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USING ENVIRONMENTAL MONITORING DATA TO ASSESS THE EFFECTIVENESS OF COOLING FOR OBJECT TEMPERATURE CONTROL

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ABSTRACT

Limoges enamels are temperature sensitive with increased risk of damage at high temperatures. Acoustic emission (AE) monitoring has shown the AE energy increases with large diurnal increases in temperature. During previous heatwaves at Ranger's House, pieces of glass from the objects' decorative surfaces have detached. To prevent damage, chillers are used in the display room. Environmental data analysis considered the performance of the chillers by assessing maximum temperatures and diurnal temperature fluctuations. The results demonstrate the chillers have successfully reduced the maximum temperatures observed in the room, as well as the largest diurnal fluctuations. The chillers have decreased the risk of damage to the collections from high temperatures and handling, by avoiding decanting the collections if high temperatures were expected. However, reducing the temperature increases the RH levels in the room affecting everything in the space, and using active control requires additional energy use. With a 2°C global temperature increase, hot summer days (max daily temperature above 30°C) are predicted to double in frequency at Ranger's House, making summer cooling more desirable for both visitors and temperature sensitive collections. The approach taken to providing local cooling, along with the limitations of the historic space will be discussed. Alternative options will be highlighted, with a view to improving the sustainability of the control method.

KEYWORDS: Limoges enamels, high temperatures, cooling, acoustic emission, environmental data, fluctuations, climate change.

1. INTRODUCTION

The Wernher Collection is a long-term loan, housed at Ranger's House in Greenwich, UK and includes Limoges enamel objects. Wernher's collection of enamels has been described as "striking in its originality" containing "several rare, exceptional pieces" (Thornton, 2002) with most dating from the 16th century. Limoges enamels are layers of glass on a copper plate. Some medieval glass compositions are unstable and sensitive to relative humidity (RH) and pollution (Thickett et al., 2017), which is managed by using showcases and environmental control measures[1] to maintain 40% RH. However, differences in the thermal expansion coefficient between copper and glass create stresses between the layers when temperature changes occur (Thickett et al., 2017), making Limoges enamels sensitive to temperature as well as RH. The Limoges room faces South/South-West, and the building has limited shading or insulation, making this room prone to overheating from solar gain, despite keeping the shutters closed, or the blinds down if the house is open.

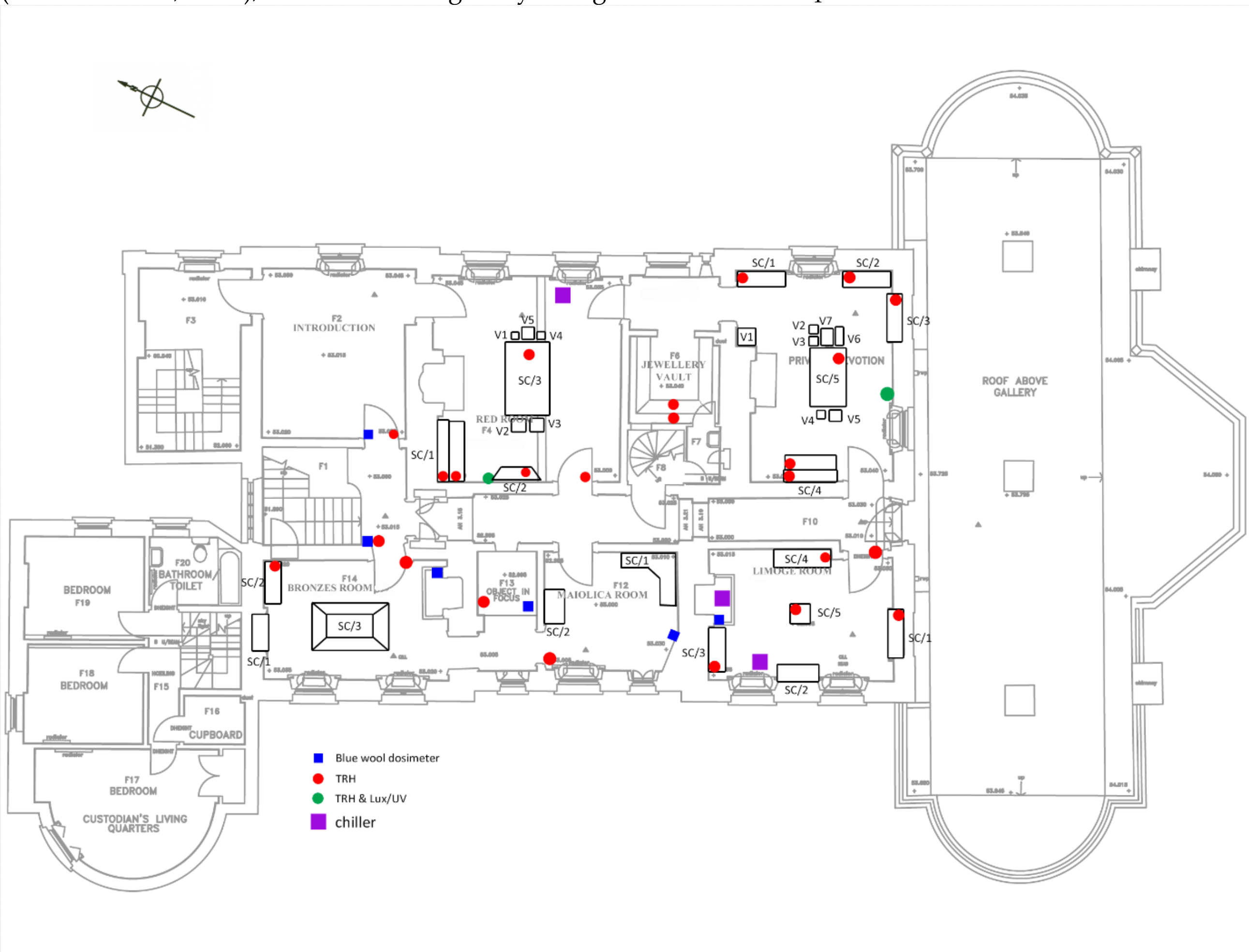

Figure 1. Ranger's House first floor plan showing the location of the chillers (purple squares) in the Limoges room (bottom right). The red room also has a window chiller (top centre). The Maiolica room is located to the left of the Limoges room.

A full timeline of the research relevant to the enamels at Ranger's House is given in the APPENDIX, with key details given here. In 2009 glass fragments spalled from two Limoges enamel plaques at Ranger's House, when temperatures rose above 28.7°C. Following the 2009 damage a chiller (Handleiding Ecos Libretto[2]) was installed in the Limoges room to reduce temperatures during the summer months (generally May-September when temperatures are higher). This was located close to showcase SC3 (Figure 1), using the adjacent window for the exhaust air vent (referred to as window chiller). Due to security concerns, the chiller could only be operated when the house was open, as the window and shutters must be open, meaning it could not be run overnight or on closed days. When the chillers are in use the Limoges room door is kept

[1] Glasbau Hahn RK2/5 RH control units, with Prosorb to allow time to react if the active control fails.

[2] Subsequently replaced by a EcoAir Artica chiller, which vents out of the window during open hours.

closed to improve their effectiveness, with a sign on the door handle to inform visitors the room is open. During the 2018 UK heatwave, temperatures exceeded 30°C and small glass flakes were found within the Limoges enamels showcases (Downes, et al. 2021). This led to some of the collection being decanted and stored in the basement, which is much cooler. As a result of the 2018 damage, the chimney in the Limoges room was lined so a chiller (electriQ P18HP) could be installed to vent constantly via the flue (referred to as chimney chiller), allowing it to run overnight, giving continuous operation, when in use during the summer. The chimney chiller began continuous operation in August 2020. Whilst other forms of cooling are available, small freestanding chillers were selected as Ranger's House is visible from all sides. Installing more permanent equipment would be visible from the outside and thus is unlikely to get planning permission for a Grade I listed[3] building.

Initial work with AE assessed the impact of halogen showcase lighting-induced temperature changes on Limoges enamels (Studer, 2009). The largest number of AE hits were recorded when the case lighting was turned on and heated up. As a result, the halogen case lights were replaced with LED lamps. Further work compared the number of AE events against the daily temperature fluctuation (Thickett, et al., 2012; Thickett, 2018), identifying diurnal temperature changes greater than 2.31-2.35°C led to AE events, with larger temperature changes creating more energetic events.

The 2018 work identified maximum temperatures, and daily fluctuations are important for damage and AE events respectively (Downes, et al. 2021). Using the weather forecast Downes, et al (2021) developed a method to avoid damage from high temperatures; if external temperatures were forecast of 26°C (or above) for six consecutive hours on two adjacent days, collections were to be decanted. Whilst this removes the collection to the cooler basement stores, handling the objects risks damage and prevents visitors from seeing these items. The method to determine when to decant was before the chimney chiller had been installed. Unknowns remained including how effective the chimney chiller was at preventing maximum temperatures being reached and limiting diurnal fluctuations in temperature. In addition, was it still necessary to decant the collection as before? This work used environmental monitoring data to assess the effectiveness of the control approach and understand operational questions around its use.

2. METHODS

Temperature and RH data is collected via a Meaco radiotelemetry system, using Rotronic Hygroclip II probes[4]. Three-point RH calibration for the probes is carried out annually by Meaco. Data from 2018 was used to look at a previous known heatwave,[5] along with data from 2019-2024 for the external sensor, Limoges room, two Limoges showcases (SC3 and SC4) and the adjacent room (Maiolica room), see Figure 1. Whilst data was not complete for all locations across all years (due to radiotelemetry hardware issues), it enabled a good understanding of the effectiveness of the chimney chiller.

The environmental data was assessed to highlight the amount of time spent above 26°C (as a gauge of warm days, related to the forecast temperatures at which collections were decanted) and the amount of time above 28.7°C (the temperature at which glass spalling was known to have occurred). Additionally, the environmental data was processed to determine the magnitude of daily fluctuations within each location. The distribution of the daily fluctuations was then calculated, including looking before and after the chimney chiller was installed in 2020.

3. RESULTS

Data from 1-8 August 2022 is shown in Figure 2. This shows the impact of running the chillers in the Limoges room, with the room (dark red) 5°C cooler than the adjacent Maiolica room (pink) across the week, although the temperature data follows the same trends. The showcases (SC3 and SC4) are located closer to the chillers and are slightly cooler (light red and orange) than the Limoges room, particularly at the maximum temperature. The time at which the maximum temperature in the showcases occurs often lags behind the room (9pm compared to 6pm). The showcase control provides stable RH conditions inside the cases. The room RHs both follow external trends and are influenced by the temperature changes. The Limoges room has a higher RH compared to the Maiolica room, due to the lower temperatures in the Limoges room with the chillers running.

[3] Listed buildings have legal protection due to their special architectural or historic nature. See https://historicengland.org.uk/listing/what-is-designation/listed-buildings/ for further details.

[4] Rotronic are now owned by PST, see https://www.processsensing.com/en-us/products/humidity-probes-hc2a-s-sh-hh.htm for sensor accuracy details.

[5] In London a heatwave is defined as a period of at least three consecutive days with daily maximum temperatures meeting or exceeding 28°C (Met Office, n.d. a)

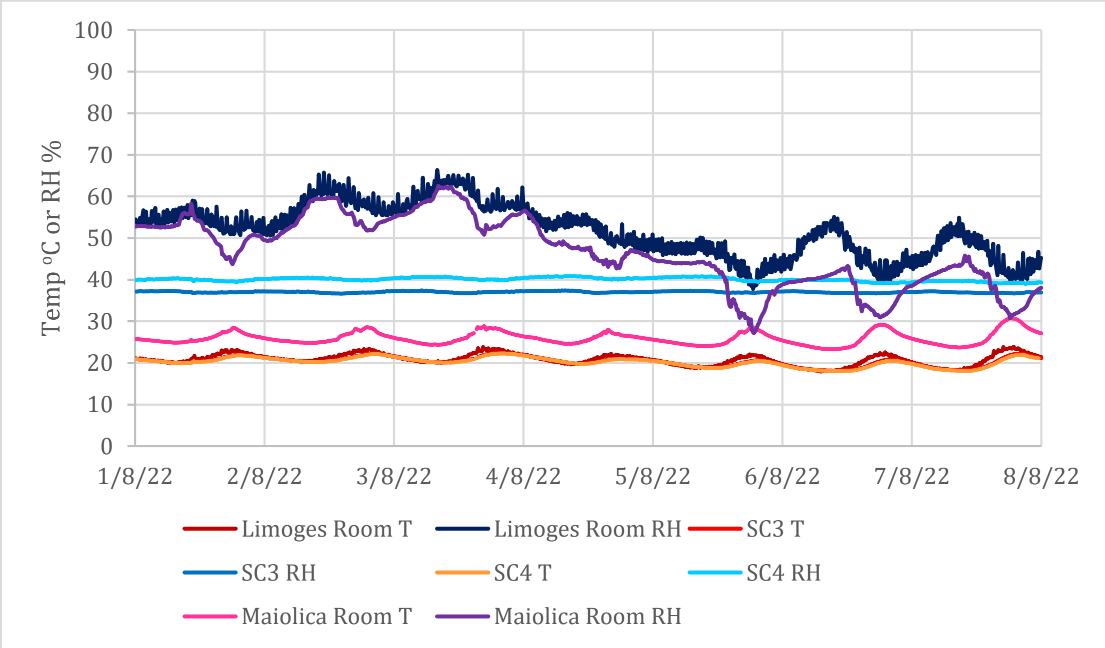

Figure 2. Graph environmental data from 1-8 August 2022 for studied rooms at Ranger's House.

3.1. Maximum temperatures

Table I shows the number of days when the maximum temperature exceeded 26°C (as a gauge of warm days, related to the forecast temperatures at which collections were decanted). The number of days when the maximum temperature exceeded 28.7°C (the temperature at which glass spalling was known to have occurred, Downes et al, 2021) is given in brackets. During the 2018 heatwave the temperature was above 26°C for days at a time in the Limoges room and showcases (SC3 & SC4), with the longest spell in excess of 15 days continuously above 26°C. Whilst the number of days above 26°C in 2019 and 2020 was approximately constant in the Maiolica room, the Limoges room and showcases showed noticeable decreases in 2020, with the continuously operating chiller installed in August 2020. In the Limoges room limited maximum temperatures above 26°C were recorded from 2021 onwards, especially in the showcases, although they are still commonly recorded in the Maiolica room during the summer months. The difference in results between the Limoges room and the showcases, being the proximity of the chillers to the showcases (see Figure 1).

In July 2022 a heatwave led to external temperatures of 40°C being recorded in London. In the Maiolica room a maximum temperature of 36.5°C was recorded, with the room above 26°C for over five days. In comparison a maximum temperature of 28.9°C was recorded in the Limoges room, with the room over 26°C for 8.5 hours. For the showcases, SC3 recorded a maximum of 26.5°C (over 26°C for 4 hours) and SC4 recorded a maximum of 25.8°C. Whilst the room exceeded 28.7°C during the July 2022 heatwave, neither case exceeded this temperature and damage was not observed on the objects, which remained in the showcases. During particularly hot weather the window chiller is utilised (if the house is open) alongside the chimney chiller to provide additional capacity to cool the space.

Table I. Number of days when the maximum temperature exceeded 26°C, figures in brackets indicate the number of days 28.7°C was exceeded. nd = no data *chimney chiller installed in August 2020

Year	External	Limoges room	SC3	SC4	Maiolica room
2018	nd	53 (36)	45 (31)	46 (32)	nd
2019	12 (10)	31 (17)	23 (11)	27 (11)	40 (26)
2020*	29 (17)	17 (8)	4 (0)	16 (8)	41 (26)
2021	20 (10)	7 (0)	0 (0)	0 (0)	nd
2022	46 (24)	12 (3)	4 (2)	4 (2)	62 (35)
2023	36 (17)	7 (0)	0 (0)	0 (0)	44 (18)
2024	nd	16 (2)	2 (0)	2 (0)	44 (17)

In 2022 28.7°C was exceeded in the showcases on two days, during a trial running two chillers on a split hose up the chimney to assess if this method could be used to increase the cooling capacity. During the late evening the hose detached from the flue and the hot exhaust air vented into the room for a number of hours, until staff returned to site and turned off the test. This led to higher temperatures into the early hours of the next day. As a result, only a single chiller is used on the chimney vent.

3.2. *Daily temperature fluctuations*

Distribution graphs assessed the scale of daily fluctuations in temperature. Less than 2.35°C was used as the initial band (blue bars in Figure 3), as AE events were recorded above this value. For the Limoges room (Figure 3 left) diurnal temperature fluctuations are often in excess of 2.35°C, with many between 5-10°C (grey bars in Figure 3). Whilst there is less data for the Maiolica room, the patterns were similar. In the showcases (Figure 3 right) the distribution shows there are smaller daily temperature changes, with less diurnal fluctuations between 5-10°C (grey bars), and most changes less than 5°C (blue or orange bars). This was most clearly seen when splitting the data pre and post the continuous chimney chiller being installed in 2020. In 2021 most showcase diurnal fluctuations are below 2.35°C, but in 2022 this shifted and since then most daily fluctuations are between 2.35-5°C. However, the distribution graphs used data for the whole year, or as much as is available, highlighting that daily temperature fluctuations can exceed 2.35°C outside of the summer months.

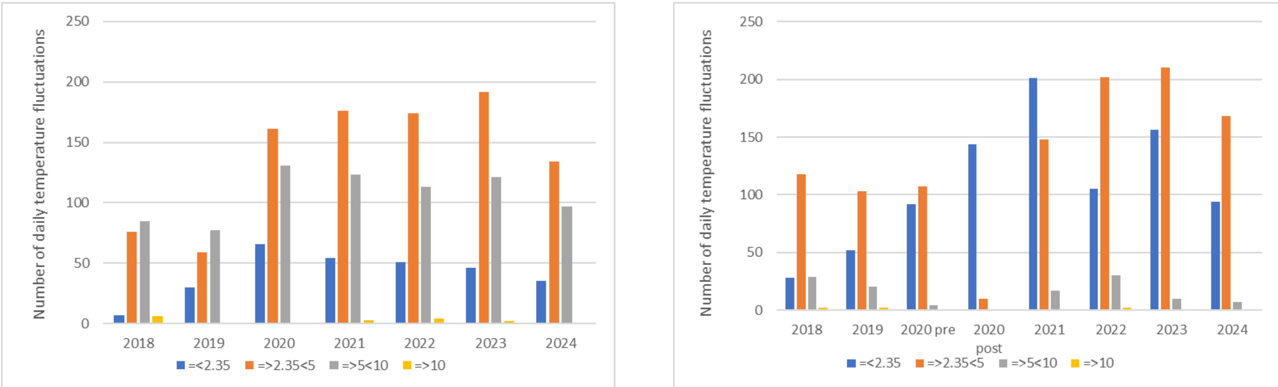

Figure 3. diurnal temperature fluctuations in the Limoges room (left) and showcase SC3 (right)

4. DISCUSSION

4.1. *Current performance*

The environmental data analysis demonstrated that the number of days, and length of time spent above 26°C (used as a gauge of warm days, related to the forecast temperatures at which collections were decanted) has been significantly reduced by introducing the chimney chiller. This has provided reassurance that the collection no longer requires decanting when temperatures are predicted to be above 26°C for more than six hours on two consecutive days. The heatwave in 2022, demonstrated running both chillers can maintain conditions within the Limoges room cases, even in extreme temperatures. However, the duration of the heatwave poses a risk as the Limoges room often gains around 1°C a day. The longer the heatwave, and higher the external temperatures, the more likely the cases are to exceed 26°C, and approach 28.7°C. If 26°C is exceeded regularly inside showcases and for longer periods of time, the collection would need to be decanted to prevent damage from occurring. As a result, the temperatures in the Limoges room are monitored closely during the summer months, alongside the weather forecast when hot weather occurs.

Whilst the chimney chiller has successfully managed to reduce maximum temperatures in the Limoges room, it has been less successful at minimising the daily temperature fluctuations. Although the largest fluctuations have been reduced for the showcases, it was hoped that continuous operation via the chimney vent would mean the diurnal fluctuations were less than 2.35°C, as there would no longer be the on/off impact of the window chiller. In practice the diurnal fluctuations still regularly exceed 2.35°C. The analysis was helpful in highlighting that these fluctuations occur all year round, not just in summer.

4.2. *Future performance and use*

Using the chillers requires additional energy use, as a result operational changes were made during summer 2024. Instead of running the chimney chiller continuously at 16°C and high fan speed, the set point and fan speed was varied based on the weather forecast. This has meant a more active involvement in managing the operation, but hopefully will result in less energy use, whilst temperatures remained suitable for the collection.

2009 was seen as an exceptional event at the time, but was exceeded in 2018 and 2022, and 2024 also had spells of hotter weather. Climate projections indicate that a 2°C global temperature increase[6], would double the frequency of hot summer days (max daily temperature above 30°C) at Ranger's House (Met Office, n.d. b). Projections of future heatwaves are also available. The Climate Change Committee has recommended preparing for a +2°C world and planning for a +4°C world (Climate Change Committee, 2021). Table II shows heatwave projections comparing these two levels with the baseline period, demonstrating that the number and duration of heatwaves, as well as their likelihood, is projected to increase at Ranger's House. Whilst the maximum temperatures are currently being controlled, how long is this achievable for, and how much energy would it take? The sustainability of the approach is being questioned.

Table II. Heatwave projections (UK-CRI.org, 2023)

Global warming level	Number of events per annum	Duration / days	Chance of a heatwave occurring each year
+1°C (2001-2020 baseline period)	1	5	57%
+2°C	2.5	9	87%
+4°C	5.6	27.4	100%

Adaptation options may include taking advantage of the cooler basement environment to create a new display. However, without a lift to the basement, this area is not fully accessible to visitors and would require further investment to make a display in what is currently a behind the scenes staff area. Another option is controlling temperatures in just the showcases, rather than the whole room, much like the existing RK2/5s do for RH control. Glasbau Hahn produce a similar unit that provides temperature control, the T-300 temperature module[7]. Although the ambient operating temperature of the T-300 would likely limit its effectiveness during heatwaves. To determine how effective this approach could be would require additional budget to test a unit in the Limoges room.

Further work is planned to investigate the link between temperature, especially maximum temperatures and AE. Although the diurnal temperature change of 2.35°C is exceeded in winter, no damage has been reported. Whilst AE might be occurring, possibly there is a different mechanism compared to when pieces are lost during heatwaves. With the losses related to maximum temperatures. Further AE monitoring of the collections will assess objects at different points during the year. This will give greater understanding of the diurnal temperature changes and the relationship with maximum temperatures. Understanding this relationship will enable better management of both the collection and environment in the Limoges room.

5. CONCLUSION

The installation of a continuously operating chiller has significantly reduced the maximum temperatures recorded in the Limoges room at Ranger's House. As a result, the risk of damage from high temperatures, leading to loss of surface decoration has been significantly reduced. However, the data analysis shows the chiller has had less impact on the diurnal temperature fluctuations, which are known to lead to AE events. Further work is needed to understand the relationship between AE, diurnal temperature changes, maximum temperatures, and loss of material from the objects surface. Whilst running the chillers uses additional energy, controlling only the Limoges room uses less energy than if cooling the entire building. Although alternative cooling options are available, the Grade I listed building restricts permanent installations, limiting the possible solutions. In future to reduce energy use, redisplay in cooler basement spaces may need to take place, potentially limiting access to the collections, as this space is not accessible for all. Limiting access would reduce the social sustainability, so a holistic assessment of all the needs of collections and users must be made. Environmental management protects collections, but interventions using active control (especially those requiring higher energy use) should be targeted to the specific needs and risks of a collection. At Ranger's House this has meant focussing resources in the Limoges room, to protect the enamels on display, and maintain access for all visitors. Whilst the solution found may not be ideal, it is practical, pragmatic, and successfully protecting the collections on display. However, as climate change continues, it may need to be revisited.

[6] This uses the RCP8.5 scenario to drive the climate model but relates to a temperature increase rather than a time period. The data at each warming level was calculated using a 21-year period, calculated by taking 10 years either side of the first year at which the global warming level is reached. To calculate specific metric values, an average is taken across the 21-year period. Data is available as the median ensemble member, lower (second lowest ranked member) and upper (second highest ranked member), indicating the range of uncertainty of plausible future outcomes.

[7] See https://www.glasbau-hahn.de/en/climate-control

Author Contributions: Conceptualization, methodology, data analysis, supervision and writing - original draft preparation and review and editing, NL; data analysis TB; conceptualization, writing – review and editing, DT; methodology, data analysis and writing – review and editing PL. All authors have read and agreed to the published version of the manuscript.

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APPENDIX
TIMELINE OF RELEVANT RESEARCH AND INVESTIGATIONS ON ENAMELS AT RANGER'S HOUSE (SEE REFERENCES ABOVE)

2002-2004 English Heritage commission UCL to assess climate change impacts, identifies likely high temperature increases in London.

2002-2005 Measurement of air exchange rates and assessment of RH performance of showcases at Rangers House.

2003-2004 Assessment of temperature gradients across the Limoges enamels and their display cases (Thickett et al, 2005/6)

2003-2014 Repeat FTIR measurements used to determine the peak splitting distance between the Si-OH peak and Si-O-Na peak, as a measure of the glass deterioration, especially noticeable on blue- and purple- coloured glasses. (Thickett et al, 2017)

2005-2007 Continuing measurement of showcase air exchange rates, clear window case performance is degrading.

2006	Vacuum XRF analysis of different glasses on the Limoges enamels to compare stability and the glass composition. Assessment of XRF analyser's ability to quantify sodium. (Thickett et al, 2017)
2007	Deformation of four enamels measured with laser transducers.
2007	Artsorb cassettes replaced with Rhapid gel sachets to improve RH control.
2008	Carbonyl pollutant concentrations in enamel showcases determined by University of Strathclyde and Gradko. Damaging levels of formic acid identified.
2007-2010	Effects of short low RH periods on enamel appearance assessed with curator.
2007-2011	PhD with University of East Anglia on climate change impacts on collections in historic houses, reinforces temperature increase risk.
2008-2014	Replica glass produced in Poland to mimic the vulnerable blue enamel composition. Trials begin exposing glass and determining gel layer formation with Germanium ATR-FTIR. Glass also used to trial effects of different RH on gel layer formation (unpublished).
2008-2011	Nottingham Trent University designed prototype OCT systems used to assess the gel layers and internal structures of the enamel (Thickett et al, 2017)
2009	Black glass fragments spalled from object after temperatures exceeded 28.7°C
2009	Active climate and pollution control system installed in two showcases with deteriorating enamels to properly control RH. Levels adjusted later from replica glass results.
2009	AE measurements on modern enamel samples (using 16th century glass recipes) and two Limoges objects on display at Ranger's House (Studer, 2009)
2009-2011	AE events compared to daily temperature fluctuations (Thickett et al, 2013)
2010	Window vented chiller installed
2012	Principal component thermography used to highlight presence and location of cracks in the glass (Thickett et al, 2017)
2012-2014	Additional AE events recorded and compared to daily temperature fluctuations and an equation developed to predict AE energy as a function of temperature changes. (Thickett, 2018)
2014	Increased numbers of AE sensors used with very high frequency data collection and triangulation to determine the position of AE events, found higher energy AE signals originated close to the glass-metal interface, suggesting detachment of the glass from the metal. (Downes et al, 2021)
2014	5th ICOM-CC Experts' meeting on Enamel on metal conservation held at Ranger's House.
2018	Flakes of glass found in enamels showcase after temperatures exceeded 37°C, daily inspection for fragments initiated at Ranger's House in Limoges, Red Rooms and Jewellery Vault. Enamels inspected at Apsley House and St Augustine's Abbey.
2018	XRF and FTIR (Germanium ATR microscopy) carried out on glass flakes that had spalled from objects, identified 13 of flakes as other materials and 2 smaller ones as glass. Two larger flakes. Flakes from blue enamel jewellery identified as very recent as no gel layer detected with FTIR (Downes et al, 2021). XRF could not identify which jewellery objects white flakes originated from.
2018	Most vulnerable enamel collections (6 objects from 65) identified and decanted to lower temperature storage. System devised to predict internal temperatures using forecast weather data (compared to monitored data). (Downes et al, 2021)
2019	Heating system converted to humidistatic control to lessen load on conditioning systems.
2019-2020	Chimney adapted to take continuous chiller.
2020	Continuous chimney chiller installed.
2022	UK Met Office Climate Data Portal available (include Hadley model projections on small areas)
2022-2024	Environmental data analysis to assess impact of chillers on max temp and daily temp changes
2023	UK Met Office climate projection website launched.