent. Cold storage vaults in the same building should be held slightly below 42 percent RH, depending on the temperature, so the moisture content of the paper does not change when a book is withdrawn and warmed up to the reading room temperature.

Effect of the Indoor Climate on the Building Envelope

Let us turn now to the extremely important but rather neglected subject of the influence of atmospheric moisture on the building (9). The problem can be simply stated, but not so easily solved. If the air inside the building has a higher dew point than the outside temperature, and if it diffuses or flows through the wall, then somewhere within the wall condensation will occur. The process is exactly the same as condensation on windows, but since it is invisible, it is presumed not to happen, or at least not to matter. In fact, the window condensation is sometimes the less harmful event. Moisture in walls, and in roofs, can cause serious damage very quickly. Old buildings are vulnerable because they have no provision for preventing the diffusion of air through walls. New buildings are vulnerable because they are well insulated so that the interior surface of the outer skin of the wall is close to the outside temperature. The results of condensation can be increased corrosion of metal fastenings within the wall; movement of soluble salts, whose recrystallization physically disrupts the masonry; and frost damage from the expansion of ice lenses within the wall. In continental climates, these conditions pose a serious threat to buildings.

Vapor barriers are customarily installed to prevent diffusion of water vapor through the wall. They seldom work as intended, because they are rarely installed carefully enough. The barrier must be airtight. If it is not, it will allow some air through to deposit dew in the wall, and then it will inhibit the free air circulation that would, in warmer weather, evaporate the water.

Old buildings are generally not worth making airtight. A thorough survey can give reason for optimism, however. Thick, porous, salt-free masonry walls are not unduly vulnerable if they do not have iron cramps within them. Some old buildings faced with porous stone have an impermeable backing to the stones, originally put there to prevent salt migration from brick work. I am not suggesting, therefore, that old buildings can never be humidified to counter the desiccating effect of warmed winter air, but it must be done cautiously, and after a thorough structural survey.

One welcome side effect of running a building cool is that this danger of condensation in the walls is much reduced. Not only is the dew point lower, but the amount of water vapor carried by a given volume of air diminishes sharply with temperature so that the damage done by cool humid air diffusing out to a very cold outside wall surface is very much less than the damage done by warmer air diffusing out to a surface that is an equal number of degrees below its dew point.

As I mentioned before, air-conditioned buildings are customarily operated at a slightly raised pressure so that any leakage will be of conditioned air outwards rather than of raw outside air inwards. This pressure difference is designed into the system; it is seldom imposed by active measurement and control, although there is no reason why this cannot be done. It is advantageous to run a building which is in a cold climate and is humidified to more than 35 percent in the winter at, or slightly below, atmospheric pressure. This procedure will not solve the condensation problem entirely, because it is quite possible for air to be entering the building from outside in one place, but for another part of the wall to be exposed to inside air. This phenomenon is very common in buildings with high open interior spaces such as domes. The warm, moist air within the building is less dense than the cold dry outside air and so it tends to rise, escaping from the roof while outside air enters down below.

Another phenomenon operates in buildings with cavity walls. The general air flow may be inwards, but the air entering the wall will move sideways in the cavity towards fissures in the inner wall. Water vapor diffuses through the pores in the inner wall and crosses this cavity air stream diagonally to condense on the outer leaf of the wall.

In summer a danger is the condensation of moist, warm outside air near the inner surface of the wall. This air may be moister than you might suppose from the local weather report because an additional burden of water vapor can be coming from evaporation of water that has condensed during the winter. The evaporation rate increases dramatically at the high temperature reached within a sunny wall or roof on a warm day. This spring re-activation of water accumulated over the winter can produce spectacular flows of condensate.

A building that is not airtight and is in a place with cold winters and hot summers should be operated at a positive pressure during the summer and at a negative pressure during the winter. This seasonal change in operating pressure of air-conditioning systems is never deliberately used, as far as I know, but it is undoubtedly helpful to the preservation of the building. I discovered this when modifications to the air-conditioning system of a museum building unexpectedly altered the direction of air flow and dramatically reduced the winter condensation within the walls.

The relative humidity and temperature limits are thus set by the method of construction of the building and by its local climate. There is no easy way to predict the performance of an individual building, nor is it easy to measure the direction and vigor of air movement within the walls and roof.

Buildings that are vulnerable to damage by condensation should have sensors buried in the walls and roof to record the state of the climate within the structure. Only a few studies have been published on this subject (5, 9), but the growing practice of humidifying museums and libraries, and modern trends in insulation for energy saving, no doubt combine to cause damage to buildings in cold climates.

In continental climates the best argument for maintaining a low winter relative humidity is the preservation of the building rather than the preservation of the paper within it, although one must not forget the damage done by low relative humidity to furniture and panelling. In humid summer weather the burden of maintaining this constant low relative humidity becomes very expensive. It seems reasonable, therefore, to allow the relative humidity to change slowly through the seasons between limits that should not exceed 35-62 percent. Books take a very long time to re-equilibrate to a different relative humidity and the stresses imposed by the transient uneven moisture content are not beneficial, so a very slow seasonal change should be imposed.

Passive Climate Control

We have no doubt that books should, if possible, be kept in a constant climate. Much can be done, however, to safeguard collections without the benefit of the mechanical and electronic systems that I have described. Fortunately, books and documents are rather easy to care for in less than ideal climates. The first basic principle is to put them in a set of nearly airtight and close-fitting enclosures. The second principle is to prevent rapid temperature change around the collection.

The effect of enclosure, apart from its obvious role in excluding dust, needs some explanation. The physical properties of paper, such as its dimensions and its stiffness, depend on the moisture content, which is usually around 6 percent. This water is loosely bound and will be lost to surrounding air of low relative humidity. More water will be absorbed if the surrounding air has a high relative humidity. If the air surrounding the book is isolated from the rest of the atmosphere and if this air volume is kept small compared with the volume of the book, then this exchange of water will be very small, because, although the relative humidity of an isolated volume of air will change with temperature, the amount of water that has to move from book to air, or the other way, to maintain the equilibrium is entirely negligible. The book regulates the moisture in the air trapped around it (11). Some complicated movements of water can occur on a small scale if a temperature gradient exists across the enclosure. Good thermal buffering is important and can be achieved by insulation, by close stacking of the books, by massive construction of the building, and by keeping the book stacks away from outside walls, or the walls of furnace rooms.

A slow change in air temperature that causes no steep temperature gradients around a book does no harm. A sudden upward temperature change is not too damaging either. If a book in a container is suddenly cooled, condensation will occur when the walls of the container drop below the dew point of the air within. The book will release to the air more water vapor to compensate for that lost, and a rather large amount of water will condense and drip on the book or flood the bottom of the enclosure. From there it will re-evaporate, setting up a cyclic process that will stain the book. This effect is well demonstrated by the glass-fronted boxes fixed to the walls of restaurants. If the menu is not changed frequently in winter, the passing gourmet will soon notice a stain creeping upward past the dessert list.

A very similar affliction can damage books in cases against uninsulated outer walls. The cold of a winter night can cool the back of the case, while the books remain warm because the glass front readily transmits the heat of the room. The books maintain the relative humidity of the air in the container. This condition is normally a virtue, but now it becomes a source of danger, as the condensed water dribbles invisibly down the back of the bookcase. Less dramatically, but more often, the relative humidity close to the cold back will only rise to some value above 70 percent, which allows dormant fungal spores and filaments to become active.

It is dangerous to allow the temperature of any part of a book stack to fall much below the temperature of the main body of air in the room because a roomful of air quickly achieves a uniform moisture content by convective mixing. If the temperature differs from place to place, the relative humidity must vary also. Cold walls have a boundary layer of cold air close to them which does not so readily mix into the general air circulation in the room. If water is rising in the wall, or penetrating through a porous wall, the moisture content of the air may locally be high. The two independent effects combine to give a dangerously high local relative humidity. The intermediate technology solution to this situation is to scour away the boundary layer with a draft from a fan. The permanent solution is to put insulation on the wall and cover this with an impermeable membrane.

If the average climate outside the library is within the limits set for good conservation, that is, less than 25° C and between 40 percent and 65 percent RH, then no great harm will come to collections that are not air-conditioned. Some seasons of the year, however, may be beyond these limits. The buffering capacity of the passive climate control measures described above may be exceeded, and the climate within the containers will drift towards a dangerous condition (1). Air-conditioning, even of a simple kind, then becomes essential. It may be that small free-standing humidifiers or dehumidifiers will cope with these brief seasonal periods of danger.

Much can also be done by adjusting the environment near the building. Pale paint reduces heat gain in the sun. Trees will do the same, eventually. Grass surroundings will reflect less solar energy onto the façade than will a marble concourse. The adjustment of the microenvironment, which is one of the more enjoyable fantasies of the ecological movement, can tip the balance for buildings that are not in extreme climates.

For libraries not yet built, we can rethink the whole concept of library design. On the whole, the custom of building massive, prestigious shrines to learning has served the cause of conservation well. Their natural temperature stability leads to good relative humidity stability because the daily fluctuation in atmospheric relative humidity is mainly caused by the daily temperature cycle. The moisture content of the air changes less often since it is controlled mainly by the direction of origin of the air mass that covers the region. More radical solutions are available, however, such as partial, or nearly complete, burial of the building. Existing buildings can be adjusted, for example, by installing a ventilated attic space to reduce heat conduction through the roof and to prevent roof condensation in a humidified building. Finally, in this varied collection of measures to modify the indoor climate, one should not neglect the pleasure that can be obtained from air-conditioning devices. An ornamental fountain in the lobby can be used to humidify, or to dehumidify the air, according to the water temperature.

Air Pollution Originating Within the Building

Much has been written lately on the subject of air pollution generated indoors (10). In libraries the important pollutants are formaldehyde, formic acid, and acetic acid emitted by wood, particularly plywood and particle board. Some humidifiers release gases into the air, such as diethylaminoethanol, which are used to inhibit the corrosion of steam pipes. This chemical is a hygroscopic alkaline vapor which probably reacts with the acid pollutants in air to form nonvolatile salts, which precipitate as a slimy film on surfaces. One unusual hazard in libraries is the oxides of nitrogen released by the pyroxylin cloth used to cover books.

Damaging chemicals are also released within books, but climate control cannot cure this problem because the molecule will react long before it can diffuse out from the book. We are concerned, therefore, about chemicals that emerge from the container and from the outside surface of the books. Wood should really not be used in libraries, but, of course, it will continue to be used and to survive, so the collection must be protected against its outgassing. Various techniques can be used, depending on the circumstances. Fierce ventilation is the traditional, but not now popular, method. Some research is in progress on the efficiency of various surface coatings. Until results of these studies are released, a layer of aluminum foil is recommended as an impermeable barrier, or a layer of paper impregnated with calcium carbonate, which will react with the mainly acid gases emitted from wood. This paper should also catalyze the transformation of formaldehyde into formic acid and then react with the product, but research has not yet demonstrated that this reaction actually takes place.

If the container is lined with foil or alkaline paper in this way, it seems that tight containment of books presents less danger than exposing them to the room air. It certainly ensures a constant climate. For those who are not convinced by these arguments, even a permeable container such as an ordinary envelope slows down fluctuations in relative humidity, reacts with pollutants, and gives useful protection to the contents.

Conclusion

The influences on paper storage of climate, building methods, air-conditioning technology, pollution chemistry, and reader comfort are varied and intertwined. In such a complicated environment reliance on an arbitrary set of standards can lead to great expense and ultimate failure if the standards prove impossible to realize in a particular geographical and social environment. Each institution must be regarded as a unique system for which a unique compromise must be developed by intelligent study. A knowledge of the principles which underline the standards and codes of practice that have been developed over the years is essential.

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ZUSAMMENFASSUNG – Das Klima, das in einer Bibliothek aufrechterhalten wird, ist das Ergebnis eines Kompromisses zwischen den klimatischen Bedürfnissen der Leser und der Mitarbeiter, den klimatischen Bedingungen der Gebäudestruktur, der Notwendigkeit, die Zerfallsrate der Sammlung minimal zu halten, und den Wartungserfordernissen und Betriebskosten einer mechanischen Klimaanlage. Passive Klimasteuerung mit Hilfe eines gut durchdachten Entwurfs eines Aufbewahrungsbehälters und durch Verlangsamung des Hitze- und Feuchtigkeitstransfers durch Wände, erlaubt einfachere Klimasysteme, die problemloser sind, deren Betriebskosten niedriger liegen und die weniger gefährlich sind, wenn sie ausfallen. Herkömmliche Klimaanlagen können Luft mit einem Taupunkt von ungefähr 5°C erzeugen, was ermöglicht, dass im Gebäude eine Temperatur von 18°C und ungefähr 42 Prozent relative Luftfeuchtigkeit(RL) aufrechterhalten werden können. Eine niedrigere Temperatur kann nur dann erreicht werden, wenn die relative Luftfeuchtigkeit erhöht wird oder umgekehrt. Ein niedrigerer Taupunkt kann erzielt werden, wenn die Luft mit einem Silikageltrocknungsmittelsystem nach anfänglichen Wasserentzug mit einer Kühlschlange getrocknet wird. Jedoch sind gebundene Bücher physischem Schaden ausgesetzt, wenn die RL unter etwa 35 Prozent liegt, und den Personen ist es zu kalt, wenn die Temperatur weniger als 18°C beträgt. Deshalb sind kältere oder trockenere Bedingungen nur für sorgfältig isolierte Lagergewölbe geeignet, in denen nur wenig Luft zirkulieren muss. Die relative Luftfeuchtigkeit in Gewölben sollte ein wenig unter der im Lesesaal liegen, so dass der Feuchtigkeitsgehalt des Buches sich nicht ändert, wenn dieses für den Leser erwärmt wird. Eine stabile relative Luftfeuchtigkeit ist wünschenswert, jedoch kann der Wert innerhalb der Begrenzung von 40 bis 62 Prozent gewählt werden, um die Eigenheiten des Klimas vor Ort und des Gebäudes in Betracht zu ziehen. Gebäude, die im Winter befeuchtet werden, können durch Kondensation und gefrorenes Wasser in den Wänden beschädigt werden. Plötzliche Veränderungen der relativen Luftfeuchtigkeit können vollständig verhindert werden, indem Bücher in enganliegende, fast luftdichte Behälter eingelegt werden, die sicher sind, falls es kein ständiges Temperaturgefälle von einer Seite zur anderen gibt, und die Temperatur im Umfeld nicht plötzlich absinkt. Die geringe Gefahr von lokal erzeugter Luftverschmutzung kann verringert werden, indem innere Holzoberflächen versiegelt werden und alkalisch gepuffertes Papier in die Kästen und Regaleinlagen eingelegt wird.

RESUME – Les conditions climatiques maintenues dans une bibliothèque sont le résultat d'un compromis entre les besoins climatiques du lecteur et aux du personnel, les besoins climatiques du bâtiment, le besoin de réduire le taux de détérioration des documents, les obligations d'entretien et les frais de fonctionnement de la climatisation mécanique. Un contrôle climatique passif par le choix de containers conçus à cet effet, par la diminution du transfert de la chaleur et de l'humidité au travers des murs, tout ceci permet un système de l'utilisation de l'air plus simple, moins problématique, moins cher et moins risqué en cas de défaillance. Les systèmes conventionnels de climatisation peuvent produire un point de rosée d'environ 5°C, ce qui permet une température stable dans le bâtiment de 18°C et 42 pour cent d'humidité relative. L'on peut obtenir une température plus basse en élevant l'humidité relative ou vice-versa. Un plus bas niveau d'humidité peut être obtenu en asséchant l'air par un procédé de dessication au gel de silice après une déshydratation initiale grâce à une spirale réfrigérante. Cependant, en dessous de 35% d'humidité relative, les livres reliés peuvent être endommagés et les êtres humains ressentent le froid en dessous de 18°C. Ainsi donc, des conditions climatiques plus froides ou plus sèches ne peuvent être pertinentes que dans des coffres d'entreposage soigneusement isolés, dans lesquels seul un minimum d'air ne circulera. L'humidité relative des coffres devra être maintenue un peu en dessous de celle de la salle de lecture afin que le niveau d'humidité du livre ne change pas lors de son réchauffement pour le lecteur. Une humidité relative stable est souhaitable, mais ses paramètres peuvent être choisis, dans les limites de 40-62 pour cent, pour prendre en ligne de compte les particularités du climat local et celui du bâtiment. Les bâtiments humidifiés en hiver peuvent être endommagés par la condensation de l'eau et le gel à l'intérieur des murs. Un changement subit de l'humidité relative peut être totalement prévenu par le dépôt des livres en containers de taille adéquate, étanches, qui sont sûrs si les changements de température ne sont pas extrêmes ni permanents. Le danger, bénin, de pollution locale, peut être réduit en scellant les surfaces intérieures en bois et en incorporant du papier de type alcalin dans les boîtes et le revêtement des étagères.

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