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Improving Environmental Conditions in the Tomb of Tutankhamen

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ABSTRACT

The tomb of Tutankhamen in the Valley of the Kings, Egypt, one of the major attractions of the World Heritage Site of Ancient Thebes and its Necropolis on the West Bank of modern day Luxor, is today a destination for mass tourism. Visitors to the tomb increase relative humidity, elevate carbon dioxide levels, and encourage natural ventilation which facilitates entry of dust into the tomb. These conditions negatively impact the wall paintings and remaining artifacts in the tomb and create an uncomfortable environment for visitors. The deposition of dust inside the tomb collects on uneven wall painting surfaces, obscures their legibility and necessitates cycles of cleaning, which in turn leads to further damage. Developing environmental management strategies in the tomb to counter the effects of visitors and mitigate dust entry is an important component of the collaborative project between the Getty Conservation Institute (GCI) and Egypt's Ministry of Antiquities (MoA) to conserve the tomb. These included implementation of a filtered-air supply and exhaust ventilation system to stabilize the interior microclimate and reduce dust in order to improve visitor comfort and contribute to the long-term preservation of the tomb.

ARTICLE HISTORY

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KEYWORDS

Wall painting; preventive conservation; monitoring; ventilation; dust deposition

Introduction

Since its discovery in 1922, the tomb of Tutankhamen (KV 62) in the Valley of the Kings, Egypt, has been subject to a steady influx of visitors. One of the major attractions of the World Heritage Site of Ancient Thebes and its Necropolis on the West Bank of modern-day Luxor, the tomb is today a destination for mass tourism. The condition of the tomb and the influence of visitors on its environment were studied as part of the collaborative project between the Getty Conservation Institute (GCI) and Egypt's Ministry of Antiquities (MoA) to conserve the tomb. Environmental data reveal that visitors increase relative humidity, elevate carbon dioxide levels and, along with natural ventilation into the tomb, promote the entry of fine airborne particulates. These conditions negatively impact the wall paintings and remaining artifacts in the tomb and create an uncomfortable environment for visitors. Especially challenging has been the deposition of dust inside the tomb which settles on uneven surfaces of painted walls and obscures their legibility (Figure 1 (a)). This has instigated a number of cleaning campaigns, undertaken prior to the start of the current project, which contributed to numerous losses in the painting (Figure 1 (b)). Maintenance of this kind, such as dusting, increases the risk of future damage to the wall paintings and the frequency of these actions should therefore be minimized.

Developing environmental management strategies to counter the effects of visitors and reduce dust

accumulation on the paintings is an important component of the overall project to help in the long-term preservation of the tomb. Preventive conservation measures including both stabilization of interior environmental conditions and dust mitigation were implemented through the design and installation of a filtered-air supply and exhaust ventilation system. While collection and evaluation of the monitoring data is continuing, results to date indicate that the ventilation system is effective in regulating the tomb environment and reducing dust.

The tomb and its wall paintings

Today the tomb of the boy king Tutankhamen, (r. 1333–1323 BCE) stands nearly empty apart from the stone sarcophagus and its lid, the outermost gilded wood coffin and the mummy. The rest of the golden treasures were removed to Cairo by the archaeologist Howard Carter and his team in the 1920s and 1930s. The rock cut subterranean tomb is small (277 m³) compared to the others in the Valley of the Kings—as an example, the adjacent tomb of Ramesses V and VI (KV 9) has a volume of 1572 m³—and simple comprising four chambers with only the burial chamber decorated. The paintings hold unique value in terms of their historical significance and subject matter, which depicts scenes of Tutankhamen's journey into the after-life, as well as their artistic style and techniques of



Figure 1. (a) View of the northeast corner of the burial chamber showing dust deposition on the ledges and crannies of the uneven painting surfaces. (b) Detail of flaking paint on the east wall with dust. Cleaning in areas like this has caused loss. Photos: © J. Paul Getty Trust, 2009.

execution (Wong et al. 2012). Understanding the conditions of the tomb and environmental risks to the paintings and the remaining objects was therefore of paramount importance to the project.

The burial chamber paintings were executed on rock walls that were extremely roughly cut. Even with the thin underlying clay plaster layer, the resulting painted surface is highly irregular. At the start of the project, heavy dust accumulation was a common occurrence in the tomb, settling on ledges and crannies, and obscuring the legibility of the paintings. The rate and quantity of dust deposition was most easily grasped by observing the speed at which a blanket

of dust would cover the glass on the sarcophagus in the span of only a few hours (Figure 2). Subsequent dusting of vulnerable areas increases risk of loss of original painting. Dust itself can also be harmful to painted surfaces: containing hygroscopic materials such as clays, it can encourage moisture uptake, damaging paint layers, and can cement itself to surfaces making it difficult to remove (Brimblecombe, Thickett, and Yoon 2009; Wilson-Yang and Burns 1987).

The materials composing the paintings, such as the clay plaster, can likewise encourage moisture uptake when humidity in the tomb environment rises, leading to damaging cycles of expansion and



Figure 2. A guard cleaning the glass cover on the sarcophagus. At the start of the project the glass had to be cleaned frequently to prevent it from being covered with a heavy blanket of dust. Photos: © J. Paul Getty Trust, 2009.

contraction as humidity rises and then falls. Increased humidity in the tomb can therefore contribute to the deterioration of the paintings and is also a concern due to the potential for renewed microbiological growth.

Project background and methodology

The GCI-MoA project began in 2009 when visitation levels to the tomb were high, especially during the peak season (November–April), but this came to an abrupt halt following the Egyptian revolution in early 2011. Since then visitor numbers have been significantly reduced but tourism is now beginning to recover.¹ The project therefore spans periods of high visitation, prior to the 2011 revolution (2009–2010), as well as reduced visitor numbers (2011–2017). Environmental data has been collected since the start of the project in 2009 though some loss of data occurred following the 2011 revolution and again after the *coup d'état* in 2013.

A solar-powered environmental monitoring station was installed at the project's outset to monitor general site climate as well as tomb interior microclimatic conditions. The station records exterior air temperature, relative humidity, solar radiation, wind speed and direction, and rainfall; and, interior air temperature, relative humidity and carbon dioxide in the antechamber and burial chamber at 15-minute intervals. Environmental monitoring station equipment includes: a Campbell Scientific Inc. (CSI) CR10X, later replaced with CR1000 measurement and control datalogger; a Vaisala HMP45C temperature and relative humidity transmitter, later supplemented with Onset HOBO MX1101; a Vaisala GMT220 carbon dioxide transmitter, later replaced with Onset HOBO MX1102; a Licor LI200X silicon pyranometer; an RM Young 05103 wind monitor; Texas Electronics TE525 rain gauge; solar panel, battery and modem.

Identified as an issue of concern within the tomb, dust was characterized with X-ray diffraction spectrometry (XRD, Siemens/Bruker D5005 X-ray powder diffractometer) to identify mineralogical components, high-magnification microscopy to assess physical appearance and quantify particle size distribution (Keyence VHX-6000 digital microscope), and environmental scanning electron microscopy (ESEM, Philips XL30 ESEM-FEG) with an attached energy dispersive X-ray spectroscopy (EDX, Oxford X-Max 80 mm Large Area silicon drift detector) to identify elemental components and provide additional particle size assessment. Rates of dust deposition were also assessed quantitatively using collection pans and qualitatively using a handheld digital microscope (Dino-Lite AD-7013MT) to visually gauge dust accumulation in control areas over fixed periods. Select areas of the burial chamber wall paintings were identified,

brushed clean, and then reimaged to measure the amount of dust deposited over different periods. Assessments of airborne particulates were conducted at various locations within the tomb using handheld particulate counters (Met One GT-521S and Aerocet 531) to examine size fraction concentrations from 0.3 to 10 μm .

The efficacy of the ventilation system in the tomb was largely evaluated by comparisons of the interior environment with and without mechanical ventilation during different seasons. Tomb air change rates were assessed by measuring the dilution of sulfur hexafluoride (SF_6) with a photoacoustic gas monitor (LumaSense Technologies INNOVA 1412) as a means of understanding the impact of ventilation on the tomb environment. Air flow at the supply and exhaust vents was also evaluated by measuring air velocity at these locations using a vane thermomanometer (Dwyer 8901) and multiplying it by the vent surface area.

Finally, experiments to measure the impact of a fixed number of visitors in the tomb for a set length of time with and without mechanical ventilation were undertaken with battery-powered dataloggers (Onset HOBO MX1101 and MX1102) and hand-held sensors.

Results and discussion

Pre-2011 revolution tomb environment

In the pre-2011 revolution period when visitation levels in the tomb were high and no mechanical ventilation was present, environmental monitoring showed a mean air temperature and relative humidity (RH) in the burial chamber of 26.2°C and 28% in winter-spring (November–April) and 28°C and 51% in summer-autumn (May–October), respectively. In 2009, a steady rise in RH and, to a lesser degree, air temperature in the burial chamber can be seen at the start of the summer season in May which peaks in September (Figure 3(a)). A high of 70% RH was reached during this month while exterior RH averaged only 21%. Calculated from concurrent air temperature and RH, the dew point temperature in the burial chamber also followed a similar trend to the RH, and suggests that visitors act as a moisture source within the tomb during the summer-autumn months. Daily fluctuations in RH exceeded 20% during 20% of the 2009 dataset, though the daily fluctuation stabilized below 10% during the rise of interior RH from May to September.

Lack of air movement into and out of the subterranean space contributes to the high RH events as the minimum exterior air temperature often exceeds the air temperature within the tomb (Figure 3(c)). This creates differences in air density and pressure and limits dilution of interior air by exterior air infiltration.

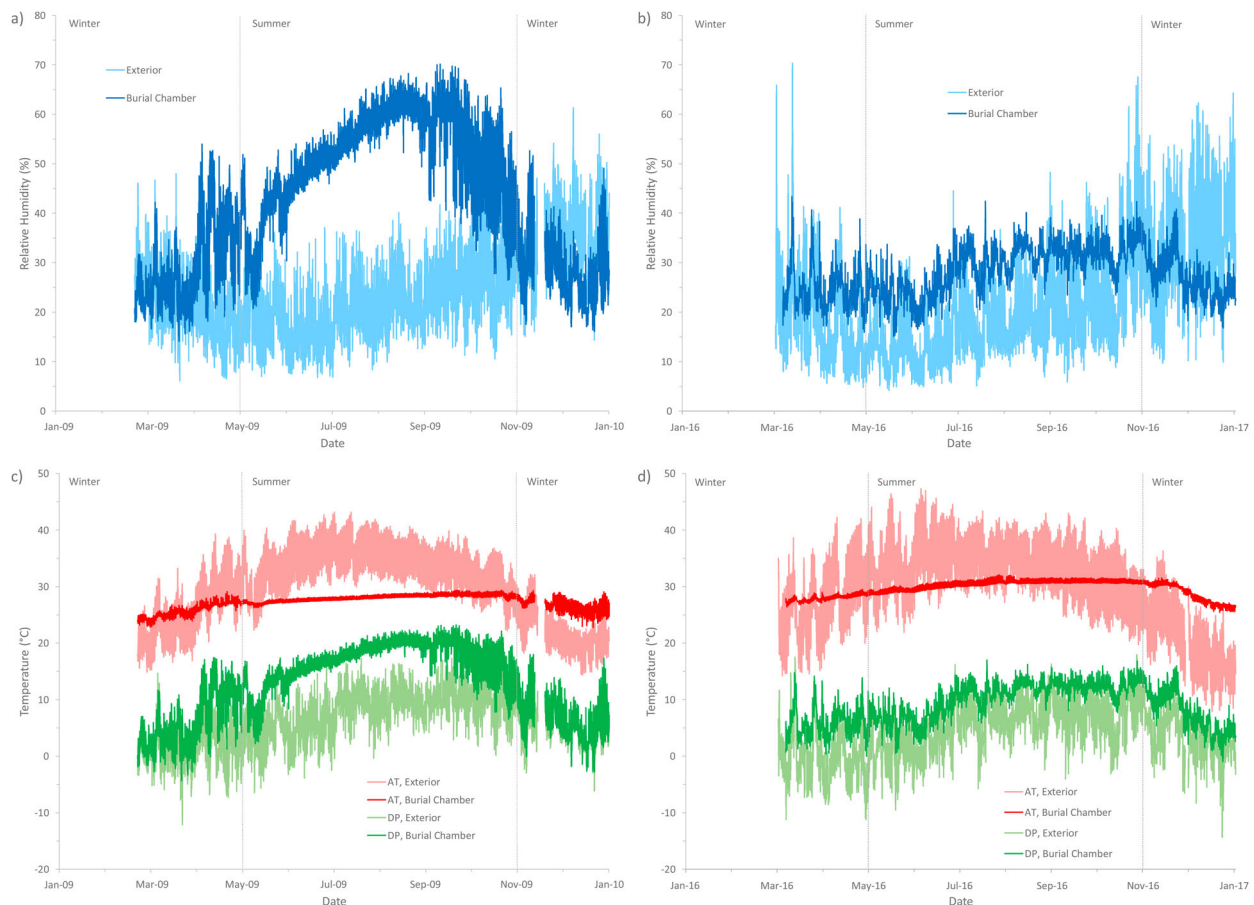


Figure 3. (a) Exterior and interior burial chamber relative humidity in 2009; (b) Compared with 2016 with ventilation system running; (c) Exterior and interior burial chamber ambient temperature and dew point temperature in 2009; (d) Compared with 2016 with ventilation system running. Images: © J. Paul Getty Trust, 2017.

As such, summer-autumn visitation to the tomb, even at levels below that observed during the more popular winter months, may have a cumulative effect on the interior RH. The lack of natural ventilation in the summer-autumn period is also demonstrated in the inability of daily minimum interior carbon dioxide concentrations to return to the baseline conditions commonly observed during the winter season.

By contrast, in winter, exterior air temperatures are lower than the tomb interior, which promotes natural ventilation and results in interior RH that more closely follows exterior conditions (Figure 3(a) and (c)). The influence of the outside environment is also observed in the similarities between exterior and interior dew point temperatures during the winter months (Figure 3(c)). In order to improve interior conditions throughout the year for the tomb and its paintings, new limits were set for the tomb that sought to limit maximum RH to 60% and daily maximum RH fluctuations to 20%.

During this period of heavy visitation prior to the 2011 revolution, carbon dioxide levels regularly exceeded 3500 ppm (the detection limit of the sensor) throughout the year. A maximum acceptable carbon dioxide limit of 1500 ppm has now been set for the tomb to provide a safe and reasonably

comfortable environment for visitors which takes into consideration background carbon dioxide concentration of 400 ppm (ANSI/ASHRAE 2016). In order to achieve this limit recommendations for daily visitor numbers and length of visit will also be made. The maximum visitor number at the time of writing is set at 20 with a typical length of visit of 10 min.

Dust characterization

The physical appearance of the collected dust samples was characterized under magnification with particular emphasis on particle morphology and fiber content. The dust sample collected from the lower section of the east wall painting using a soft brush contained both brightly colored synthetic and translucent natural fibers. Within this fiber network are bound mineral particles and small paint flakes of various colors (yellow, black, blue, and red). The latter could be a consequence of mechanical abrasion of the painted surface during sample collection (Figure 4). These paint flakes in the wall painting dust sample demonstrate that similar losses may result from cleaning interventions such as dusting.

The mineralogical and elemental composition of dust was investigated by XRD and ESEM-EDX,

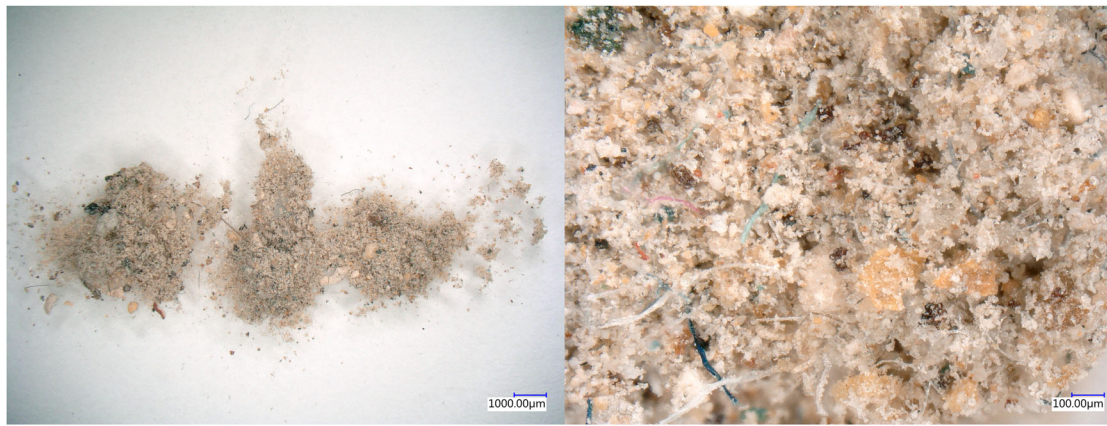


Figure 4. (a) A dust sample from the east wall paintings; (b) Magnified image showing particulate, fibers, and paint flakes. Photos: © J. Paul Getty Trust, 2017.

respectively. Analysis of a dust deposition sample collected from the ‘magical brick niche’ feature on the west wall of the burial chamber showed the presence of calcite, quartz, anhydrite, feldspars, ankerite, and sepiolite, similar in composition to limestone and plaster samples from the tomb and matching results from a dust sample from the Tomb of Amenherkhepshef (QV 55) in the neighboring Valley of the Queens (Demas and Agnew 2012, p. 255). Calcium was observed as a major elemental component in all dust samples, while other samples also included aluminum, magnesium, and phosphorus as significant elements.

Digital microscopy and ESEM-EDX were used to explore particle size and distribution in the dust samples. Analysis of the sample from the east wall painting demonstrated that particles were extremely fine, generally less than 10 µm, but these were often agglomerated and difficult to separate into individual particles using dispersion between two glass slides with ethylene glycol as the dispersant.

Ventilation system

Mechanical ventilation systems have been installed at other sites such as the Scrovegni Chapel in Padua (Basile et al. 2005), the Sistine Chapel in the Vatican (Grabon et al. 2015), and a new system is planned for the refectory of the convent of Santa Maria delle Grazie in Milan (Freeman 2017) which already places restrictions on visitor numbers. These systems and visitor limits are designed to counter the negative impact of visitors and pollutants on the monuments and their wall paintings.

In the tomb of Tutankhamen, elevated interior humidity and carbon dioxide levels were the initial reasons behind the decision to install ventilation in the tomb. Concern over dust accumulation on the wall paintings further supported this decision and led to the filtered-air supply being added to the design of the system. Installed in October 2015 and operated

during visitation hours (approximately 6am–5pm), the ventilation system supplies filtered ‘clean’ air at the south end of the visitor platform and then extracts the ‘dirty’ air at the north end, thus enveloping the visitors in the antechamber and limiting spread of the dirty air into the burial chamber (Figure 5(b)). Visitors are not allowed access into the burial chamber.

Supply and exhaust fans are located outside of the tomb, placed behind a low stone masonry site wall that provides acoustic and visual screening² (Figure 5 (a)). Air is distributed to and from diffusers and grilles inside the tomb by rectangular galvanized sheet metal ducts, which are concealed beneath a new raised floor assembly in the antechamber and by medium density fiberboard (MDF) panels in the corridor. In most areas, for efficiency, the duct cross section does not exceed a width to height aspect ratio of 1:4; however, the ratio is higher in narrow areas of the tomb, such as the entry ramp, stairs, and door jambs, to allow sufficient space for visitors to pass next to the ductwork.

Based on assumed rates of carbon dioxide (4 cm³/s) and moisture (100 g/hr) production per person and a capacity of 25 visitors (determined by the maximum physical space within the antechamber), the recommended air supply and extraction air flows were 330 L/s. In practice, however, the supply air flow was set to 430 L/s as a means of slightly over-pressurizing the tomb to reduce the infiltration of unfiltered air (through natural ventilation) and to compensate for filters as they begin to clog. The exhaust air flow was found to be 236 L/s perhaps due to leakages in the ductwork. Air flow is regularly assessed at the supply and exhaust vents to evaluate the operating efficiency of the ventilation system.

Recommendations for filtering the air supply were for a G4 (MERV 7–8) washable pre-filter and a F8 (MERV 14) bag filter. The particle size efficiency of the bag filter should reduce both the larger and smaller size fractions, 90% or better reduction for the 3.0–

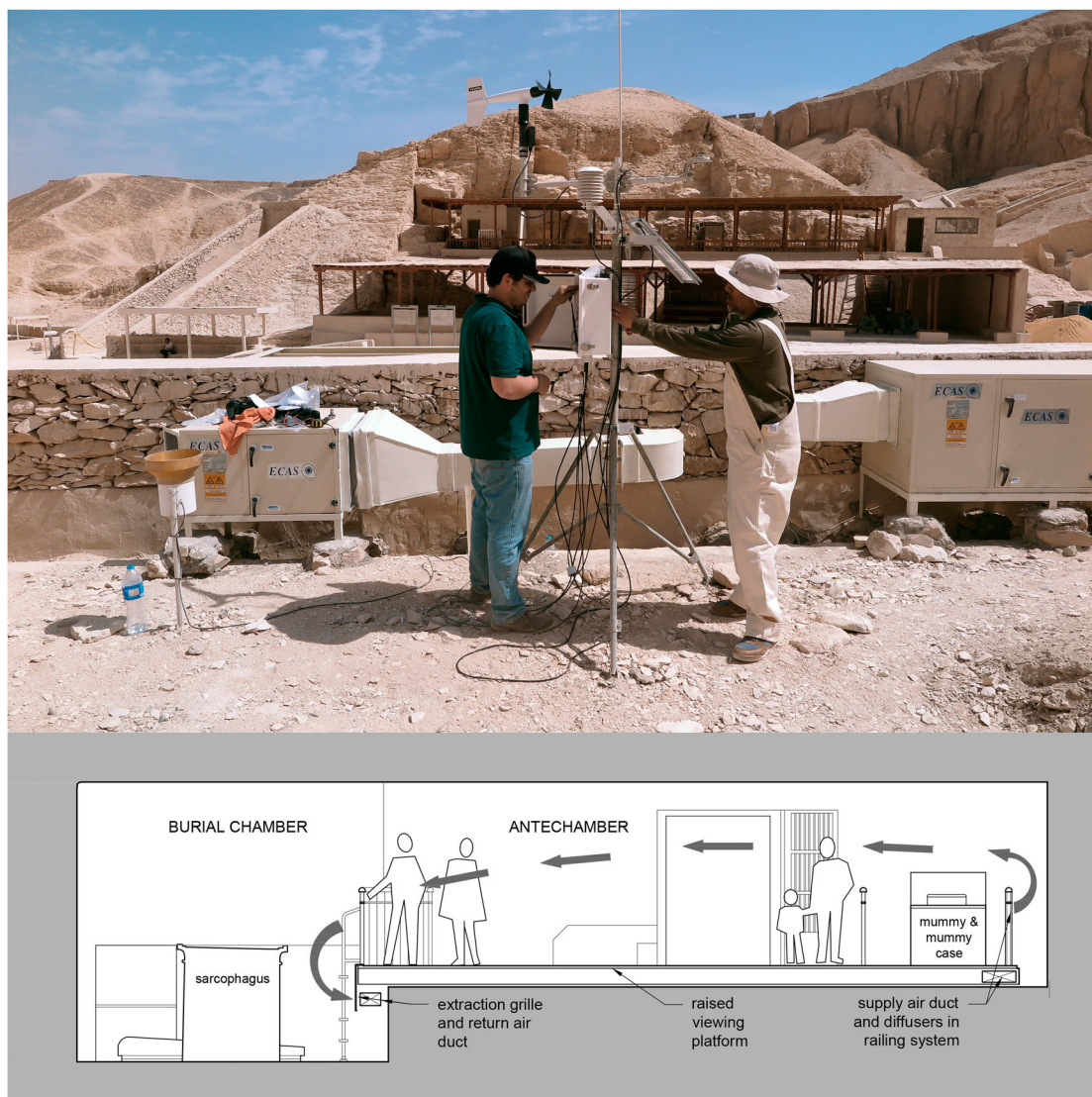


Figure 5. (a) The ventilation system and weather station; (b) A schematic cross section of the ventilation system, illustrating the locations of supply air diffusers and extraction grilles, and visualization of air flow across the antechamber tomb and burial chamber. Photo: © J. Paul Getty Trust, 2016. Graphic: © J. Paul Getty Trust, 2018.

10 μm and 1.0 μm –3.0 μm size fractions, and 75% to 85% reduction for the 0.3–1.0 μm fraction (ASHRAE 2007). In practice, a G3 filter (MERV 5–6) was installed due to the difficulty of obtaining the G4 filter in Egypt. Regular cleaning of the pre-filter and replacement of the bag filter is being undertaken by local workers. Study of the post-installation environmental conditions is ongoing in order to determine the optimal schedule for filter replacement.

Prior to installation of the ventilation system, the tomb was thoroughly cleaned to prevent recirculation of dust already in the tomb; metal grille flooring was installed outside the tomb entrance to trap dust from shoes prior to entry; the entrance to the tomb was closed off with a masonry wall and solid door to prevent dust entry through natural ventilation at night; and a non-recirculating air curtain was positioned at the entrance door to limit dust transport by visitors and isolate the interior and exterior zones at the entrance, which would decrease the natural

ventilation rate or unfiltered air movement into the tomb. The 1200 mm long air curtain provides an air volume of 1710 m^3/h , with a high speed of 11 m/s and a low speed 9 m/s.

Post-installation tomb environment

Monitoring data collected following installation of the ventilation system when compared with pre-2011 environmental data allows assessment of the effect of the system on the tomb environment. While the post-installation interior air temperature showed a similar trend as seen in pre-2011 data—that is, a narrow band that rises during summer-autumn months—the range of air temperatures in 2016 during this season (28.4–32.1°C) was higher than that seen in 2009 (26.3–29.4°C) (Figure 3(d)). This may be a result of the ventilation system supply drawing in warm exterior air into the tomb, as well as higher exterior temperatures in 2016. Post-installation interior

relative humidity and dew point temperature largely match their exterior values (Figure 3(b) and (d)). In 2016, seasonal values for mean interior relative humidity were 25% in winter-spring and 29% in summer-autumn, the latter reduced from an average of 51% recorded in the summer-autumn of 2009. Improvements were also seen in the daily relative humidity variations, with fluctuations over 20% RH reduced to only 1% of the year compared with 20% in 2009.

The fact that the summer-autumn dew point temperature inside the tomb is similar to that of the exterior suggests that the ventilation system is bringing dry air into the tomb and mitigating moisture added by visitors. Additionally, peak interior carbon dioxide concentrations following installation of the ventilation system (1500–2000 ppm) were below the maximum levels observed before 2011 (~3500 ppm) and occur with much less frequency, implying the dilution of interior air with that of the exterior. However, as 2016 visitor numbers remain well below the pre-2011 revolution level, it is difficult to demonstrate adequately the role of the ventilation system in improving the tomb environment. Though designed to accommodate the heavy visitation previously observed at the site, the ventilation system is addressing a current environment in which reduced visitation has already decreased the moisture and carbon dioxide levels in the tomb.

Air change

Defined as a measure of the frequency at which the air is replaced per hour, the air change within the tomb can have a significant effect on interior environmental conditions. Air movement can be influenced by the movement of visitors, the architectural layout of the tomb and its geometry, ventilation (natural and mechanical), and seasonal environmental variations, particularly the gradient between interior and exterior air temperature. Measurements of air change in the tomb provided further insight into the infiltration of exterior air. Assessments conducted without mechanical ventilation during the winter months (~1.5 air changes per hour or ACH) differed considerably from those carried out in the summer (~0.1 ACH). Winter air change measurements typically coincided with warmer burial chamber air temperatures compared to that of the exterior, while summer measurements corresponded with exterior air temperatures greatly exceeding that of the interior by as much as ~15°C. With an operating ventilation system, air change in the tomb during winter increased from ~1.5 ACH to ~2.5 ACH and ~0.1 ACH to ~3.1 ACH during summer. Understanding the sources of air entering the tomb, through natural and mechanical ventilation, is important for preventing dust entry into the tomb.

Visitor impact experiments

Similar to a previous study conducted in the tomb of Nefertari (QV 66) in the adjacent Valley of the Queens (Maekawa and Preusser 1993), visitor impact experiments in the tomb of Tutankhamen evaluated interior air temperature, relative humidity, dew point temperature and carbon dioxide when exposed to a fixed visitor number and duration. The experiments were conducted during the winter with and without operation of the ventilation system to allow for the comparison of visitor effects on the tomb environment during periods of mechanical and natural ventilation.

The initial phase of each experiment emptied the tomb for 20 min, during which air temperature, RH, and carbon dioxide appeared to exhibit slight decreases. Once visitors (~20) entered the tomb for a predetermined period (5 or 30 min), immediate increases in RH, dew point temperature, and carbon dioxide were apparent along the visitor path into the tomb (i.e. entrance stairway and corridor) and in the antechamber. At the end of the time period, the tomb was again emptied for 20 min and environmental conditions were monitored. While a return to pre-experiment levels was observed with mechanical ventilation, the interior conditions were unable to recover to baseline levels when the ventilation system was turned off. This indicates that periods of visitation without natural ventilation, as occurs during the summer-autumn season, may lead to significant increases in moisture and carbon dioxide.

Airborne particulates

Though variability was observed in the in situ readings of airborne particulates due to a range of factors including visitation and active conservation work, the assessment of size fractions from 0.3 to 10 µm showed that the smaller airborne particles consistently exhibited the highest concentrations. In terms of distribution within the tomb, particulate levels at the interior supply vent on the south end of the antechamber remained lowest, indicating a reduction of airborne particulates by the filtration system. By comparison, particulate concentrations in the burial chamber were elevated, likely associated with dust transport into the tomb from visitation and natural ventilation. Installation of an air curtain at the tomb entrance should aid in limiting dust entry into the tomb. Measurements at each location were also conducted at multiple heights (~0.5, 1, and 2 m) to explore vertical distribution, however, no stratification in airborne particulate concentrations was observed. The impact of filter replacement on airborne particulates is significant and therefore regular maintenance of the ventilation system to ensure optimal operating conditions is required.

Conclusions

At present, the improvements in environmental conditions within the tomb are significant and will contribute to the preservation of the wall paintings and remaining artifacts. Continued evaluation of the filtered-air supply and exhaust ventilation system is expected to show ongoing stabilization in RH and carbon dioxide levels as well as reduction of dust inside the tomb. However, the overall effectiveness of the ventilation system on the stabilization and improvement in tomb environmental conditions will only be fully evaluated when visitor numbers return to their pre-2011 levels. Furthermore, the ventilation system itself, is not without its own challenges, requiring periodic maintenance and eventual servicing that poses yet unanswered questions about its future sustainability and replicability at other sites.

Dedication

The authors announce with regret the passing in 2016 of our colleague Shin Maekawa who made significant and lasting contributions to the preservation of Egypt's cultural heritage through GCI collaborative projects over more than twenty-five years, and dedicate this paper to him. Shin was a long-serving member of the GCI (1989–2016). In addition to his involvement in the tomb of Tutankhamen and Valley of the Queens projects in Egypt, he also conducted environmental work at Herculaneum in Italy, at the Mogao Grottoes at Dunhuang, China, and at the iconic mid twentieth-century Eames House in Los Angeles to name but a few of the multitude of field projects in which he participated. Shin also engaged in nitrogen anoxia research, leading to the development of oxygen-free museum display cases for the mummy collection in the Egyptian Museum in Cairo, and later for the Constitution of India documents in New Delhi. Shin went on to spearhead research into collections in hot and humid environments, co-authoring the 2015 publication *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates*.

Notes

1. At its peak in 2010, Egypt received 14.7 million tourists with approximately 9000 per day visiting the Valley of the Kings and of that an estimated 500 per day were going to the tomb of Tutankhamen, which requires purchase of an additional ticket (sources: Weeks and Hetherington 2014 and Central Agency for Public Mobilization and Statistics (CAPMAS)). In 2016, there were only 5.4 million tourists but in 2017, Egypt was the second fastest growing tourist destination in the world (source: UNWTO World Tourism Barometer, vol. 15, August 2017). Yearly visitor data to the tomb of Tutankhamen based on ticket sales in 2010 numbered

136,061 compared with 108,961 in 2017, indicating that tourism is indeed starting to rebound (source: MoA).

2. The supply fan (type BDB-250 CM double inlet centrifugal fan with backward curved impellers) and exhaust fan (type CBP 7/7) were manufactured by Soler & Palau Sistemas de Ventilación, S.L.U. of Spain and assembled in boxes and fan cabinets with acoustic insulation and vibration mounting in Egypt by Egyptian Company for Air Systems.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

- ANSI/ASHRAE (American National Standard Institute (ANSI)/ American Society of Heating, Refrigerating, and Air-Conditioning Engineers). 2016. *Standard 62.1-2016 – Ventilation for Acceptable Indoor Air Quality*. Atlanta: ASHRAE.
- ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers). 2007. *Standard 52.2-2007 – Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Atlanta: ASHRAE.
- Basile, G., E. Mancinelli, M. Marabelli, P. Santopadre, M. Ioele, V. Fassina, A. G. Stevan, R. Cesareo, and A. Castellano. 2005. "The Scrovegni Chapel. Multidisciplinary Research and Environmental Protection." *ICOMOS-Heft des Deutschen Nationalkomitees* 42: 85–98.
- Brimblecombe, P., D. Thickett, and Y. H. Yoon. 2009. "The Cementation of Coarse Dust to Indoor Surfaces." *Journal of Cultural Heritage* 10: 410–414.
- Demas, M., and N. Agnew, eds. 2012. *Valley of the Queens Assessment Report: A Collaborative Project of the Getty Conservation Institute and the Supreme Council of Antiquities, Egypt*. Vol. 1, Conservation and Management Planning. Los Angeles: Getty Conservation Institute.
- Freeman, N. 2017. "Helping to Save Leonardo da Vinci's 'Last Supper' with 'Advanced Air Filtration System'." *ArtNews*. Posted on 4/12/17. Accessed February 24, 2018. <http://www.artnews.com/2017/04/12/eataly-helping-to-save-leonardo-da-vincis-last-supper-with-advanced-air-filtration-system/>.
- Grabon, M., J. Anderson, P. Bushnell, A. Calvo, and W. Chadwick. 2015. "The Sistine Chapel: New HVAC System for Cultural Preservation." *ASHRAE Journal* 57: 20–34.

- Maekawa, S., and F. Preusser. 1993. "Environmental Monitoring at the Tomb of Nefertari." In *ICOM-CC 10th Triennial Meeting, Washington D.C. Preprints*, edited by J. Bridgland, 616–623. Paris: ICOM Committee for Conservation.
- Weeks, K. R., and N. J. Hetherington. 2014. *The Valley of the Kings: A Site Management Handbook*. New York: The American University in Cairo Press.
- Wilson-Yang, K. M., and G. Burns. 1987. "The X-ray Photoelectron Spectroscopy of Ancient Murals in the Tombs at Beni Hasan, Egypt." *Canadian Journal of Chemistry* 65 (5): 1058–1064.
- Wong, L., S. Rickerby, A. Rava, A. Phenix, J. Mazurek, and R. Kamel. 2012. "Examination of the Wall Paintings in Tutankhamen's Tomb: Inconsistencies in Original Technology." In *The Decorative: Conservation and the Applied Arts*, edited by S. Cather, A. Nevin, J. T. Townsend, M. Spring, J. Kirby-Atkinson, and D. Eastop, *Studies in Conservation* S322–S330. London: International Institute for Conservation.