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CLEAR WEATHER PRECIPITATION INSIDE A MUSEUM: A CASE STUDY IN MICROMETEOROLOGY

Tim Padfield and David Erhardt

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Tim Padfield and David Erhardt

Conservation Analytical Laboratory
Smithsonian Institution
Washington, DC 20560
USA

Solutions of wood fireproofing salts drip from its roof into the Arts and Industries Building of the Smithsonian Institution. This has occurred on clear sunny days in the spring and early summer since the present roof was installed three years ago. This paper describes how the construction of the roof, the materials used and the local environmental conditions have caused this unusual phenomenon. We describe the techniques used to measure the environmental conditions within discrete layers of the roof. The measurements have not yet followed the roof through its annual cycle, but we propose a mechanism based on data gathered so far.

The Arts and Industries building of the Smithsonian Institution was finished in 1881. It was built as a temporary shelter for some of the pieces from the Philadelphia Bicentennial Exhibition. It continued in temporary use sufficiently long to be put on the National Register of Historic Buildings and its future seemed secure - until it was re-roofed about three years ago. The new roof displays the peculiar property of dropping rain into the halls below during fine summer weather above.

Our investigation of this bizarre phenomenon is not yet complete, but our ideas and the experimental techniques we have developed may interest the reader and we hope to have learned much more by the time of this Ottawa meeting of ICOM Conservation Committee. The problem was first reported verbally by R. M. Organ at the 1980 Vienna Congress of I.I.C. under the title: "Rain within, no rain without: how a roof reversed its role."

The rain is in fact a concentrated solution of fireproofing salts leached out of the roof timber. This is a mixture of boric acid, ammonium sulphate and ammonium dihydrogen phosphate. Evidently some condensation is occurring within the roof but the timing mechanism for the escape of the liquid into the museum halls is a puzzle.

The roof is sketched in fig l. The particular part that gives trouble, the "transitional roof," is marked by hatching. The details of construction are shown in fig 2.

The new roof was designed to match the old in appearance both inside and out and in thickness. It had to be better insulated and fire resistant. It had to be installed without risk to the exhibits below, many of which were massive machines, difficult to remove and store. These various demands forced an unorthodox design.

The roof consists of a set of prefabricated plywood boxes stuffed with insulation. Each box just spans two of the original roof girders. The top layers of tarred paper and lead clad copper sheet were applied after the boxes had been bolted to the girders. This method of construction means that there are gaps in both the vapour barrier and in insulation between the boxes. The copper roof is not airtight, so air can flow through the roof. The boxes will also breathe through the daily cycle of thermal expansion and contraction of the air within. All parts of the roof are therefore exposed to flowing air and will add or subtract moisture according to the local RH, which in turn is defined by the local temperature, the moisture content of the plywood laminae and the rate of diffusion of water through the plywood.

At times the roof becomes so wet that salt solution formed at the wood surfaces migrates upwards through the tar paper layer. The lead cladding on the under surface of the copper roof sheets is badly corroded with a patina of lead borate hydrate, basic lead phosphate and lead carbonate. The zinc coated steel ceiling panels are also corroded and the iron girders are partly covered with an efflorescence, mainly of fireproofing salts. Ammonium dihydrogen phosphate is a good nutrient and so fungal hyphae twine around its crystals on the wood surface.

In winter air always moves outwards through the roof. This is the 'Stack Effect'. The warm, relatively moist air in the building is lighter than an equal column of cold outside air. This warm air will float upwards and escape through the porous roof to be replaced by a flow of cold air through the door. In summer the process reverses. The rate of percolation of air depends on the temperature difference.

Moisture will condense on the roof timber above 80% RH at all normal temperatures. This is a consequence of the hygroscopicity of ammonium sulphate which impregnates the wood. Above about 80% RH this substance absorbs water from the air to form a saturated solution. Even below this RH the salt enhances the moisture absorption of the wood, making it a powerful buffer for atmospheric moisture. One might suppose that condensation would occur first on the salt impregnated wood - but this is not always so. On a cold winter night the outer metal skin becomes so much colder than the top of the plywood that air reaches 100% RH at the inner metal surface before it reaches 80% RH at the wood surface.

Condensed moisture can migrate slowly through the plywood. Moisture taken up from the box cavity by the upper plywood migrates to the upper surface and evaporates to re-condense on the metal skin, often as ice. When the skin warms up the ice melts, the water clings to the metal, flows down the slope and escapes to the outside of the roof through the folded-over horizontal joints. So the roof partially dries itself through a condensation process!

In summer the moisture accumulated in the upper plywood returns to the interior. Air enters the roof and warms above ambient as it passes through the sun heated roof. Its RH drops so the plywood releases moisture to the warm air. Warm moist air is also forced out of the box sections as the top plywood heats up. Remember that moist wood tries to maintain a constant RH in the surrounding air regardless of the temperature. This warm moist air cools as it passes between the box sections to the cool interior of the building. Its RH increases but there is only a small area of wood in its path to buffer the increasing RH. Eventually condensation occurs on the tops of the metal girders which are cooled by the well stirred air inside the building and have become coated with an efflorescence of fireproofing salts.

This multitude of interacting processes makes difficult the accurate diagnosis which must precede any remedial work. We have therefore been forced to make measurements! Our experimental techniques may be of some interest because the measurement of relative humidity in confined spaces has received much less attention than measurements in free flowing air.

There are several physical processes that have been harnessed to measure relative humidity. In a confined space with little exchange of air and good heat insulation some of these measurement processes will themselves affect the RH of the air they are sampling. In a remote, rather inaccessible place the list of suitable RH sensitive processes is further restricted by the need for automatic data collection and long cable runs. We chose one of the group of RH sensors which use the change in electrical resistance of a hygroscopic electrolyte. One suitable and long established sensor is the type PCRCII made by the Phys-Chemical Research Corp. 36 West 20th Street, New York, NY 10011.

The sensor is a polystyrene wafer with a sulfonated surface layer which increases in conductivity as the RH increases because the adsorbed water film allows the sulfonic acid groups to ionize. This surface has two electrodes printed on in an interlocking maze. The amount of water involved in the equilibrium is minute and the sensor does not appreciably alter the RH of even a small volume of still air.

The flatness of our chosen sensor is a great advantage for studying laminar structures but the sensitive surfaces must be held away from other materials, drips and floods. We rolled a sheet of stiff polyester film into a cylinder and stapled it. Another roll of polyester was pushed into this cylinder to prevent the metal staple from short circuiting the sensor. The springy composite cylinder was then squashed into an oval while the sensor was inserted (see fig. 3 for details of sensor construction).

There are calibration problems with these variable resistance sensors and also some complexities in processing the observed resistance of the device into RH. The resistance must be measured by an alternating current circuit - even momentary d.c. will destroy the calibration. Most electronic data recorders insist on a d.c. voltage source. The simple conversion circuit shown in fig.4 uses a stabilized 1.4 v a.c. supply across the sensor and a fixed resistor in series. The voltage across the fixed resistor is rectified by the ac/dc converter and is then sent to the data recorder. The 60 Hz signal can be transmitted over a few hundred feet of cable without appreciable losses.

This sensor is temperature sensitive and the temperature coefficient of the RH itself varies with both temperature and relative humidity. There is a small amount of hysteresis. Nevertheless this sensor, or similar devices which use the resistance change of absorbent surface films with RH, seems the best for this sort of job.

The temperature sensors are copper-constantan thermocouples. They are made of 0.010 inch dia. wire insulated by a bake-on silicone coating and further protected from the corrosive salt solution by a polyethylene sleeving filled with magnesium oxide.

Another vital measurement is the direction of air flow through the roof. We detect this flow in a tube passing through the roof. A thermocouple within the tube indicates either the inside or the outside temperature depending on the direction of the movement of air. All these sensing devices are sketched in fig. 3 together with a drawing of our outside weather station.

The way in which the sensors are disposed through the roof is drawn in fig. 5. Our tentative interpretation of the condensation processes is summarized in fig. 6. We hope to be able to refine this in our final report so there is no detailed description!

Acknowledgements: We are grateful for the help and interest shown by Robert Ridgley, who designed the roof.

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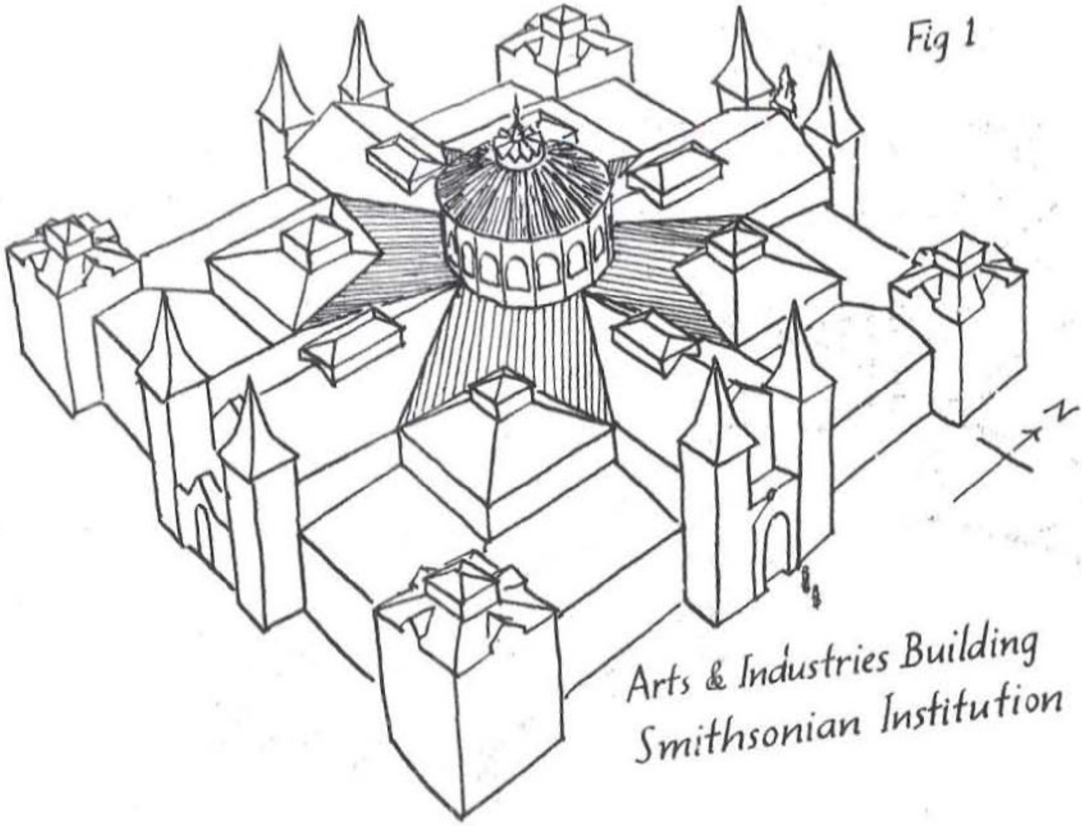
Fig 1



Arts & Industries Building
Smithsonian Institution

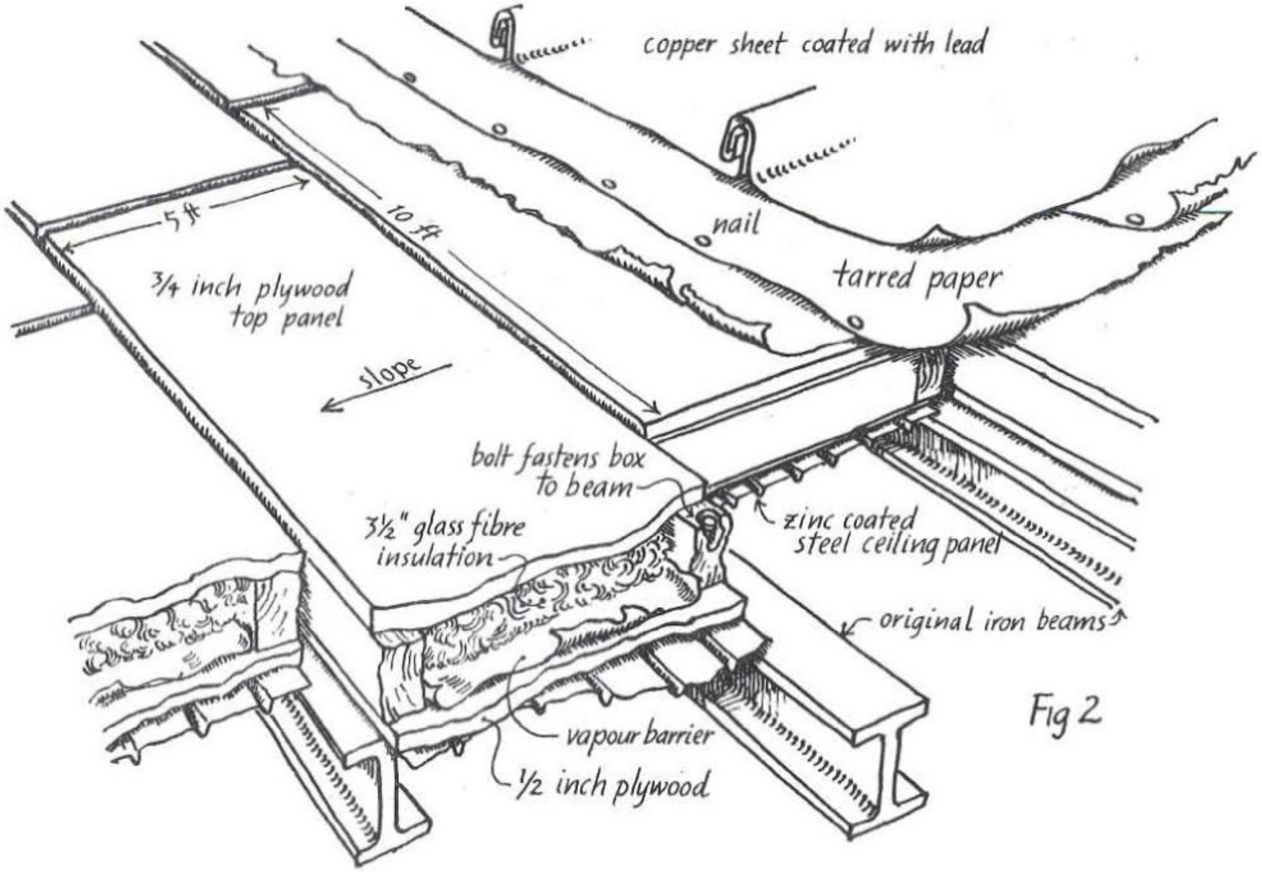

copper sheet coated with lead
nail
tarred paper
10 ft
5 ft
3/4 inch plywood top panel
slope
bolt fastens box to beam
3½" glass fibre insulation
zinc coated steel ceiling panel
original iron beams
vapour barrier
½ inch plywood

Fig 2

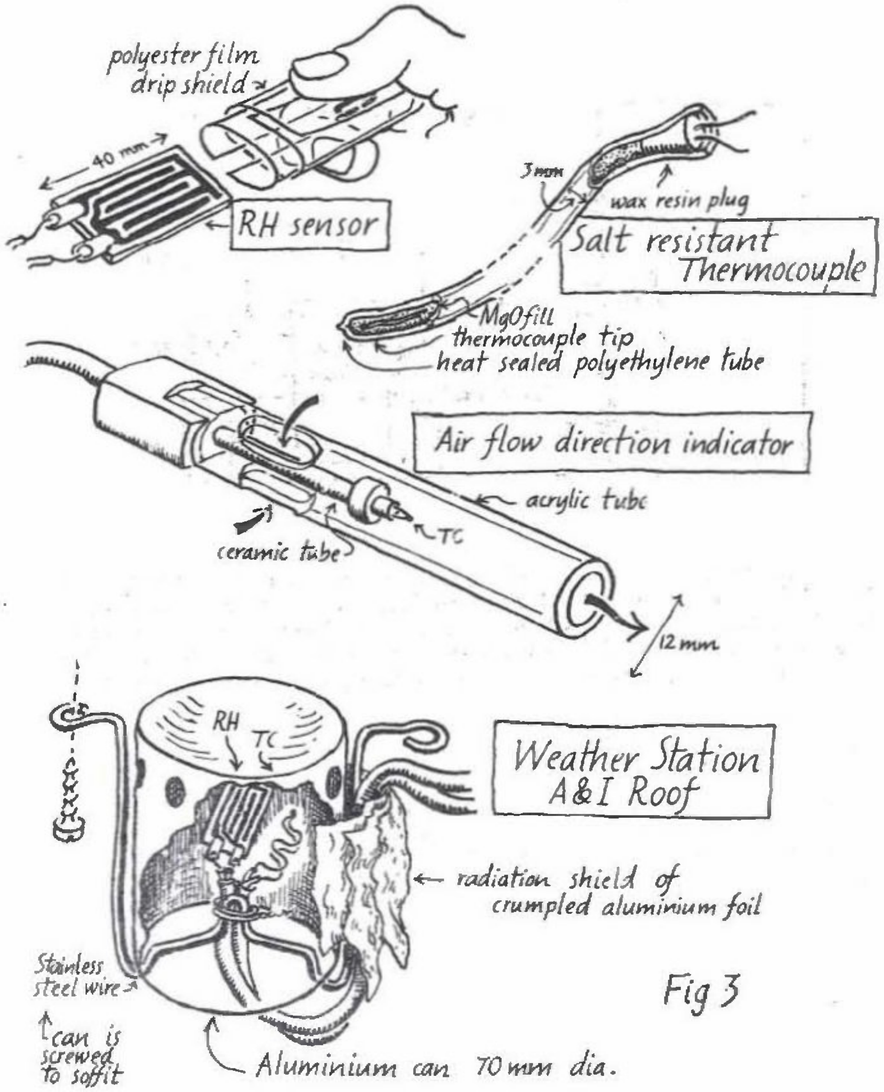

polyester film drip shield
40 mm
RH sensor
3mm
wax resin plug
Salt resistant Thermocouple
MgO fill
thermocouple tip
heat sealed polyethylene tube
Air flow direction indicator
acrylic tube
TC
ceramic tube
12 mm
RH
TC
Weather Station A&I Roof
radiation shield of crumpled aluminium foil
Stainless steel wire
can is screwed to soffit
Aluminium can 70 mm dia.

Fig 3

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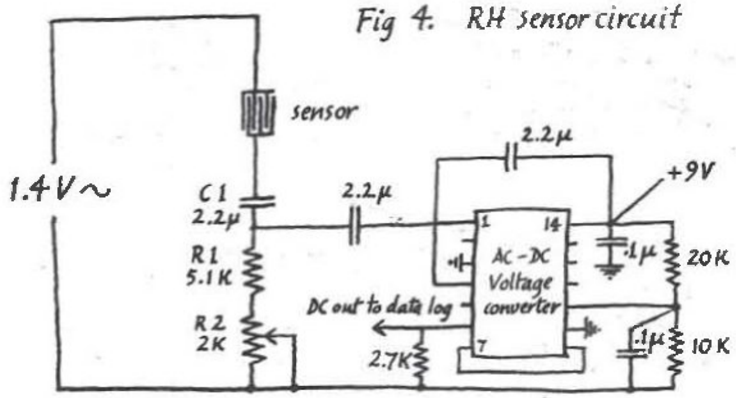
Fig 4. RH sensor circuit



A stable ac voltage of about 1.4V is applied across the resistor chain: Sensor, R1 and R2 in parallel with the 16K internal resistance of the ac to dc converter which is an Analogue Devices type AD 536 AJD. The ac voltage developed at the junction of C1 and R1 varies with the resistance of the sensor. This voltage passes to the ac to dc converter. The dc output goes to the data logger.

Notes on the circuit:

R1 and R2 plus the internal resistance of the converter are chosen to prevent the sensor passing more than 0.7 mA at 100%RH. C1 prevents dc from hitting the sensor - it would be destroyed. All other components bias the various inputs to the converter according to the manufacturer's recommendations.

Fig 5

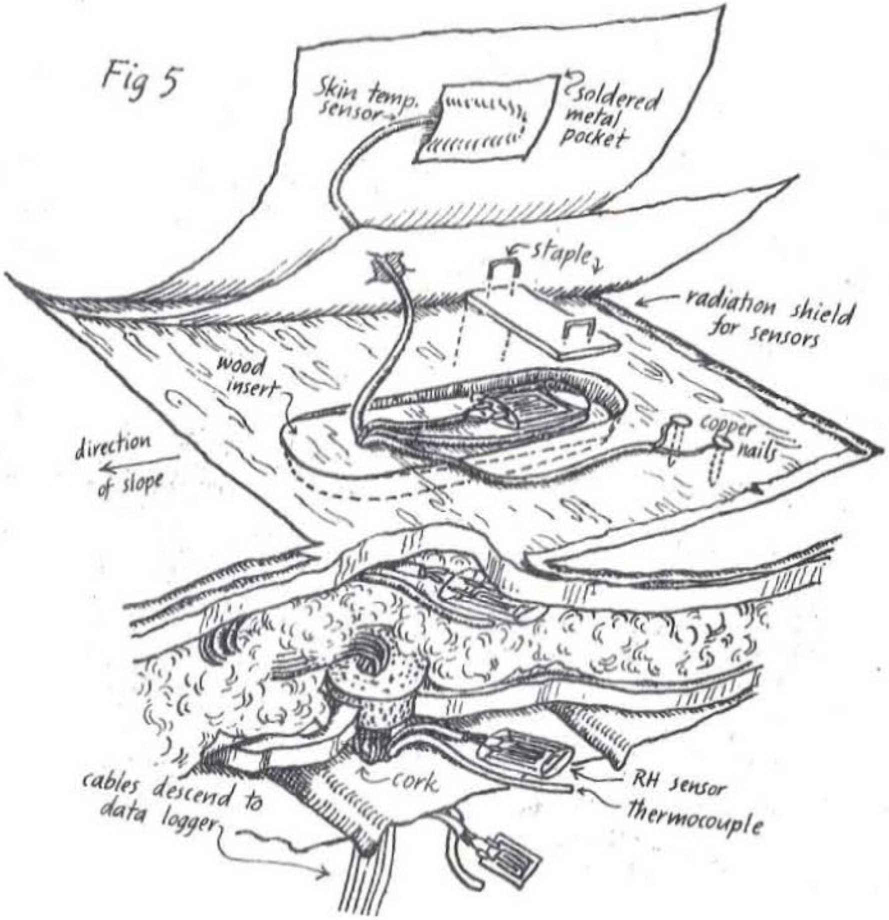
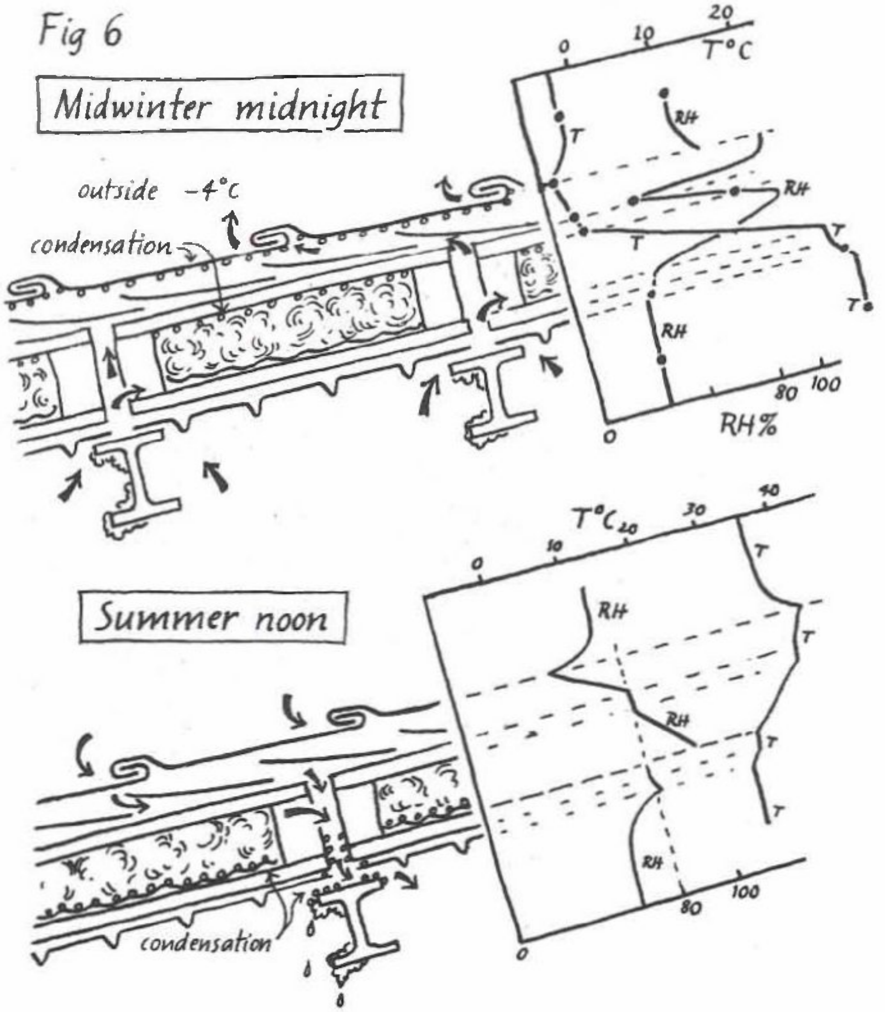

Skin temp. sensor
soldered metal pocket
staple
radiation shield for sensors
wood insert
copper nails
direction of slope
cork
RH sensor
thermocouple
cables descend to data logger

Fig 6


Midwinter midnight

Summer noon

In winter air passes through the roof from the inside. Condensation occurs on the upper inner surface of the box and on the lower surface of the roof skin. These are the coldest surfaces of the two main air spaces in the structure.

In summer air enters the roof from outside. The upper plywood, moistened by winter condensation, buffers the airs above it to 80% RH at a temperature raised above ambient by solar radiation falling on the grey roof. This air stream descends between the boxes and is augmented by warm moist air expanding outwards from the box interior. The air cools and water condenses out, dissolves the efflorescence and drips to the floor.