KW. Series 4

17251

THE DANGERS OF INSTALLING AIR CONDITIONING IN HISTORIC BUILDINGS

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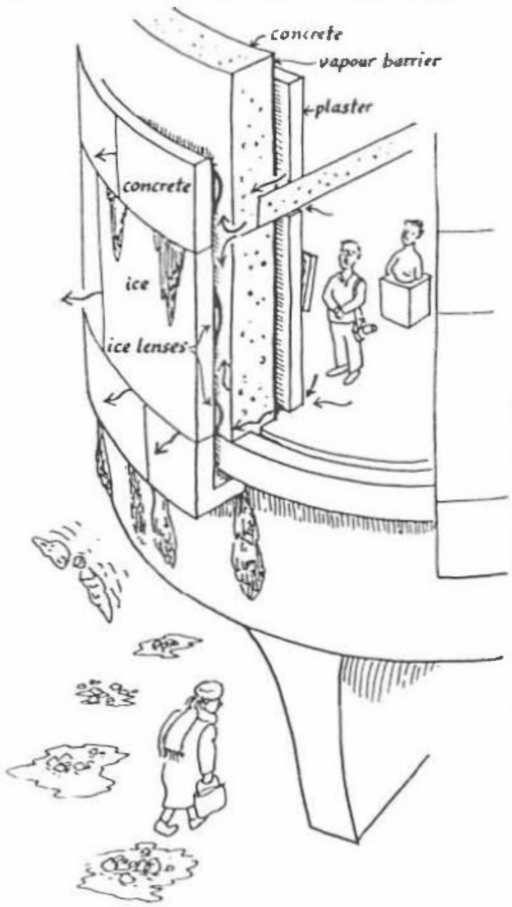
When air conditioning is installed in a historic structure a large difference in temperature and in water vapour concentration develops across the walls and roof during certain times of year. There is then a serious danger of condensation and of soluble salt movement within the wall.

The physics of the process at its simplest is illustrated by the winter condensation within the wall of the Hirshhorn Museum in Washington DC. The interior of this building is maintained close to the present informal climate standard for museum galleries in the USA: 21°C and 50% relative humidity. The building is pressurised so that polluted air from outside does not penetrate to contaminate the filtered air inside. Inevitably, some air flows out through the walls. During the winter the air cools during its journey through the wall. The moisture content of the air remains constant, or nearly so, until the temperature reaches the dew point. This is the temperature at which the vapour pressure of the water in the air reaches the saturation value. As the temperature drops below the dew point water condenses out of the air onto nearby surfaces. The dew point for air at 21°C and 50% RH is 10°C.



The night temperature in Washington during the three coldest months of the year is often below 10°C. Condensation therefore happens frequently in the walls of the Hirshhorn Museum. Figure 1 shows the result on a particular day in early spring. The night had been cold so that ice formed behind the outer skin of the wall. The morning sun warmed the wall so that the ice melted. The melt water dripped down and emerged at weep holes. On the outside the water re-froze because the breeze was brisk and the air was dry, so that the water cooled by evaporation. This secondary ice clung to the surface of the wall until a general warming of the air caused it to melt and fall onto the concourse below. The impressive quantity of shattered ice showed just how much water had accumulated during one night.

Figure 1. The Hirshhorn Museum, Washington DC.

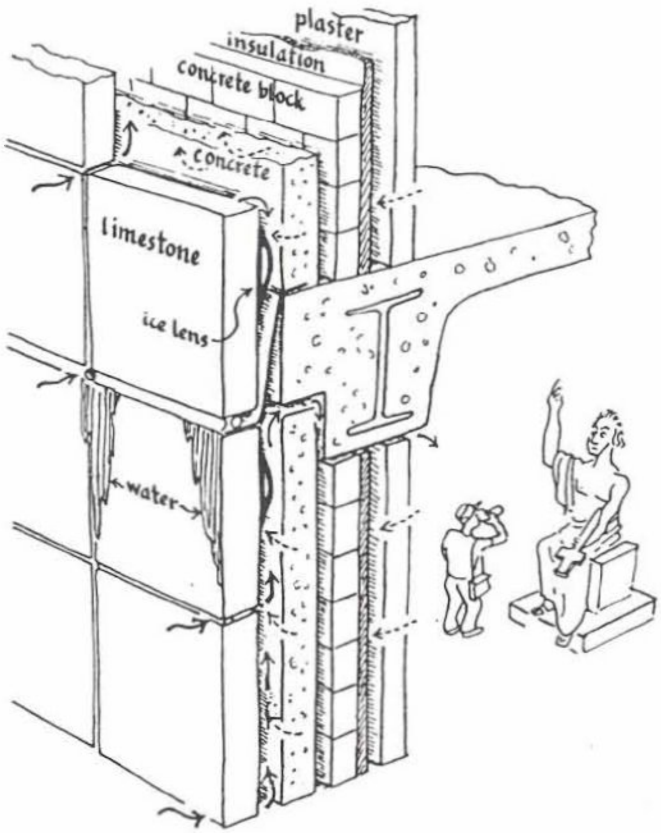


Figure 2. The National Museum of American History, Washington DC.

The National Museum of American History (Figure 2) also shows streaks of meltwater emerging from the limestone facade on sunny mornings after cold nights. This building operates at a negative pressure and so there is a flow of air from the outside into the building. The outside air in winter has a rather low moisture content and could not possibly be the cause of the weeping evident on the facade. The most likely explanation is that the construction of the wall causes the infiltrating air to move sideways through the cavity behind the facing stone until it finds a crack which allows it to pass through the concrete inner wall. During this transverse air movement water vapour from the inner wall, derived from the warm and humid inside air, moves diagonally across the gap to condense on the inner surface of the outer wall.

The Museum Support Center of the Smithsonian Institution provides an instructive example of the effect of air pressure differences. This building began operating with a positive inside pressure but after two years some equipment was installed that resulted, unintentionally, in a negative pressure inside. The ice formation inside the walls diminished after this change but still some parts of the wall suffer winter condensation through outward penetration of inside air. During the summer the outside air penetrates the wall and deposits dew on cool surfaces within the wall. An investigation of the wall suggested that air flows along definite paths through the wall, leaving some parts isolated from the influence of the air stream, or even seeing diffusion of moisture from the opposite direction.

One might assume from these examples that damage to buildings could be ameliorated, though not prevented, by dropping the pressure below atmospheric in the winter and raising it above atmospheric pressure in the summer. This can be done in buildings that have no tall interior spaces. In a tall building the natural buoyancy of warm, moist air will exert an outward pressure on the roof while cold winter air is being drawn in at the door below.

It is very difficult to prevent the movement of moisture from a humidified interior to the cold skin of the building. A vapour barrier only works if it is airtight and prevents the flow of air. If it is not absolutely airtight it can cause damage rather than prevent it. For this reason the necessarily incomplete application of impermeable materials to old buildings is dangerous.

These first examples have been modern buildings. Their walls contain only inorganic materials with a limited ability to absorb and desorb water. In this respect they are similar to ancient masonry walls. Many buildings contain hygroscopic materials such as wood, particularly in the roof. These materials complicate the response to moisture because they absorb and desorb water according to the relative humidity of the air that surrounds them.

The Arts and Industries Museum of the Smithsonian Institution is next door to the Hirshhorn Museum. The roof was made of sheet metal laid over wooden laths with plaster infill which in turn rested on a metal ceiling supported on iron trusses. This roof was replaced, after about a century of service, in the late 1970's. The new roof (Figure 3) was designed to be installed without removing the exhibits from the galleries below. It was therefore made in prefabricated box sections so that parts of the roof could be stripped and re-covered during a working day. The roof was to be insulated to modern standards of energy efficiency, but had to be no thicker than the uninsulated roof that it replaced. It had to be fireproof to modern standards. All these demands, combined with the power of modern equipment to maintain a warm, humidified atmosphere within during the winter, caused trouble that was only diagnosed by placing sensors in the roof and by conducting a laboratory simulation of the condensation process.

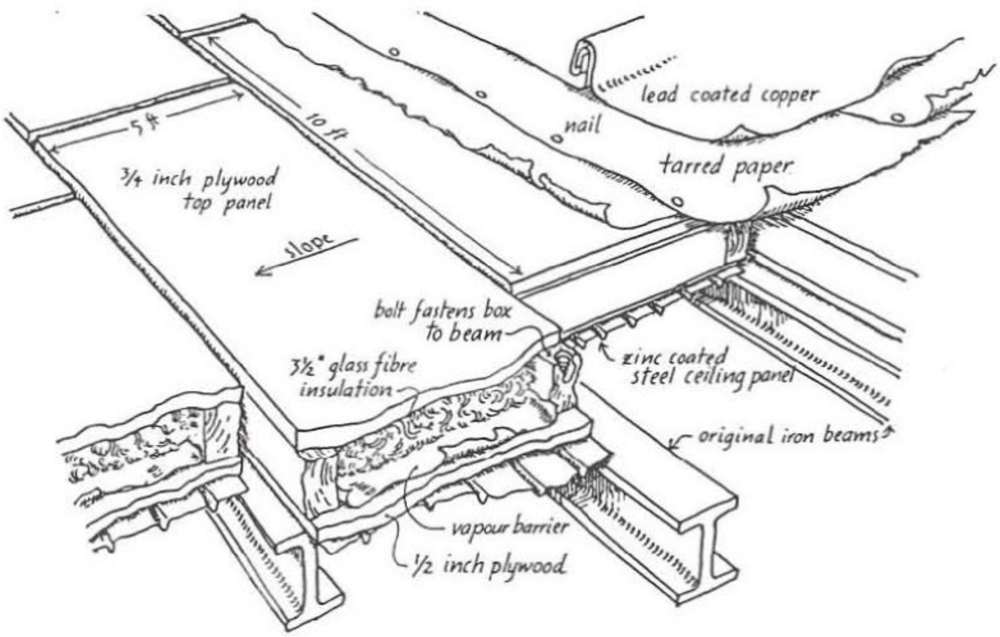


Figure 3. Roof design of the Arts and Industries Museum.

The new roof certainly kept the rain out and the heat in but it soon showed one unfortunate defect: rain poured into the galleries during warm, cloudless, sunny weather in spring. The reason for this clear weather precipitation is sketched in Figure 4. During the winter (on the left) the warm, humidified interior air penetrates into the roof sections, cools as it passes through the porous glass fibre insulation and deposits dew on the plywood that supports the sheet metal roof skin. The wood absorbs the water so no condensation is apparent during the winter. The water absorption is enhanced by the fireproofing salts in the wood which form a saturated solution when the air reaches a relative humidity of about 80%.

During the early summer (to the right) the sun heats the grey metal of the roof to 75°C. The wood below the metal becomes warm and the water stored up during the winter is vapourised into the insulation. It diffuses down to the vapour barrier and there condenses, because the cool interior of the building is below the dew point of the moist air which originates at the under surface of the heated wood. The vapour barrier is made of polyethylene film, which is hydrophobic so that the water collects as discrete drops on the surface. There is still no indication of trouble within the roof. After about three days of warm weather so much water has accumulated on the polyethylene that the drops begin to run together and quickly gather into a torrent which runs down the slope of the roof until it meets the lower edge of one of the box sections. Here the vapour barrier stops and the water passes over the lower plywood layer of the box, dissolving the fireproofing salts. The surge of contaminated water now escapes from the box and falls on to the metal ceiling and then into the gallery below. The process is dramatic and seemed at first to be very mysterious, particularly as eye witnesses described clouds forming in the tall rotunda at the centre of the building!

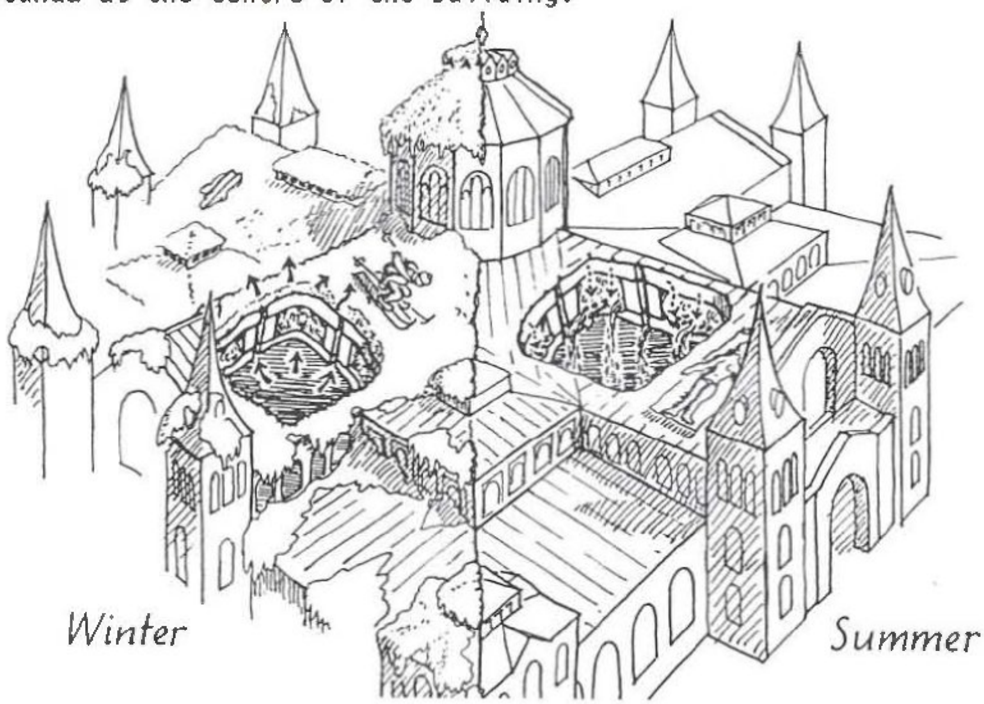


Figure 4. The condensation process in the roof of the Arts and Industries Museum, in winter and in summer.

In all these examples the structure of the part of the building which causes trouble is fairly uniform. Even though the cracks play an essential part in the processes, they are evenly distributed within a basically uniform section.

Buildings in more highly decorated styles of architecture present other problems. Here I will use as an example yet another of the Smithsonian Institution's buildings, The Renwick Gallery, near the White House in Washington. The sandstone facade on the brick wall of this building had been crumbling for many years. Two years ago the Institution completed a thorough renovation of the building. The original stone was evidently not durable and the original quarries are now inaccessible. An international search failed to turn up a quarry that could provide stone with a close match in appearance and a guarantee of better performance, so the facade was rebuilt with blocks of cast stone made from tinted concrete.

The damage was attributed, in part, to movement of salts from the massive brick wall into the stone facing, which was not protected by an impermeable layer. To prevent salt movement the wall was reconstructed with an air gap between the original inner brick wall and the new facing blocks of concrete. Stainless steel pins separate the two parts of the wall. Sensors were embedded in the walls as they were rebuilt so that the climate within the structure could be monitored for several years to demonstrate the success, or to warn others against the defects of the design.

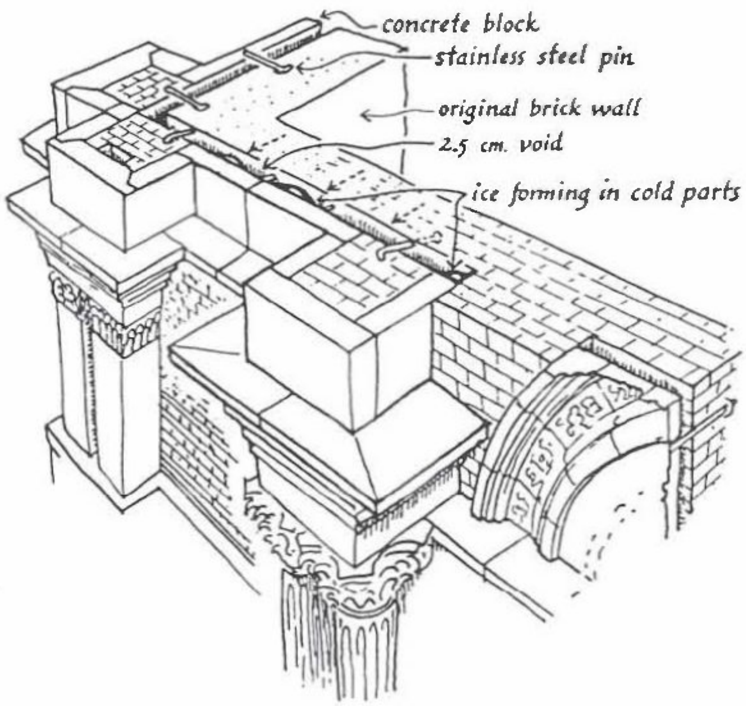


Figure 5. The wall construction of the Renwick Gallery.

The void that separates stone from brick does not exactly follow the contours of the outer surface, so it is at a different temperature at different points. The air in the building is humidified in winter. This air penetrates the wall, which has no vapour barrier. In the colder parts of the void it will deposit dew. Air diffusing into the warmer parts will be able to circulate through the void to supply more dew to the cold points. There is therefore an accumulation in a few cold spots of water that has penetrated the wall over a large area. A small, uniform leakage of air through the wall can therefore result in serious damage in a few places (Figure 5).

These case histories show that it is very difficult safely to install air conditioning that provides adequate relative humidity for the display of artifacts, in buildings which are set in climates that impose a real need for air conditioning. The fundamental problem is the large difference in air temperature and in air moisture content between the inside and the outside. Only a rather unusual and expensive design can provide a new building with adequate defences; for an old building it is hardly ever possible to add an adequate barrier to air flow.

Clearly we cannot just adapt an old building to museum use by installing the standard industrial air conditioning plant. We have first to survey the building and study the local climate records to estimate the likely danger from condensation. Then we have to draw up a specification for the absolute limits to variation in temperature and relative humidity of the interior. The two are linked by the need to keep the dew point of the inside air low in winter. The outside temperature and relative humidity determine the minimum summer temperature that can be imposed inside. The specification for the interior climate will also be influenced by the nature of the collection and it may not be the same for all parts of the building. For a general collection the limits would be a relative humidity between 35 and 65 percent with a slow drift within these limits. The temperature should usually be held below 28°C but above the weekly average dew point of the outside air in summer.

For people the relative humidity can be quite low without discomfort. The minimum temperature for comfort is about 18°C. The winter climate is therefore set by the need for a relative humidity above 35%, for the objects, and a temperature above 18°C, for the people. The summer temperature is set by people's discomfort working above 26°C. If there are no people permanently stationed in the building the problem is solved because the temperature can be allowed to drift down in winter to maintain a low dew point and to drift up in summer to stay above the outside dew point. It is the demand for a comfortable winter temperature for people with a comfortable relative humidity for objects that is the main cause of trouble.

The best solution is surely to draw on the experience shown in local adaptation of architecture to climate and add to this the extra means of control conferred by modern technology, using not just the mechanical devices but also such innovations as accurate medium term weather forecasts so that the air conditioning can anticipate cold weather and cause a controlled fall in the indoor temperature. In this way we can enjoy the satisfaction of an intelligent response to the variability of the natural world.

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I was helped in this research by Robert Ridgley and Gary Brenner of the Smithsonian Institution's Office of Design and Construction and by John Frieman and Deborah Spenser, both formerly at the Conservation Analytical Laboratory.

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ABSTRACT

Condensation within walls and roofs of buildings in a cold climate is an inevitable consequence of warming and humidifying the air within them because the dew point of the air inside the building is, for several months of the year, higher than the temperature of the outer surface of the building. The vapour barrier which is often installed to prevent diffusion of humidified air into the walls is not usually able to prevent transfer of moisture through air flow caused by the buoyancy of warm humid air in a tall building or by the pressure difference generated by the air conditioning equipment. The museum buildings of Washington DC, both old and new, testify to the difficulty of maintaining a humidity within that will preserve the collections without at the same time damaging the building. Sensors installed within the structures have clearly demonstrated the complexity of the patterns of air flow and of moisture transfer. Condensation, ice formation, corrosion and rot in walls and roofs may show no symptoms but still cause serious damage over the years. For historic buildings that house historic collections the specification for the interior climate must be a compromise based on a study of the construction of the building, the local climate and the nature of the collection. In particular it may be necessary to change the interior climate slowly through the seasons to minimise the difference between the inside and outside temperature and water vapour pressure.