Understanding storage environmental stability during power outages: A key issue in sub-tropical climates

Edward Kinfai Tse¹, Waishan Tsui²

¹Government Records Service-Preservation Service Office, Kwun Tong, Kowloon, Hong Kong, ²Conservation Office, Leisure and Cultural Services Department, Kowloon, Hong Kong

Efficient air-conditioning systems facilitate climate control in modern museums, libraries, and archives. The climate in Hong Kong is typically hot and humid, so the survival of collections is highly dependent on 24-hour air-conditioning systems to maintain the desired environment in repositories of archives and books, or artefact stores. The continuous operation of such systems in turn relies on a number of factors, such as uninterrupted electricity supply, an active maintenance programme, daily monitoring of their performance and quick response to irregularities as well as backup or alternative systems to support the air-conditioning load in case they are down for servicing. From the risk management point of view, unlike the latter four factors, electricity supply is an external factor that cannot be guaranteed. Fluctuation in the power level that results in stoppage of air-conditioning equipment is not uncommon even in well-developed countries. Long power outages could be catastrophic as they might lead to irreversible damage to collection items as a result of fast, large, changes in temperature and relative humidity (RH) towards the external environment if the air-tightness or hygrothermal stability of the storage are not good enough. Understanding storage environmental stability, especially during electrical power disruptions, is an essential part of the preservation measures and disaster preparedness necessary to protect valuable collections in cultural heritage institutions in the region.

Keywords: Air-tightness, Hygrothermal behaviour, Power outage, Storage environmental stability, Sundaresan and Krishnaswamy method

Government record services and the Hong Kong public records building

The Government Records Service (GRS) of Hong Kong is the central records management and service agency of the Hong Kong Special Administrative Region Government (HKSARG), responsible for appraising and preserving records of archival value, valuable government publications, and printed materials. The archival holdings are mainly held at the purpose-built Hong Kong Public Records Building (HKPRB), which is an 11-storey building comprising storage facilities, research and study areas, a lecture hall and exhibition hall, and preservation and reprographic studio. Nine of the archive and library repositories and three acclimatization rooms, with floor areas between approximately 7.5 m² (acclimatization room) and 340 m² (large paper repository), have dedicated 24-hour operating air-conditioning systems. A building management system controls all of the air-conditioning systems at fixed set-points of 18 ± 1°C and 50 ± 2% RH for paper material; 13 ± 1°C and 35 ± 2% RH for microfilm material; 2 ± 1°C and 35 ± 2% RH for photographic materials, and 15 ± 1°C and 40 ± 2% RH for electronic record materials. A dedicated direct digital control panel has been installed for each repository. With reference to ISO 11799 Annex B and the capability of the air-conditioning system control, these fixed set-points were adopted about 13 years ago with the intention of restricting temperature and RH variations. These systems provide an air supply with the desired temperature and RH to the repositories by means of industrial grade dehumidifiers and humidifiers, and an air handling unit (AHU) that distributes the conditioned air to the repositories via vents, with the corresponding air return located near the AHU. In addition to ventilation, the specifications also require positive room pressurization.

The Preservation Service Office of the GRS was aware that the existing air-conditioning system was highly dependent on a continuous electricity supply to maintain service, and that power outages would present a risk to the collection. This raised the question...
of how long a power outage would take to harm the archival collections or in the case of machine malfunction, how long the air-conditioning system could be allowed to halt and the interior climatic conditions could be sustained before excessive temperature or RH could bring about damage to the collection. Originally we thought this kind of information might be embedded in the design documents of the HKPRB 13 years ago. It turned out that information regarding air-tightness or thermal insulation was not specified in the design stage of HKPRB but only the allowed mean temperature and RH values and their corresponding fluctuations, which was standard practice at that time. With the objective of determining the buffering capacity of the archival storage in order to deduce the tolerance time of power outages or stoppages of the air-conditioning systems, we therefore developed a functional test in the archival repositories to understand the performance of the building envelope. In a qualitative sense, it is the hygrothermal stability and air-tightness that determine the overall performance of the archival storage.

The main idea of the test was to simulate the situation of a sudden power outage or stoppage of the air-conditioning equipment but in a controlled and well-monitored environment in all the archival repositories of HKPRB and to measure the interior climate responses in terms of temperature and RH. Therefore, after a preliminary study, we are confident that turning off the air-conditioning systems would not trigger a drastic climate change in the interior in a short period of time. We think it is safe to conduct the test in each repository with the archival collection remaining in the storage racks.

**Climate monitoring and testing procedures**

Before the test, 12 climate sensors in the target repositories and an external sensor on the roof of the building were installed. The climate sensors are wireless and can measure and relay the temperature and RH data in real time, to allow simultaneous monitoring of the interior and exterior environment of the repository building. In this way, excessive deviation of the parameters can be detected immediately so that the experiment can be stopped and the air-conditioning system can then be turned on again to restore the storage environmental conditions. One may argue that it is prudent to remove the archival collection from the repository under study first so that the risk of large fluctuations in temperature and RH which are detrimental to the preservation of the collection can be totally eliminated. However, as the archival materials in the store are contributing to its buffering capacity, given the paper materials are in very large quantity (mass) compared to the volume of air, without them, the measurement would not be realistic or could even be deceptive. Even different packing methods or protective storage containers may affect the results. Thus, it is necessary to conduct the test in each repository. The testing procedures started with halting the air-conditioning system for three days in August 2012, with typical external ambient conditions of 28.6°C and 81.0% RH on average (Hong Kong Observatory, 2012), to simulate the effect of a power outage. The sensors recorded and transmitted every 15 minutes. If the buffering capacity of the storage is doubtful, one may adopt a data sampling period of 1 minute or less just to record and monitor the change in temperature and RH. The downside of using a shorter sampling time would be the price of handling the very large quantity of data generated in data storage and data processing which already have a huge degree of redundancy in them.

**Model of response curve**

When there is a power outage or sudden stoppage of air-conditioning equipment, the situation can be considered as a sudden drive or step change stimulation...
to force the interior environment to a level closer to the exterior environment (see Figs. 1 and 2). As the interior condition has already been in an equilibrium state, such a step change stimulation perturbs it to a new equilibrium state. The system response to a step change can be very complicated. Initially the transient state of the response is observed which may fluctuate along the new equilibrium level depending on the time constant of the system and the damping factor or the buffering capacity of the interior climate against change. Then after a certain period of time, the fluctuation dies down and the new equilibrium level is reached; this is the steady state. As this study was intended only for estimating the performance of the building envelope, the process of change can be approximated by a first-order model (see red dotted curve in Fig. 3) with a good extent of agreement in the steady state to simplify the calculation and model-fitting work. Our objective is now simplified to estimating the time constant, the lag time of the model based on the initial observations while monitoring the climate conditions and restoring the air-conditioning when the temperature or relative humidity rise almost to the upper tolerance limit.

**Calculation methodology**

Usually the response can be approximated with the model equation,

\[ y(t) = A \left( 1 - e^{-\frac{t - t_D}{\tau_c}} \right) \]  

where \( y(t) \) is the system response observed over time; 
\( A \) is the magnitude of the step change; 
\( e \) is the exponential constant; 
\( t \) is time; 
\( t_D \) is lag time of response to stimulation; and 
\( \tau_c \) is time constant of the system

Rearrange the model equation to facilitate graph plotting as

\[ \ln \left( \frac{A - y(t)}{A} \right) = -\frac{t}{\tau_c} + \frac{t_D}{\tau_c} \]  

where, in theory, by plotting the natural logarithm of the quantity \((A - y(t))/A\) versus time, a straight line would be obtained. The slope of the straight line would be \(-1/\tau_c\) and the y-intercept would be the ratio \(t_D/\tau_c\). However, since \(A\) is not a known quantity and has to be estimated from the data with a large degree of uncertainty, it is not a feasible method in the present case for estimating the lag time and the time constant.

A common method is to estimate 63.2% of the final equilibrium level less the initial level, as the time taken to reach this level is the sum of the lag time and the time constant (see Fig. 4). The lag time and the time constant can be easily read from the graph, provided that the equilibrium level can be ascertained from the graph.

Another commonly used method to estimate the time constant takes advantage of the fact that the first derivative of the normalized model equation at \(t = 0\) or the initial slope is equal to the reciprocal of the time constant.

\[ \frac{d}{dt} \frac{y(t)}{A} = \frac{1}{\tau_c} e^{-\frac{t - t_D}{\tau_c}} \]  

putting \( t = t_D \),

\[ \frac{d}{dt} \frac{y(t)}{A} \bigg|_{t=0} = \frac{1}{\tau_c} \]  

This last method requires one to draw a tangent at the start of the response curve after the delay time. In reality, since the equilibrium level is unknown, the slope drawn at the start of the curve is actually the ratio, \( A/\tau_c \). With these two methods, the estimated time constant values can be cross-checked against each other and the lag time can be estimated though it is difficult to find accurate values for them.
However, they are quick and easy methods to start with.

The model parameters, such as the time constant and the lag time of the temperature and RH responses in the repositories, could provide insights into the combined heat, air, and moisture transfer of building components, the buildings’ air-tightness and hygrothermal stability performance, and could enable a comparison of their energy use.

The first-order plus time delay model that was employed to approximate the response of the interior temperature and RH to a power outage is essentially an exponential growth curve with extra parameters to account for the delayed response. Since the traditional method of estimating the time constant of the model using the 63% response level is rather difficult to determine from a single point on a graph, a two-point variant, the Sundaresan and Krishnaswamy method (Sundaresan & Krishnaswamy, 1978), was used. This method requires noting the times taken to reach 35.3% and 85.3% of the steady state value (see Fig. 4), which are related in turn to the lag time and time constant by means of simple mathematical relations.

\[
\begin{align*}
    t_D &= 1.29t_{35.3\%} - 0.29t_{85.3\%} \quad (5) \\
    \tau_c &= 0.67(t_{85.3\%} - t_{35.3\%}) \quad (6)
\end{align*}
\]

**Results and discussion**

The parameters estimated from the First-Order Plus Time Delay Model from the observed response data of all the repositories and exhibition areas are shown in Table 1. The estimated time for the storage temperature and RH to a power outage is essentially an exponential growth curve with extra parameters to account for the delayed response. Since the traditional method of estimating the time constant of the model using the 63% response level is rather difficult to determine from a single point on a graph, a two-point variant, the Sundaresan and Krishnaswamy method (Sundaresan & Krishnaswamy, 1978), was used. This method requires noting the times taken to reach 35.3% and 85.3% of the steady state value (see Fig. 4), which are related in turn to the lag time and time constant by means of simple mathematical relations.

\[
\begin{align*}
    t_D &= 1.29t_{35.3\%} - 0.29t_{85.3\%} \quad (5) \\
    \tau_c &= 0.67(t_{85.3\%} - t_{35.3\%}) \quad (6)
\end{align*}
\]

One may easily think that the air-tightness and the extent of insulation of the repositories can be extracted or calculated from the specification of the archive storage building or the design documents of the construction project. There is no need to take the trouble of conducting such an experiment. It is true that some technical information in the design documents may help determine or estimate the target state of the storage. However, we all have the experience that the real situation may not even come close to the original intent of the design. It can only be told by measuring from reality. What the design target represents is the ideal situation, i.e. everything was made strictly according to the specifications without defects in workmanship and construction materials. Even if it is true that the building was constructed according to the specifications, it only holds in the first few months or years after its commissioning. The structure and the construction materials will age over time, usually deteriorating. Hence, the air-tightness and extent of insulation will change and it is expected as time goes by, that deterioration will lead to smaller time constants, shorter delay times and larger responses. It is therefore recommended to conduct the experiment and estimate the parameters for comparison with previous sets after some period of time, say, every 10 years. With these parameter sets in hand, one will then be able to estimate the deterioration rate of the building as a whole.
Table 1 Results of parameters estimated for the First-Order Plus Time Delay Model from the observation data during the simulation of power outage for all repositories and exhibition areas

| Repository      | Parameter         | Specification range | Present range (August 2011) | Lag (hour) | Time constant (min.) | Estimated change range | If no power, estimated to rise to | Time taken to rise out of tolerable limits (hour) |
|-----------------|-------------------|----------------------|-----------------------------|------------|----------------------|------------------------|----------------------------------|-----------------------------------------------|
| Library (1)     | Temperature (°C)  | 18 ± 1               | 20.40 ± 2.95               | 0          | 1145.04              | 4.48                   | 24.88 – 29.31                   | 57                                            |
|                 | RH (%)            | 50 ± 2               | 47.43 ± 4.78               | 0          | 105.00               | 0.57                   | 48.00 – 53.77                   | Very long time                               |
| Library (2)     | Temperature (°C)  | 18 ± 1               | 23.10 ± 2.37               | 0.25       | 510.20               | 3.28                   | 24.58 – 27.88                   | 26                                            |
|                 | RH (%)            | 50 ± 2               | 51.37 ± 4.27               | 0.75       | 270.76               | 5.20                   | 56.57 – 59.93                   | Very long time                               |
| Paper (1)       | Temperature (°C)  | 18 ± 1               | 17.70 ± 1.67               | 0          | 539.57               | 2.50                   | 20.20 – 22.66                   | Very long time                               |
|                 | RH (%)            | 50 ± 2               | 50.83 ± 5.00               | 0.25       | Cannot be estimated  |                        |                                  |                                               |
| Paper (2)       | Temperature (°C)  | 18 ± 1               | 19.13 ± 1.43               | 0.25       | 652.17               | 1.94                   | 21.06 – 23.46                   | Very long time                               |
|                 | RH (%)            | 50 ± 2               | 51.28 ± 3.84               | 0          | 218.02               | 4.81                   | 56.08 – 60.08                   | Very long time                               |
| Paper (3)       | Temperature (°C)  | 18 ± 1               | 18.70 ± 1.15               | 1          | 646.55               | 2.19                   | 20.89 – 22.79                   | Very long time                               |
|                 | RH (%)            | 50 ± 2               | 47.27 ± 5.68               | 0          | 545.45               | 17.48                  | 64.75 – 72.58                   | 27                                            |
| Paper (4)       | Temperature (°C)  | 18 ± 1               | 18.75 ± 0.73               | 0          | 657.89               | 3.09                   | 21.64 – 22.59                   | Very long time                               |
|                 | RH (%)            | 50 ± 2               | 46.78 ± 3.51               | 0          | 329.67               | 2.92                   | 49.69 – 53.69                   | Very long time                               |
| Photographic    | Temperature (°C)  | 2 ± 1                | 1.40 ± 3.60                | 0          | 477.71               | 5.95                   | 7.35 – 13.75                    | 24                                            |
| Microfilm       | Temperature (°C)  | 13 ± 1               | 13.63 ± 2.37               | 0          | 852.27               | 2.05                   | 15.68 – 19.08                   | Very long time                               |
|                 | RH (%)            | 35 ± 2               | 31.80 ± 8.63               | 0          | 2542.37              | 16.20                  | 48.00 – 57.30                   | 127                                           |
| Photographic    | Temperature (°C)  | 13 ± 1               | 13.63 ± 2.37               | 0          | 852.27               | 2.05                   | 15.68 – 19.08                   | Very long time                               |
| Microfilm       | RH (%)            | 35 ± 2               | 31.80 ± 8.63               | 0          | 2542.37              | 16.20                  | 48.00 – 57.30                   | 127                                           |
| e-Record        | Temperature (°C)  | 15 ± 1               | 16.13 ± 2.78               | 0          | 464.40               | 4.09                   | 20.23 – 24.63                   | 23                                            |
|                 | RH (%)            | 40 ± 2               | 43.33 ± 5.37               | 6.75       | 2941.18              | 6.30                   | 49.63 – 55.47                   | 147                                           |
| Exhibition hall | Temperature (°C)  | 18 ± 1               | 21.10 ± 2.25               | 0.25       | 519.03               | 3.07                   | 24.17 – 26.70                   | 26                                            |
|                 | RH (%)            | 50 ± 2               | 50.38 ± 5.90               | 8.75       | 355.45               | 7.54                   | 57.92 – 65.74                   | 27                                            |
Moreover, it would not be surprising to find that the rate of change in the parameter sets in each repository may be different from one another.

The result of this experiment also provides a foundation for further investigation of the practicable range of temperature and RH of the repository. We understand our current practice of controlling the environment is expensive and challenging and we also reckon that the impetus of reducing carbon footprint and environmental sustainability will prompt us to review the current environmental specification. However, due to the fact that the temperature and humidity levels in Hong Kong are generally high in all seasons with one or two weeks of drastic fall in the two coldest months of the year, it is essential to maintain a stable environment of the repository to preserve our various kinds of collection. We therefore need to collect more evidence to inform our decision on the practicable range of temperature and RH of the repository. The data we collected in this experiment identify the degree of air-tightness and insulation of each repository that can certainly help us to further investigate the correlations between the mechanical feasibility of the air-conditioning system and the prevailing climate of each repository. We also need to assess the risk to the collection from the environmental conditions we measured that fall outside our specifications. Understanding the environmental behaviour of the repository is therefore the first step to review the environmental specifications.

The archive’s building fabrication and materials govern the microclimate for the collections stored within. Air-conditioning systems are the most common approach to achieve international environmental standards, and to counteract the deleterious effects of a hot and humid climate. Our experience suggests that optimizing the efficiency of the existing building envelope as a preservation enclosure for the collections should be considered as a more effective approach in preventive conservation. Understanding the hygrothermal behaviour of the storage building envelope through functional testing is therefore to be recommended. The more we understand the building envelope and its performance, the more we can further refine the settings for the environmental control of storage areas, thus facilitating sustainable conservation.

Acknowledgement
The authors gratefully acknowledge the GRS of Hong Kong for their immense support for the project.

References
Hong Kong Observatory. 2012. The Weather of August 2012. Available at: http://www.hko.gov.hk/wxinfo/pastwx/mws201208.htm.
Sundaresan, K.R. & Krishnaswamy, P.R. 1978. Estimation of Time Delay Time Constant Parameters in Time, Frequency, and Laplace Domains. The Canadian Journal of Chemical Engineering, 56(2): 257–62.