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PREVENTIVE CONSERVATION

Principles for developing low-cost, sustainable stores

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Abstract
Indoor climate performance, construction costs, energy use and energy cost are reported for English Heritage Trust collection stores and others, completed and in planning, in England and Denmark. Using basic warehouse construction methods with modest air exchange rates combined with dehumidifiers and no heating proved effective in achieving acceptable relative humidity and temperature levels in mixed/cool humid climates. Energy use and cost was also low. Separating materials by vulnerability into different storage zones is a key principle for effective and sustainable climate control. There was good correlation between predicted and actual damage rates for polychrome stone and copper alloys in the store environment which informed the relative humidity specifications. Access by staff, volunteers and visitors was not hindered by the cool store temperatures.

INTRODUCTION

The environmental performance of a store should be driven primarily by the needs of the collection present. Improving understanding of the tolerance of objects to relative humidity (RH) fluctuations is an important contribution to sustainability. Store design principles including low air infiltration, uninsulated floor slabs, no heating and using dehumidification will result in effective environmental control and low energy use (Ræder Knudsen and Rosenvinge Lundbye 2017). Using evidence from the performance of three English Heritage Trust stores and from others completed and in planning, the key principles for achieving low-cost, sustainable stores are presented for mixed/cool humid climates (ASHRAE 2019; Table 1). The practical application of these principles is described.

Table 1. Principles for achieving low-cost, sustainable stores

1	Separate materials by sensitivity to RH into separate storage zones
2	No insulation is required in the floor slab
3	Basic warehouse construction methods with modest air infiltration is acceptable
4	No heating is required and temperatures will remain above freezing
5	Keep storage zones free of windows
6	Use dehumidification to control RH below an upper limit defined by the materials in store
7	Keep staff offices and work rooms separate to the storage zones
8	Maximise air tightness to reduce energy use
9	Preventive conservation expertise is essential for design and delivery

BACKGROUND

English Heritage Trust (EH) is a charity responsible for the care and presentation of over 400 sites and half a million objects in England. Most collections are in store (78%) and consist of mixed-material archaeological, social history, decorative arts and paper-based objects. A national collections risk and condition survey completed in 2010 highlighted that storage conditions were the highest risk (Xavier-Rowe and Fry 2011). This led to a focus on improving storage which has resulted in the completion of three stores at Wrest Park near Bedford in the midlands, Helmsley in the north of England and Temple Cloud near Bath in the south west.

ZONING BY MATERIAL

Materials vulnerability to RH, temperature (T) and pollution will vary for robust materials like stone and ceramics and very sensitive materials

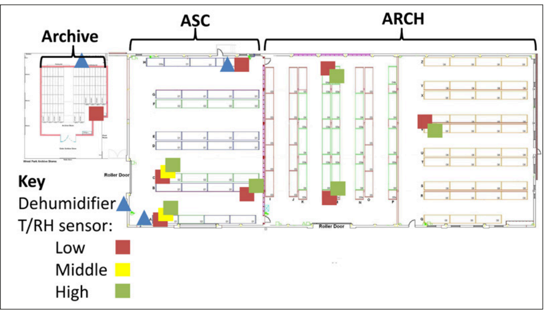

Figure 1. Plan of the Wrest Park collections store showing the location of sensors and dehumidifiers in the archaeology zone (ARCH), architectural studies collection (ASC) and in the archive room. Overlapping squares of different colours indicate monitoring in the same location at different heights

Figure 2. Helmsley collections store

Figure 3. Temple Cloud collections store

like archaeological iron, paper and plastics. Segregation by material sensitivity is therefore the first step towards sustainable storage by designing different zones with different environmental requirements. At the Wrest Park store which opened in 2013, the storage space is divided into three zones (Figure 1). The largest zone, at 6,060 m³, houses archaeological stone, ceramics and bone in conditions predicted to be below 80% RH with no environmental control. The second zone, at 2,523 m³, houses architectural objects made from wood (painted and gilded), plaster and historical metal with conditions predicted to be below 75% RH using two Munters MCS300 desiccant dehumidifiers. The third and smallest storage zone, a ‘room within a room’ (262 m³), stores the most sensitive materials including archaeological metalwork and paper, and conditions are maintained below 50% RH using one Munters MCS300. This approach was also successfully delivered at two further stores, Helmsley (2,193 m³), completed in 2016 (Figure 2), and Temple Cloud (1,941 m³), completed in 2017 (Figure 3), both of which are controlled by two Munters MCS300. Both of these stores house materials that are more sensitive to RH in small, insulated rooms controlled by two Munters MG90 desiccant dehumidifiers.

BUILDING CONSTRUCTION

A variety of lightweight standard construction methods have been used for EH stores. There are no windows in storage spaces and external doors are kept to a minimum. Removing insulation from the floor slab is important for regulating internal temperature, as heat absorbed over summer can be released into the store over winter (Padfield et al. 2017).

The Wrest Park store is a refurbished 1950s brick building owned by EH. The roof and large windows were replaced with insulated metal panels and the existing floor slab was retained. The archive room was built inside the building with no shared external walls. Details about the construction can be found in Xavier-Rowe et al. (2014).

The Helmsley and Temple Cloud stores are both leased under long-term agreements. The landlords funded construction to a basic specification agreed with EH. At Helmsley, the lower part of the walls are made of brick and blockwork cavity construction (380 mm thick) to a height of 2,325 mm. The upper part of the walls are constructed from PVC-coated steel sheet on the exterior and interior to a total building height of 5,375 mm, with 160 mm of fiberglass insulation and a total wall thickness of 192 mm. PVC-coated steel panels are also used for the roof, with 240 mm of fiberglass insulation. The archive store shares two external walls and has two internal walls constructed from single concrete blockwork. There is a work room above the archive store. The floor slab is 175 mm thick.

The Temple Cloud store is constructed from a metal frame and insulated coated sheet metal panels to form the walls and roof (80 mm thick) and a 200 mm-thick floor slab. The archive store shares two external walls with an additional concrete blockwork internal skin and two internal walls. There is an office space above the archive store.

AIR EXCHANGE RATE AND DEHUMIDIFICATION

Achieving a low air exchange rate is essential to achieving an acceptable internal climate (Ræder Knudsen and Rosenvinge Lundbye 2017). BS EN 16893:2018 standard recommends that 'a new storage building or space shall be built to maximise air tightness. Air infiltration shall be less than 0.5 m^3 per square metre per hour at 50 Pa' (BSI 2018).

Two units of measurement for air exchange rate are widely used. Air changes per hour (ACH) at 50 Pa measures the number of times the volume of air in the room is exchanged in one hour. The BS EN standard uses $m^3/m^2/h$ @ 50 Pa, which measures air change through one cubic metre per hour. To convert from $m^3/m^2/h$ to ACH, the building envelope (m^2) is divided by the building volume (m^3) and multiplied by the air permeability (m^3/h).

Air exchange rates for three EH stores (four storage zones) have been tested. These are compared to RH and temperature ranges achieved over 12 months and the energy cost to run dehumidifiers (Tables 2, 3). This indicates that an air exchange rate as high as 2.36 $m^3/m^2/h$ (1.37 ACH) combined with dehumidification will maintain acceptable RH ranges between 45% and 70%. In the zone storing robust archaeological collections (predominantly stone, ceramic and bone) in the Wrest Park store, acceptable conditions have been achieved at 1.35 $m^3/m^2/h$ (0.58 ACH) with no climate control, which is almost three times the recommended standard.

The stores with the lowest ACH in Table 3 also recorded the lowest energy use.

RH is controlled using small standalone desiccant dehumidifiers vented to the outside. The number of dehumidifiers can be calculated using the air exchange rate, volume and the RH set point. Using measured or predicted T/RH data, the quantity of moisture that must be removed to achieve the desired RH set point can be calculated. Factoring in the manufacturer's dehumidifier capacity, the size and quantity of units can be defined. For

Table 2. Climate performance and energy cost in English Heritage Trust stores

Storage zone & volume	Climate control energy cost per year (a)	T min	T max	% RH min	% RH max	RH specification
A (6,060 m^3)	0	6.5	23.1	41	71	< 80%
B (2,523 m^3)	£801	6.8	24.7	37	61	< 55% (b)
C (262 m^3)	£452	9.6	24.7	42	61	< 50%
D(1,477 m^3)	£512	5.9	22.1	48	71	< 65%
E (97 m^3)	?	6.5	21.6	56	60	< 60%
F (2,353 m^3)	£3,118 (c)	8.0	23.3	38	57	< 60%
G (157 m^3)	?	13.6	23.7	46	54	< 50%

(A) Wrest Park archaeology: stone, bone, ceramics
(B) Wrest Park architectural: historical metal, wood, plaster
(C) Wrest Park archive: archaeological metal finds & paper
(D) Helmsley large social history: mixed materials
(E) Helmsley archive: social history mixed materials
(F) Temple Cloud archaeology: stone, ceramics, bone
(G) Temple Cloud archive: archaeological metal finds & paper
(a) Based on average energy cost per kW/h of £0.1437 in 2018 (https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh, accessed 16 November 2019)
(b) Upper limit will return to < 75% when a furniture beetle outbreak in wooden pallets has been resolved in an estimated 2 years
(c) Energy cost for the whole store including a separate office space

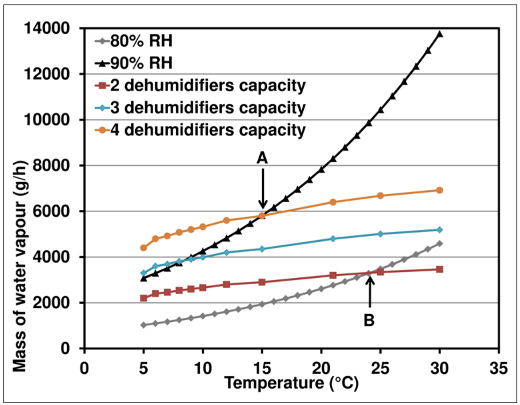

Figure 4. Quantity of moisture: (a) removed to meet 75% RH set point at a constant 80 or 90% RH and (b) removed by 2, 3 or 4 Munters MCS 300 dehumidifiers

Table 3. Construction cost, climate control, energy use and air exchange rate for stores completed and in planning in England and in Vejle, Denmark

Store & construction year	Area of whole building (m²)	Construction cost ex. tax incl. racking (£/m²)	Volume of stored objects (m³)	Construction cost per m³ incl. racking (£/m³) (a)	Energy use large & small zone (kWh/m³/year)	Air exchange rate m³/m²/h@50Pa	Air exchange rate ACH@ 50Pa
Wrest 2013	1,394	688	8,845 (large: 6060, small: 2523)	122	large: 0 small:2.2	1.35 & 2.23	0.58 & 1.2
Helmsley 2016	408	1,595	1,477	304	large: 2.6	2.36	1.37
Temple Cloud 2017	471	834	1,941	183	large: 9.2	4.5	1.1
Vejle 2013 (b)	2,535	900	5,650	389 (c)	large: 1.4 small: 0.4	?	< 0.01
Duxford 2019 (d)	1,452	2,041	7,260	408	7.39 [predicted for whole building]	?	0.03
Sedgwick 2019 (e)	720	3,278	1,974	1196	?	?	2.58
Alnwick 2020 (f)	714	1,639	2,856	410			
SMG 2020 (g)	26,000	846	95,758	230			
BM ARC 2023 (h)	15,628	4,095	49,014	1,306			

(a) Adjusted for inflation at 2.4% a year to end of 2018 using bankofengland.co.uk/monetary-policy/inflation/inflation-calculator (accessed 16 November 2019)
(b) (Ræder Knudsen and Rosenvinge Lundbye 2017)
(c) Converted to pounds from €593
(d) Duxford The Paper Store – https://www.architype.co.uk/project/duxford-paper-store/ (accessed 30 November 2019) and IWM Duxford Paper Storage Design and Access Statement, May 2017 http://plan.scambs.gov.uk/swiftlg/MediaTemp/1147079-706252.pdf
(e) Sedgwick museum geological collections store, University of Cambridge, The Colin Forbes Building, User Guide, January 2019 (Balmforth and Wallace-Johnson 2019)
(f) Alnwick Collection Store (Reverchon 2019)
(g) Science Museum Group – Based on estimated costs. Building ONE Collection Storage Facility, Pre-Application Enquiry – Design and Access Statement 2017 – https://www.sciencemuseumgroup.org.uk/wp-content/uploads/2017/11/2.-Building-ONE-Design-Access-Statement.pdf
(h) British Museum Archaeological Research Collection - Based on estimated costs. British Museum ARC External Lighting Strategy 2019 – http://publicaccess.wokingham.gov.uk/NorthgatePublicDocs/00456938.pdf and https://www.theartnewspaper.com/news/british-museum-to-open-new-storage-facility

stored collections with a high proportion of hygroscopic materials, the potential buffering effect may also need to be calculated (Padfield and Aasbjerg Jensen 2011). An example calculation is given in Figure 4 using the data from the architectural studies collection zone in the Wrest Park store using 2.23 m³/m²/h (1.2 ACH), 2,523 m³ and the original specified set point of below 75% RH. Two high humidity worst-case scenarios were plotted. The mass of water vapour that must be removed in grams to achieve the set point was plotted for 80% and 90% RH at a constant level and a temperature range of 5°C–30°C. Overlaid is the amount of moisture that two, three and four Munters MCS300 desiccant dehumidifiers can remove per hour (according to the manufacturer), which varies with T and RH. Only capacity data up to 80% RH was available, so this was used each time. Capacity is exceeded where the lines intersect. The data shows the period when two dehumidifiers will be effective, and the extra capacity each additional one adds. In this instance, the probability of temperatures in the high 20s and an RH over 80% is low, and for the vast majority of the time the two dehumidifiers would give surplus capacity (indicated by arrow B in Figure 4). At a constant 90% RH, the capacity of four dehumidifiers would be exceeded at temperatures above 15°C (arrow A in Figure 4). Two dehumidifiers were installed and have been successfully controlling the RH below 75%, and over the past year below 55%, to help control a furniture beetle outbreak in the wooden storage pallets.

Each dehumidifier is controlled by a single manufacturer's sensor connected by a two-metre lead. The position of this sensor is adjusted using data from several independent Meaco radio telemetric calibrated sensors located across the storage zone (Figure 1). The accuracy of the probes is essential to this process. The Meaco sensors use HTX transmitters which have Rotronic probes (± 0.8% RH accuracy, ± 0.2°C) calibrated every two years at three points with UKAS certified salt pots. The manufacturer's sensors and BMS fixed sensors can be difficult to calibrate and can slip rapidly, and will only represent conditions in one location. Considering the data from several locations in the store, a representative or worst-case location can be selected. This is reappraised annually from the data.

Conservation heating, another option for controlling RH in the northern hemisphere, is unable to provide control over the summer months due to upper temperature limits. Analysis of the available isoperms has shown that in all instances conservation heating will decrease the permanence of paper collections (Lankester and Thickett 2021). The excavation records in the archive rooms hold a major portion of the significance of the archaeological collection. This decrease in permanence has been verified with climate monitoring of rooms moving from uncontrolled to conservation heating. Hence dehumidification was used in the stores. Desiccant dehumidifiers are used as they are still effective at low temperatures over winter (Klenz Larsen 2018). They can also run the fan without desiccating; this allows mixing of air in the space which can ventilate high loading stores with emissive collections, such as wood or acidic paper.

TEMPERATURE

Not heating storage spaces is proving to be a key factor in achieving low-cost, sustainable stores. Removing the requirement for heating simplifies the RH specification to the upper limit only. This has had a significant impact on reducing construction costs for EH stores. In the UK (and for many loan agreements), the temperature band widely recommended for museum collections is 16°C–24°C (Arts Council England 2016). In reality, the upper limit is not achieved, as summer external temperatures are increasingly reaching 30°C and above. The lower limit of 16°C is also not valid for historic house collections, which tend to control RH through conservation heating, possibly resulting in temperatures dropping as low as 5°C in winter.

The requirement to heat to 16°C is solely related to human comfort. Provided freezing is avoided, most cultural heritage materials are not adversely affected by low temperatures. There is extensive evidence of well-preserved collections in unheated buildings (Schulze 2013). Efflorescence has been reported to form on pure, unpigmented beeswax below 16°C (frequently quoted as 13°C) (Novotná and Dernovsková 2002), although it is also observed to form more slowly at room temperatures. Exudates have been reported on some plastics at 7°C (Lauridsen et al. 2017), but were re-adsorbed when the temperature increased. Paint films, particularly acrylics, become more brittle below 11°C, increasing the risk through handling. Colder temperatures also have the positive effect of reducing insect pest activity. For most materials it is therefore an acceptable risk

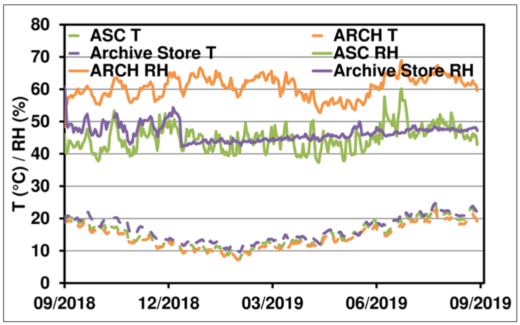

Figure 5. Wrest Park store RH and temperature in the archaeology (ARCH) zone, architectural studies collections (ASC) zone and in the archive store

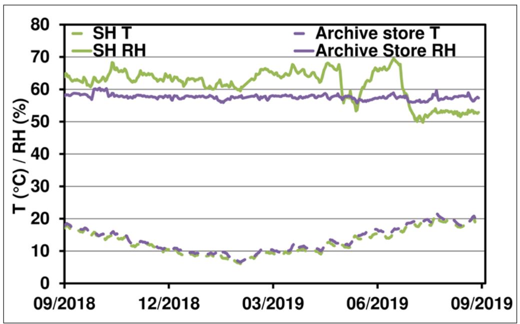

Figure 6. Helmsley store RH and temperature over 12 months in the social history collections zone (SH) and archive store

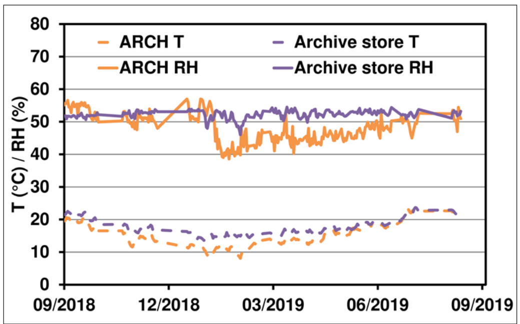

Figure 7. Temple Cloud store RH and temperature over 12 months in the archaeology zone (ARCH) and archive store

and a benefit in terms of extending preservation lifetimes to store in low temperatures. In the UK, if proposed storage buildings are designed to be unheated, compliance with the Part 'L' of the Building Regulations 2010 relating to insulation of the floor slab is not required.

All three EH stores are unheated and have recorded winter temperatures that do not drop below 5°C (Figures 5–7). The first year of operation of the Wrest Park store (2014) was the coldest in the UK for 25 years. The hottest year on record in the UK was 2018. The lower temperature is unlikely to be matched in coming years, while the upper temperatures are very likely to increase.

DAMAGE PREDICTIONS

Damage functions for copper alloy and polychrome stone were used to define the environmental specifications for recent EH stores (Xavier-Rowe et al. 2014). The accuracy of the predictions was tested by measuring damage phenomena during 2018. The measurements took place in the Wrest Park store as this houses the polychrome stone fragments and most non-archaeological copper-alloy objects. Salt damage to stone was monitored following a method that has been tested and validated experimentally (Thickett and Stanley 2017). T and RH were measured with Rotronic HygroClip II probes running on a Meaco radiotelemetry system. At each temperature value, the salt transition RH for thenardite (sodium sulfate annhydrate) to mirabilite (sodium sulfate decahydrate) was calculated. The measured RH was determined to be above or below this value. Transitions from below to above were counted. As the transition occurs at a sharp, well-defined RH value for a given temperature, the RH accuracy of the measurements is critical. Small errors can have disproportionate effects on the results if the RH is near the critical value (64%–80% over the temperature range experienced). Calibration is essential and a three-point calibration is required to track the ageing of the sensing elements in the probe, especially as the higher RHs experienced previously can deteriorate some probes rapidly. Previous work has shown the transition RH can vary in porous media such as stone, and the published free values were used here for clarity (Bionda 2016, Thickett and Stanley 2017). The initial assessment used calculations with a range of experimentally derived responses to generate sets of figures for comparing the existing and newly planned stores. The bronze corrosion rate was measured with an AirCorr I logger with a copper/tin sensor.

Table 4 compares damage measured during 2018 to predicted values. The total number of events where the transition line was crossed from the thenardite to the mirabilite region, inducing expansion, was within 10% of those predicted before the store was built. Many heritage institutions use RH sensors with accuracies up to 3%. Adding 3% to every June value, for example, would increase the number of transitions to 21 from 13, demonstrating the importance of accurate calibration for this type of work. The measured copper corrosion rates were within 21% of the predicted rates, except in March and October, which showed higher variation. Outdoor pollution concentrations may be a factor. Although no contemporaneous pollution measurements were made, the nearest government monitoring station showed very high ozone concentrations in March and October (Table 4). These high ozone levels correlate with the months with worst agreement between the predicted and measured copper corrosion rates and the concentrations are higher than those used in the original predictions. October was also the month with the highest RH in the store.

Figure 8. Primary school children visiting the archaeology zone in the Wrest Park store

Table 4. Number of predicted and calculated thenardite to mirabilite transitions presenting greatest risk to Thetford polychrome stone and copper/tin alloy corrosion rate

Month (2018)	Salt transitions (number)		Copper/tin corrosion rate (g/m²)		Ozone concentration (ppm)
	predicted	measured	predicted	measured	
Jan	0	0	2.03	1.62	61
Feb	0	0	2.03	2.43	58
Mar	0	0	1.96	2.70	68
Apr	0	0	1.82	2.16	60
May	0	0	1.69	1.62	51
Jun	10	13	1.82	1.45	62
Jul	0	0	1.49	1.62	51
Aug	0	0	1.82	1.89	50
Sept	8	5	1.76	1.76	42
Oct	9	11	1.69	2.50	71
Nov	7	2	1.82	1.89	39
Dec	0	0	1.96	1.68	45
Annual total	34	31	21.89	22.84	NA

ACCESS

Increased access by staff, researchers, volunteers and the general public inevitably follows a store project as documentation and packing is improved (Xavier-Rowe et al. 2014). Unheated storage zones have not hindered access to EH stored collections as confirmed by three collection managers who were interviewed. They confirmed unanimously that cooler stores were not affecting access for activities relating to repacking, documentation, research, education and public visits. Volunteers, for example, continue to help once a week in the Wrest Park store with cleaning, packing and documentation. Forward planning is used to ensure extended periods of time in the stores are limited in the coldest months. Separate heated spaces are provided away from the storage zones and are essential for breaks and for extended examination of objects. Moving objects from below 7°C to heated study rooms may present a risk of condensation which in practice has been a low risk as temperatures do not drop below 5°C. Repacking projects, if required, have continued throughout the coldest months in the stores. Educational visits by primary school children have continued throughout autumn and early spring (Figure 8).

CLIMATE ZONE

Once an environmental specification (required for the objects) has been developed for different storage zones, the design of the building and services needs to consider the external environment. Chapter 24 of the *HVAC Applications Handbook* (ASHRAE 2019) gives an indication as to which climate bands are possible in which climate zones with different types of buildings. It is important to realise that passive features that work in one environment may generate unexpected issues in a different climate zone.

LOW COST

Stores can prove to be expensive both to build and operate with mixed results in achieving the climate specified. This situation is partly to do with narrow climate specifications used in the past. The requirement to heat and cool to comfort levels for staff and visitors has also been a factor leading to expensive HVAC systems.

Construction costs excluding land and including racking systems for EH stores and a selection of others both completed and in planning are listed in Table 3. This information was gathered by the authors through personal contacts and from what is available on the internet. Cost per metre cubed is a better reflection of actual storage capacity, but the standard measurement remains metre squared. Both measurements are listed in Table 2, which suggests that construction costs for a sustainable store with specialist racking will range from £304 to £410/m^3. Using warehouse construction methods, the cost is reduced to £183 to £230/m^3. Refurbishing a building can cost as little as £122/m^3. Costs over £1,000/m^3 are also noted, with the increase linked to specialist design/construction and HVAC control systems.

CONSERVATION LEADERSHIP

Preventive conservation expertise is essential for achieving sustainable stores in practice. Both the preventive conservator and conservation scientist need to work together to define the environmental specifications, building design and climate control to ensure that risk assessment and evidence inform decisions. It is the authors' experience that without preventive conservation expertise in a leadership position on a store project, the principles for sustainable low-cost stores are unlikely to be achieved due to the dominance of building design protocols led by the architect and M&E consultants.

CONCLUSION

To achieve low-cost sustainable collection stores, several factors need to be in place. Basic building construction methods achieving modest air exchange rates have been shown to deliver acceptable RH and T conditions at sustainable annual energy costs. Segregating materials into separate storage zones with appropriate RH set points ensures that the necessary climate conditions can be achieved. Energy use can be lowered further through increasing air tightness but at an increased investment in the build design and construction materials. Not heating storage spaces reduces the construction and energy costs and increases the preservation lifetime of materials. Cool stores during winter have not hindered access. Preventive conservation expertise is crucial, ideally in a leadership role on a store project, to ensure scientific evidence is used to inform the design and control methods.

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MATERIALS LIST

AirCorr I
http://www.cwaller.de/english.htm?aircorr/e_aircorr1_plus.htm~information

Meaco
https://meaco.co.uk/

Munters MCS300 and MG90 desiccant dehumidifier
https://www.munters.com/pt/munters/products/dehumidifiers/mcs300/

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