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Infrared thermal imaging as a collections management tool

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Abstract

As natural history collections often contain specimens that require quite different environmental conditions from one another it makes sense to try to understand the sometimes subtle differences in conditions provided within the storage and display areas concerned so that the specimens can be arranged accordingly to better suit their particular needs. Modern digital infrared thermal imaging technology is now highly portable and provides exactly the sort of detailed data required in a way that other environmental data logging equipment cannot and presents it in a highly visual format that is generally intuitively understood and easily analysed with proprietary software. However, there are many factors influencing the accuracy and interpretation of the data so training is required. Fortunately, the cost of equipment is falling. Uptake of the technology for collections management purposes in museums is in its infancy due to a lack of awareness of how the technology can be applied.

Keywords: Infrared Thermal Imaging; Temperature; Humidity; Store Room.

The changing climate within museums

It is not just the global climate that is changing. Within the confines of museum storage and display areas, environments might soon become more varied than recently. For many years British Standard 5454 'Recommendations for the storage and exhibition of archival documents' dictated that environmental conditions for archive and museum collections should be 50% relative humidity (RH) +/- 2%, and 19ºC temperature +/- 1ºC. This very narrow target of ideal environmental conditions was withdrawn in March 2012 and replaced with the National Archives' 'Guide for the storage and exhibition of archival materials' and 'Specification for managing environmental conditions for cultural collections' (National Archives, 2012a; 2012b), published by the British Standards Institute. These two documents reflect the changes in policy called for by the National Museum Directors Conference (NMBC) in 2009 after cultural heritage institutions were asked to reduce their reliance on fossil fuels while meeting their responsibility to preserve collections. The NMDC adjusted their own environmental guidelines to a much broader range of 40-60% RH and 16-25˚C in an attempt to reduce energy consumption by museums and related institu-

The previous very narrow range of environmental parameters recommended by the MLA was a target that was increasingly costly to attempt to meet in typically old, leaky, energy-hungry museum buildings that are largely 'horribly inefficient and unsustainable' (Staniforth, 2011) and often beset with various degrees of listed status preventing useful remedial action. Therefore relaxing the target to the new recommended range of environmental conditions will in theory save both money and greenhouse gas emissions. But what about the collections? The new approach places the actual environmental needs of particular types of objects at the center, rather than setting universal ranges applicable to all. It makes sense therefore not only to understand as fully as possible the different environmental requirements of specific types of object within a collection, but also to gain as good an understanding of the storage or display area as possible, to make the best use of any subtle differences between and within the areas in question – especially if the environmental controls in the institution are going to be relaxed and a wider range of conditions are likely to be experienced.

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The different environmental requirements of natural history sub-collections

Specialist curators in larger museums will know exactly the environmental requirements of the collections within their care, and hopefully will have storage areas providing the right conditions suitable for their specific collections. However, most small to medium sized museums are likely to have a general natural history collection containing a wide variety of material, probably all located in the same store. For historical reasons the specimens may be packed in a particular order that does not necessarily best reflect the environmental needs of the objects.

Generally, areas in which natural history collections are stored should be kept as cool as practically and economically possible. A cooler environment benefits specimens not just by reducing pest activity (Carter and Walker, 1998; Pinniger and Meyer, 2001) but the lower the temperature the lower the rate of all damaging biological activity and chemical reactions generally and for this reason low temperatures can help to preserve DNA in specimens themselves. Advice varies slightly but stores containing a wide variety of natural history material should be maintained at about 13ºC to 15ºC (Carter and Walker, 1998) even though this is lower than would generally be comfortable for people working in the collections (for which 16ºC to 18ºC is recommended. Active cooling is expensive however, so the practical solution is to provide as low a temperature as the institution can afford whilst not making it impossible for workers to spend some time in the collection area. The caveat is that relative humidity should not exceed 60% nor fall below 45%. Rapid and extreme fluctuations (even within the parameters above) should be avoided as this can be more damaging to specimens than generally being near one of the limits with gentle changes (Carter and Walker, 1998).

At high humidities mould growth can occur and insect pests become more common, as with higher temperatures. Higher temperatures can also cause consolidants and adhesives to slowly weaken and fail (Fitzgerald, 1995). Natural history specimens preserved in fluid particularly benefit from cool conditions of about 13ºC to 15ºC (Carter and Walker, 1998) as it reduces evaporation and the rate at which the specimens deteriorate. It is recommended that botanical specimens be kept at between 45% and 55%RH and 18ºC to 22 ºC (ICON, 2013a), and zoological specimens between 45% and 55% and temperature levels as stable as possible but between 10ºC and 22ºC (ICON, 2013b). It is generally agreed that geological and palaeontological material should be stored with minimal daily fluctuations at around 15ºC to 25ºC but more importantly between 45% to 50% RH. RH of 55% would be the very upper limit because at 60% RH pyrite oxidation (pyrite 'decay') can be triggered in some susceptible material (Buttler, 1994; Newman, 1998; Larkin, 2011) so a much lower humidity, around 40% RH, would be better for these specimens. However, if sub-fossil material is also present in the collection, especially mammoth ivory and teeth, then RH as low as this would probably cause it to crack, along with some clays or mudstones of various ages (possibly containing fossil specimens) that may delaminate. This is an example of why it is important to understand which specimens in a collection and even in a sub-collection may require quite different conditions so their needs can be accommodated suitably.

Microclimates can be created for some specimens with lidded sealable containers employing silica gel or Artsorb but this may not be practical or economically feasible, depending on the material. Storage environments can be controlled to an extent by the intelligent use of dehumidifiers and radiators, preferably controlled by humidistats (particularly in winter) but in a large store room they may struggle to make more than a local difference especially if there is a large rate of air exchange. In smaller rooms they affect all the specimens indiscriminately.

The subtly different environments within a room

It is important not only to understand what parts of a collection require a higher or lower humidity or temperature but also to know which part of your storage area best provides the optimum conditions for the specimen or sub-collection as not only will conditions vary from store to store but even within a store. There will inevitably be some stratification, especially in higher-ceilinged rooms with no active air circulation and more dramatically so if heated in winter. The surfaces of external walls will probably be at a slightly different temperature to those of internal walls. There will be drafts around doors and window frames and unless large glass window panes are very well double or triple glazed they will conduct heat effectively to the outside, and act as a source of 'coolth' in a room. Poorly lagged or unlagged hot water pipes will create localised warm spots diurnally, and even plant running servers, lifts, heating or ventilation systems can create permanent warm spots on the walls of adjoining rooms.

If these sorts of environmental peculiarities within a room are quantified and understood, the variations can be exploited by rearranging specific parts of a collection, taking into account the needs of the material. However, whilst most museums now record the environment of at least some of their stores some of the time, even the best live telemetric environmental data logging system only produce data relating to a very small area around the sensors in what is a probably a large and varied three dimensional space. Until recently, it would have been extremely time consuming and costly to investigate and understand subtle differences, requiring multiple sets of environmental data loggers and associated number crunching and graph wrangling to produce a sketchy picture of the temperature and RH gradients across a room. Therefore it is generally underappreciated just how much environmental conditions can vary within a store room or gallery.

However, recent improvements in infrared thermal imaging technology and a consequent drop in the price of the equipment has the potential to revolutionise the way we assess and manage our museum environments.

Infrared thermal imaging: how it works and how it is normally applied

Everything with a temperature above absolute zero emits heat. Generally, the higher an object's temperature, the greater the infrared radiation it emits. However, the exact amount of infrared radiation emitted depends on two factors: the temperature of the object's surface, and the 'emissivity' of the material, relating to the material's innate ability to emit heat. The temperature of the object's surface is affected by the energy conducting through it, the exact structure of the object, the energy being radiated on to it and even the water content of the object. Therefore the pattern of heat radiating from an object will reflect variations in its internal state. For instance if part of a brick wall is damp, this will affect its emissivity and it will show up in an infrared image**.**

Emitted infrared radiation lies between the visible and microwave portions of the electromagnetic spectrum. A thermal imaging camera (Fig. 1) scans this part of the spectrum in the same way that a digital camera scans the visible light portion, and produces an image on the LCD screen in much the same way as a normal digital camera would (in fact most models will also take a normal digital photo at the same time as the infrared image is taken, as a record of what the infrared image is showing). The image or video is captured and stored on a card in the camera simply by pressing a button, as on a normal camera. However, the resulting radiometric image allows detailed temperature values to be analysed easily with appropriate software as every single pixel is in fact a temperature measurement. These data points can be highlighted on the resulting image (see Figs. 2 to 8). As well as individual pixels, areas of various shapes can be selected and the data within the area can be analysed automatically to give the minimum, maximum and average values. This allows for fair and accurate comparisons between portions of images. An infrared camera with a resolution of 60 x 60 pixels provides the equivalent data of 3,600 individual digital thermometers but visualised perfectly and all at the same time. An infrared camera with an image resolution of 640 x 480 pixels will give 307,200 temperature data points. Depending on the exact model used (see Fig. 1 for an example), the temperature range measureable should be between about minus 20ºC to plus 120ºC and the accuracy should be about 0.1ºC to 0.045ºC.

Heat loss by radiation can account for up to 60% of a normal building's total energy consumption (Hugo, 2001). Infrared thermal imaging usefully reveals conductive heat losses resulting from such issues as missing insulation or improperly installed insulation and excessive thermal bridging (Fig. 2a).

Fig. 1. An example of an infrared thermal imaging camera: The author's 'FLIR E40bx' in use. Image resolution 160 × 120 pixels (providing 19,200 data points); digital infrared still images and video; range minus 20°C to plus 120 ºC; thermal sensitivity <0.045 °C; built-in 'normal' digital camera (3.1 megapixels); one LED spotlight; and wireless/Bluetooth technology.

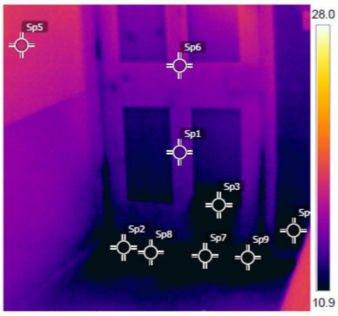
It can also show the cold air being brought into a building by drafts (Fig. 2b). In addition to energy loss, air leakage can also cause condensation to form within and on walls, which is also visualised by infrared imaging. Other causes of hidden moisture that infrared can reveal include leaking roofs, plumbing leaks and water intrusion in basements.

Usefully, infrared images also visualise the wasted heat energy from appliances consuming electricity whilst being left on standby unnecessarily. It can also reveal any thermal stratification issues. This is the layering of differing air temperatures from the floor to ceiling (Fig. 3). This results from the natural process of heat rising in an internal space but it can be an issue in that it creates quite different microclimates of temperature and therefore RH throughout the air column. In regards to energy conservation it has been suggested that stratification is the single biggest waste of energy in buildings today. In buildings with stratification, temperature differentials of up to 10ºC can be found over a height of 10m on average. In extreme cases temperature differentials of 10ºC have been found over a height of 1m. Thermal de-stratification is the process of mixing these internal air temperatures to effectively eliminate the stratified layers and achieve temperature equalisation throughout the space, saving energy on heating because previously the heat was accumulating where it was least needed. In a de-stratified building temperature differentials can be reduced to 1ºC to 2ºC or less from floor to ceiling. In commercial or industrial buildings with warm air heaters and high ceilings, de-stratification fans can reduce energy use by 20% by blowing warm air back down to ground level where it is needed.

Measurements	°C
Sp1	5.2
Sp2	13.8
Sp3	14.4
Sp4	14.3
Sp5	3.9
Sp6	4.4
Sp7	4.2

a

Measurements	°C
Sp9	6.1
Sp5	17.5
Sp7	5.7
Sp1	13.3
Sp4	10.8
Sp3	7.6
Sp2	6.4
Sp8	6.1
Sp6	14.9



b

Fig. 2. (a) This infrared image taken outside early in the morning is of museum offices and store rooms losing heat: the glowing areas of this external wall are where radiators are sited on the other side of the wall and are conducting heat through the wall to the extent that these areas on the outside of the external wall are consistently about 9ºC or 10ºC warmer than the surrounding wall. This image shows how the temperature data related to individual pixels can easily be shown in an image.
(b) The gaps through which cold drafts (between 7ºC and 10ºC cooler than the surrounding air) are blowing under this museum door are big enough to allow access to large pests including rodents.

Measurements	°C
Sp6	16.1
Sp8	17.3
Sp3	19.1
Sp7	17.2
Sp1	15.4
Sp4	16.3
Sp2	14.6
Sp5	15.8
Sp9	17.4
Sp10	17.0

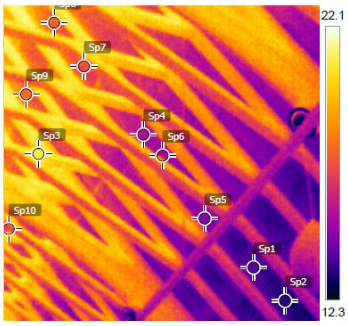


Fig. 3. This high-ceilinged museum display area has stratification issues. Shown here is the top quarter of the air column, within the raftered ceiling, where there is 2.5ºC of stratification. The difference between the very bottom of the air column at ground level to the top was 7.5ºC.

Infrared thermal imaging and collections management

Obviously infrared thermal imaging can facilitate understanding how energy can be conserved in museums by highlighting insulation issues (Fig 2), discovering equipment left on standby and revealing inefficient equipment (Fig. 4), but it is also a very useful tool throughout the year for helping with collections management issues. Although infrared thermal imaging does not measure air temperature directly but the temperature being radiated from surfaces this is still very useful. Thermal imaging can locate and visualise drafts coming in from outside through cracks and holes that insects can probably exploit to gain access (Fig. 2) so a draft proofing plan based on infrared imaging would help to reduce pests getting access into a museum building. Where equipment such as servers, lifts or heating, ventilation and air conditioning systems create so much warmth in an adjoining room there can be a permanent warm spot on the other side of a connecting wall (Fig.5) which may be a museum store. This might be an ideal location for a storage cabinet of material requiring slightly lower RH.

In displays, the temperature of the lights can be quantified, useful not just for deciding how inefficient the bulbs may be but for making judgements about how appropriate they are for the material within the display case that may be exposed to undesirably high temperatures.

Conditions within in a store or gallery will probably vary the most in the winter due to some external walls being colder combined with the presence of unlagged or poorly lagged hot water heating pipes. These can be obvious but sometimes you simply will not know where the hot water pipes run as they may lie unnoticed within a wall, ceiling or floor. For example, during a recent energy conservation survey unlagged or poorly lagged hot water heating pipes were discovered running under the length of the floor of an art store including right under a large permanent area of clutter (Fig. 6). As the temperature of the carpet under this clutter was at 23˚C this was an area ripe for a pest infestation. No-one knew about the warm pipes so this area would not have been checked. A simple remedy to the situation was to move the clutter elsewhere, allowing a more even heating of the room and making the warm spot a lot less attractive to pests.

Similarly, curators were horrified to discover during a recent thermal imaging demonstration that warm pipes appeared to run behind sections of the bookshelves in their rare books and manuscripts room (Fig. 7). Parts of the wall behind the books were over 14ºC warmer than equivalent parts of the walls in stacks nearby. The spines of the books facing in to the room were over 2ºC warmer than the spines of other books nearby. Some books were removed from the warmer shelves and infrared imaged taken of their spines which faced in to the room and then of the opposite edge of the book that faced the warm wall. There was an average of 2ºC difference

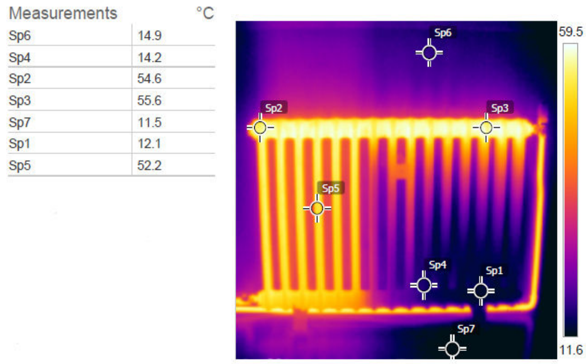


Fig. 4. This radiator located in a museum store room is clearly not functioning properly and may need bleeding.

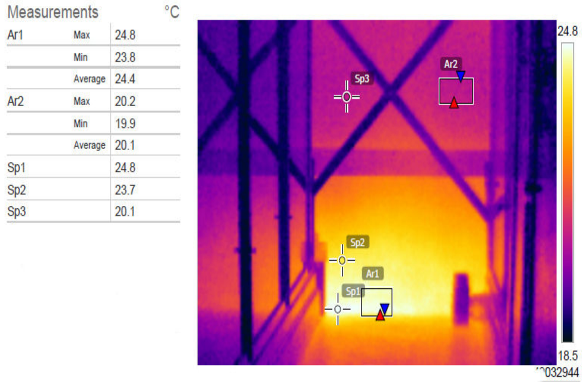


Fig. 5. This warm spot low down on a wall was found in a part of a store containing very valuable bird remains. No-one had any idea that this part of the wall was permanently warmer than the surrounding walls (by over 4ºC in this image). There is HVAC machinery in the room next door, creating this warmth. This image shows how areas can be selected (e.g. Ar1 and Ar2) and the maximum, minimum and average temperature within the area drawn is automatically calculated and easily be compared to other areas. As many of these boxes (or circles) can be drawn as needed.

Fig. 6. Unlagged or poorly lagged hot water heating pipes were discovered running under the entire length of the floor of this art store during a recent energy conservation survey. They ran right under a large permanent area of clutter where the temperature of the carpet was at 23˚C, making this area under the boxes and tables ripe for a pest infestation.

between the two edges of the books, which could result in a theoretical difference of about 20% relative humidity across the object - and the rear of these books were over four degrees warmer than the spines of the books on the cooler shelves nearby. If this had been discovered in a natural history storeroom the curator might consider storing certain parts of the collection here (such as geological material prone to pyrite decay) unless the temperatures involved were considered too high or were found to fluctuate too much. The area could be insulated to reduce the localised warming.

Where the temperature differences within a storeroom are less extreme, specimens requiring a lower RH might be best stored against an internal wall on the higher shelves where the air is generally warmer. Sub-fossil material (especially tusks, ivory and mammoth teeth etc), fluid-preserved specimens and osteological material could be stored in areas that are stable but cooler on average with a higher RH, such as on lower shelves against an external wall away from radiators and unlagged hot water pipes. Other material – the bulk of the collection - can be stored in the middle ground.

In some rooms, many different interesting things are seen to be happening. In a particular image of an art gallery stratification can be observed, very cool air is issuing through HVAC vents (even though it was winter) and there is localised warming high on the wall resulting from an inefficient spotlight (Fig. 8). There is a difference of up to 8ºC between various parts of this gallery wall and this is likely to have an effect on RH levels as well. Traditional environmental monitoring would not reveal a fraction of these subtle differences.

Infrared thermal imaging cameras are demonstrably useful for gaining a much better understanding of museum environments and they have dropped in price over the last few years. However, the cameras are still very expensive in the context of museum budgets. Also, they do have to be operated by someone trained in their use or the wrong data can be collected and the images can be misinterpreted. For instance, undertaking infrared surveys outside is best done at night long after the sun has gone down, or very first thing in the morning before dawn, as direct sunlight interferes with what is being surveyed. Materials warmed by the sun can stay warm for many hours. This can be true for south-facing walls and roofs/ceiling even inside a

Measurements		°C
Ar1	Max	22.3
	Min	20.5
	Average	20.9
Ar2	Max	19.2
	Min	17.6
	Average	18.6
Sp1		17.0
Sp2		31.2

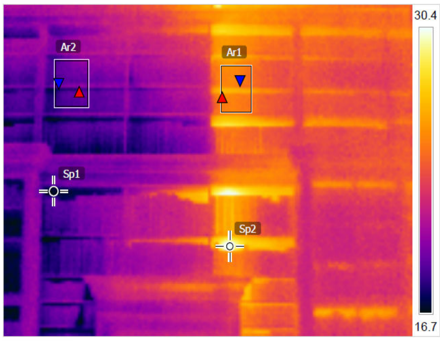


Fig.7. The rare books room where warm pipes behind one section of the wall led to some objects being exposed to environments over 14°C warmer than others, with RH also no doubt varying as much as a consequence.

Measurements		°C
Ar1	Max	19.2
	Min	18.9
	Average	19.1
Ar2	Max	19.0
	Min	15.9
	Average	17.1
Sp1		13.0
Sp2		20.9
Sp3		18.5

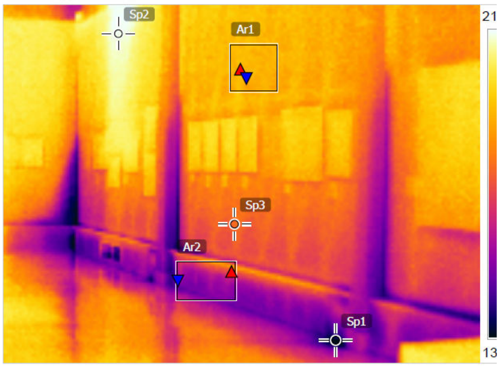


Fig.8. This art gallery was recently checked as part of a museum's energy conservation survey. 'Sp2' is a warm spot on the wall created by a nearby spotlight and it is about 2°C warmer than the average for area 'Ar1' which is part of the wall nearby that is only slightly lower in height. Cool air is issuing from the vents at the bottom of the wall, adding to the stratification and uneven temperatures and RH. Note that the very shiny hardwood floor is reflecting the infrared in the same way it reflects visible light.

surfaces of materials, subsequently lowering the temperature differences between hot and cold areas. Thermal imaging is at its best when there is a good temperature gradient (at least 10˚C) between the inside of a building and the outside. In the UK this mostly occurs between November to about March or April.

At all times the camera should be set for the right emissivity of the materials being surveyed. For instance concrete has a different emissivity value from brick or wood etc. The camera needs to be as parallel as possible to the surface being assessed (which can make surveying roofs a bit difficult). The images have to be interpreted carefully. Some materials reflect infrared radiation much like a mirror or smooth metal surfaces can reflects visible light (Fig. 8); sometimes damp areas can be interpreted as cold areas and vice versa; warm spots might be 'real' situations or might be a temporary artefact of warming by sunlight; on walls, changes in the image might simply be a result of changes in materials or even just the paint; heating systems create temperature differences that can cause misleading thermal patterns; and cool air flows from ventilators or air conditioning systems can cool down the surfaces of materials while the object underneath the surface is actually warmer.

Infrared thermal imaging: the cost
As energy costs have risen steeply at a time when portable infrared technology has greatly improved, the ability of these cameras to reveal where energy is being wasted – and importantly where it can be conserved - has made them very attractive and their various applications in the building, engineering and energy industries has helped to bring down their cost.

Bottom of the range infrared cameras now start at about £1,700, but in terms of image resolution you do not get much for your money (usually about 60 x 60 pixels for this price). A decent entry-level infrared camera useful for assessing museum environments currently costs in the region of £3,600 and would provide an image resolution of 160 × 120 pixels or 19,200 data points, as used for all the images in this paper. Although the point of purchasing such equipment would be to save a museum money by reducing energy wastage and to improve collection storage conditions this is still likely to be too expensive for most small to medium museums. Although larger museums or museum services might be able to justify it, there is also the high cost of training to consider. A more affordable option would be to employ for a day or two a trained specialist with their own equipment and an understanding of museum collections who would assess the rooms or buildings in question and provide a detailed report.

Conclusions

For many years infrared thermal imaging has been used to show where energy is being wasted in buildings, enabling effective energy conservation plans to be devised and savings to be made in carbon dioxide as well as in financial terms. It is now clear that infrared thermal imaging can also be applied effectively in museums as a collections management tool to enable a much more detailed understanding of the subtle, and sometimes not so subtle, environmental differences within a storage or display area. This can help curators to ensure that sensitive specimens are placed in the most appropriate environment available.

Infrared thermal imaging has not been used in museums for collections management purposes simply due to a lack of awareness of the relevance of the technology rather than the cost, which is falling. A large budget for hardware and training is not even necessary as only a relatively small sum would be required to hire an experienced museum professional to get the best possible use out of storage and display areas for the long-term benefit of specimens.

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