Research Report Series 37/2023

Conserving Stained Glass Windows Using Tracery and Partial Environmental Protective Glazing

A comparative study on the efficacy of tracery, partial and full environmental protective glazing

Tobit Curteis

Domenico D'Alessandro, Stephen Clare, Jack Clare

Conserving Stained Glass Windows Using Tracery and Partial Environmental Protective Glazing

A comparative study on the efficacy of tracery, partial and full environmental protective glazing

Tobit Curteis

Domenico D’Alessandro, Stephen Clare, Jack Clare

2024

NGR: SX 92108 92550
Print: ISSN 2398-3841
Online: ISSN 2059-4453

For more information email Res.reports@HistoricEngland.org.uk or write to:

Historic England, Fort Cumberland, Fort Cumberland Road, Eastney,
Portsmouth PO4 9LD

Summary

Stained glass windows are works of art in their own right. They also form part of the building envelope, separating the internal and external environments, which makes them vulnerable to environmental damage caused by rain, wind and pollution on the exterior and by condensation on the interior. Over time, this can lead to irreversible damage to the body of the glass and the glass paint. Installing environmental protective glazing (EPG) is generally the only effective way to protect vulnerable historic glass *in situ*.

The main purpose of EPG is to reduce the impact of damaging environmental conditions on the historic glazing by installing a layer of modern glass on the weather side, with the space in-between ventilated to create a thermal buffer for the historic glazing. It has been used in various forms since the late 19th century, with considerable design developments taking place over time.

Our understanding of EPG has improved greatly in recent years, due to detailed theoretical and practical studies, including the Historic England research programme started in 2011. This culminated in the publication of the Historic England research report *Conserving Stained Glass Using Environmental Protective Glazing* in 2017, and the Historic England guidance *Stained Glass Windows: Managing Environmental Deterioration* in 2020 (updated in 2024 to include recommendations for partial and tracery glazing, based on the results of this study). These studies focused on known examples of EPG applied to full lancet type window lights. They confirmed that correctly designed EPG systems afforded effective protection from condensation as well as from rain and wind loading.

In practice, many stained glass windows include intricate shapes and distinctive arrangements rather than the simple geometry of a lancet. To understand how EPG performs when used with smaller glazing sections, this study led by Tobit Curteis and carried out at Exeter Cathedral between 2021 and 2022 considers three different applications:

1. Full EPG applied to a lancet window, to act as a control.
2. Tracery EPG, applied to a tracery light.
3. Partial EPG, applied to a small section of stained glass set within plain quarry glazing.

The research demonstrates that, although there were some minor performance variations, in general the tracery and partial EPG performed in a similar way to full EPG, improving thermal buffering and significantly reducing the risk of condensation on the historic glass surfaces. As with all EPG installations, the general building environment needs to be in

reasonable condition for the EPG to perform most effectively. In practice, every EPG system will need to be designed by an experienced and accredited stained glass conservator to suit the specific constraints of the building and window being treated.

Contributors

Tobit Curteis, Tobit Curteis Associates LLP

Stephen and Jack Clare, Holy Well Glass

Domenico D’Alessandro, Historic England

Acknowledgements

The authors are grateful to the Dean and Chapter of Exeter Cathedral for allowing the research to be carried out in the cathedral; to the cathedral architect, Camilla Finlay of Acanthus Clews Architects, for enabling the tests to be undertaken in conjunction with the conservation project in the Chapel of St Gabriel; and to Robyn Pender of Historic England for support in the design of the research. We would also like to thank Leonie Seliger of the Cathedral Studios at Canterbury Cathedral for reviewing the results of the research. Funding was provided by National Heritage Lottery Fund and Historic England.

Date of survey/research/investigation

Research was carried out between March 2021 and May 2022.

Contact details

Email: Conservation@HistoricEngland.org.uk

Contents

1. Introduction

To the casual observer, often viewing from a distance, stained glass can appear robust: a composition of richly coloured glass within a leaded matrix, supported by durable stone tracery. The reality is very different. Glass is vulnerable to deterioration caused by the interaction between the chemistry of its materials and the surrounding environment. It is the interface between the internal building microclimate and external weather, and, as such, is commonly subjected to extreme environmental conditions.

Figures 1 and 2: Microbiological growth disfiguring and causing damage to the glass paint (left) and loss of body glass due to dissolution on the exterior surface of the glass (right).

Glass can suffer considerable deterioration but show little visible change from a distance. However, at a certain point, artistic detail is lost and, eventually, structural integrity fails. It is then no longer able to provide the functional element of the building envelope for which it was designed.[1]

To control the deterioration of stained glass, it is necessary to control the environment to which it is exposed. One option is to move the historic glass to a stable internal location, such as a museum. However, once removed from its original surrounding, the stained glass loses both its historic context and significance. To conserve the stained glass *in situ*, it is necessary to install a system of secondary glazing. This provides a barrier between the internal and external conditions, and allows the historic glass to be maintained in a more benign environment, thus reducing its chemical deterioration.

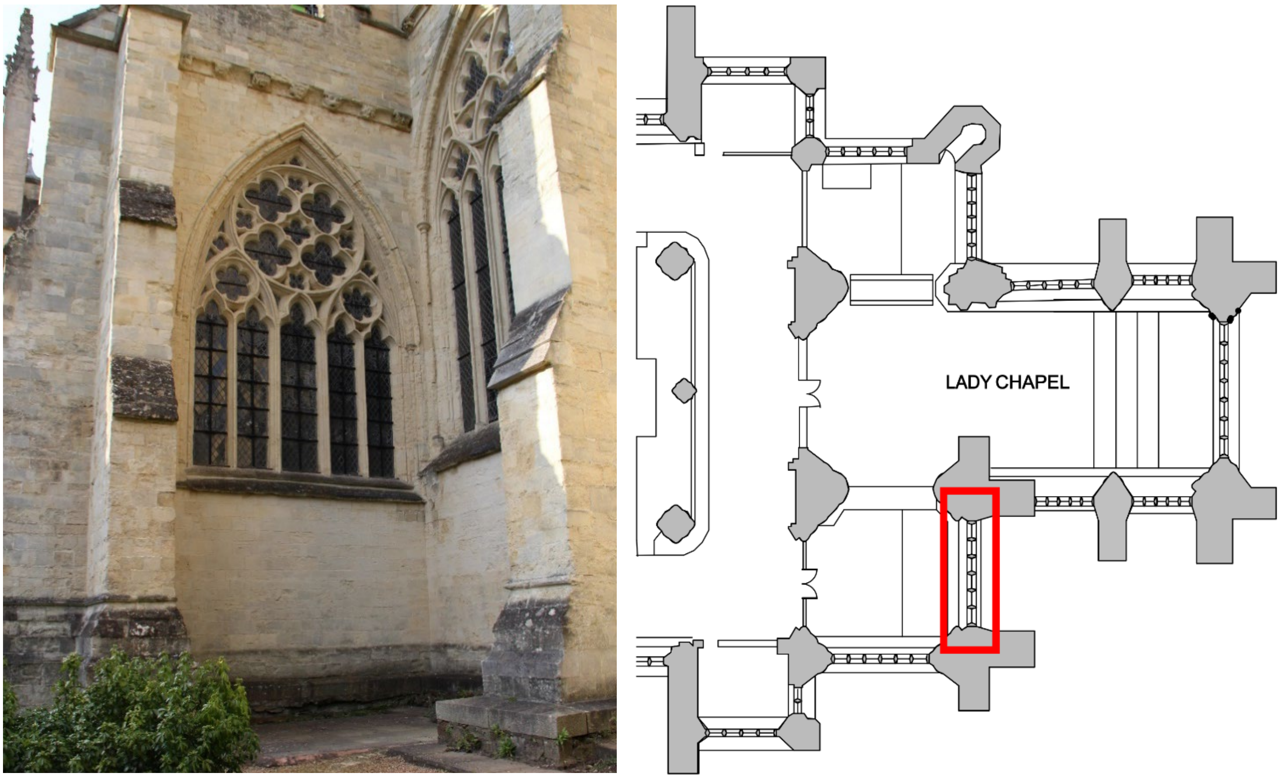
Secondary glazing has been employed since the late 19th century, with designs changing as the understanding of building physics has improved. Previously referred to as 'isothermal glazing', the system is now termed environmental protective glazing (EPG). EPG was the subject of an extensive research project, published as an Historic England Research Report in 2017.[2] This formed the basis for the Historic England guidance on the design of EPG, published in 2020.[3]

While the 2017 report was extremely useful in defining the effective design parameters of EPG, the inclusion of partial and tracery lights would have complicated the results, and so the research was limited to the study of large lancet-type window lights. In reality, the geometry of historic stained-glass windows is far more complex, often including ornate tracery and, in some cases, sections of historic glass inserted into areas of plain glazing.

The results of the 2017 study indicated that the principles relating to air movement and condensation control, that applied to large lancet window lights would also apply to smaller, more irregular glazed spaces – albeit with a reduction in performance due to the inability to provide clear airflow and the smaller gap between the historic and modern glazing layers. Because existing field testing and monitoring on smaller glazed sections was very limited, it was not clear to what extent the benefits of EPG would be reduced for smaller areas of stained glass.

In 2021, cathedral architects, Acanthus Clews Architects in collaboration with Holy Well Glass, carried out an EPG project on the east window at the Chapel of St Gabriel at Exeter Cathedral. It involved applying EPG to small sections of medieval glass set within plain quarry glazing, and also to areas of medieval glass in the tracery at the head of the multi-light window. The Dean and Chapter of Exeter Cathedral allowed testing to be carried out on the partial and tracery EPG installations. A temporary full EPG installation was also constructed on one of the large lancet lights on the window to act as a control.

The EPG was designed and installed by Holy Well Glass, and funding was provided by the National Lottery Heritage Fund and Historic England.



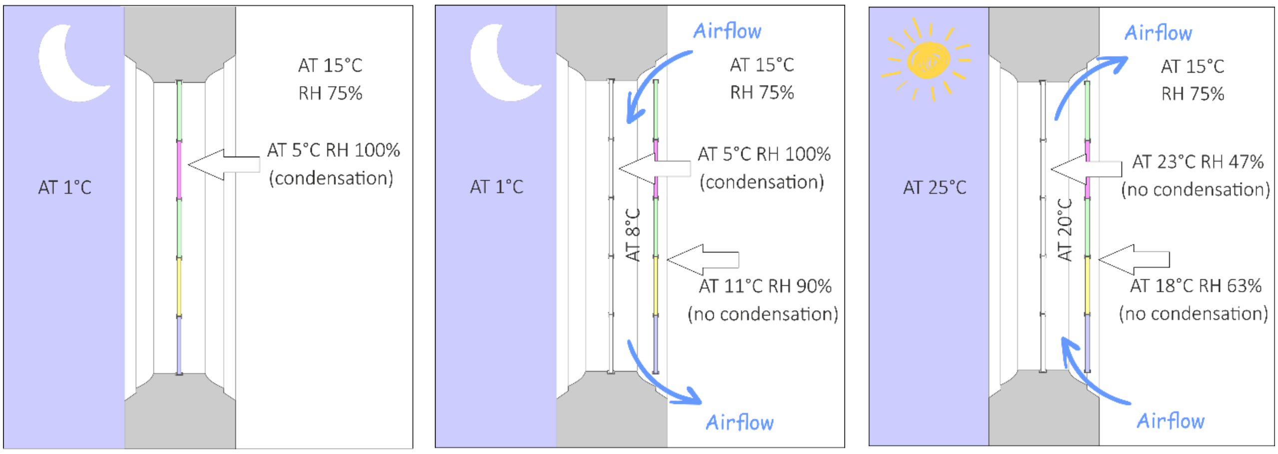
Figures 3 and 4: Plan showing the location of the Chapel of St Gabriel and the external view of the east window. [Figure 4 Drawing © Acanthus Clews Architects]

This research report gives details and results from the EPG project at the Chapel of St Gabriel. It does not address the question of the aesthetics of EPG which is considered in detail in the 2017 study. The report will form the basis for an update to the Historic England guidance document published in 2020.

2. How EPG works

2.1. EPG design

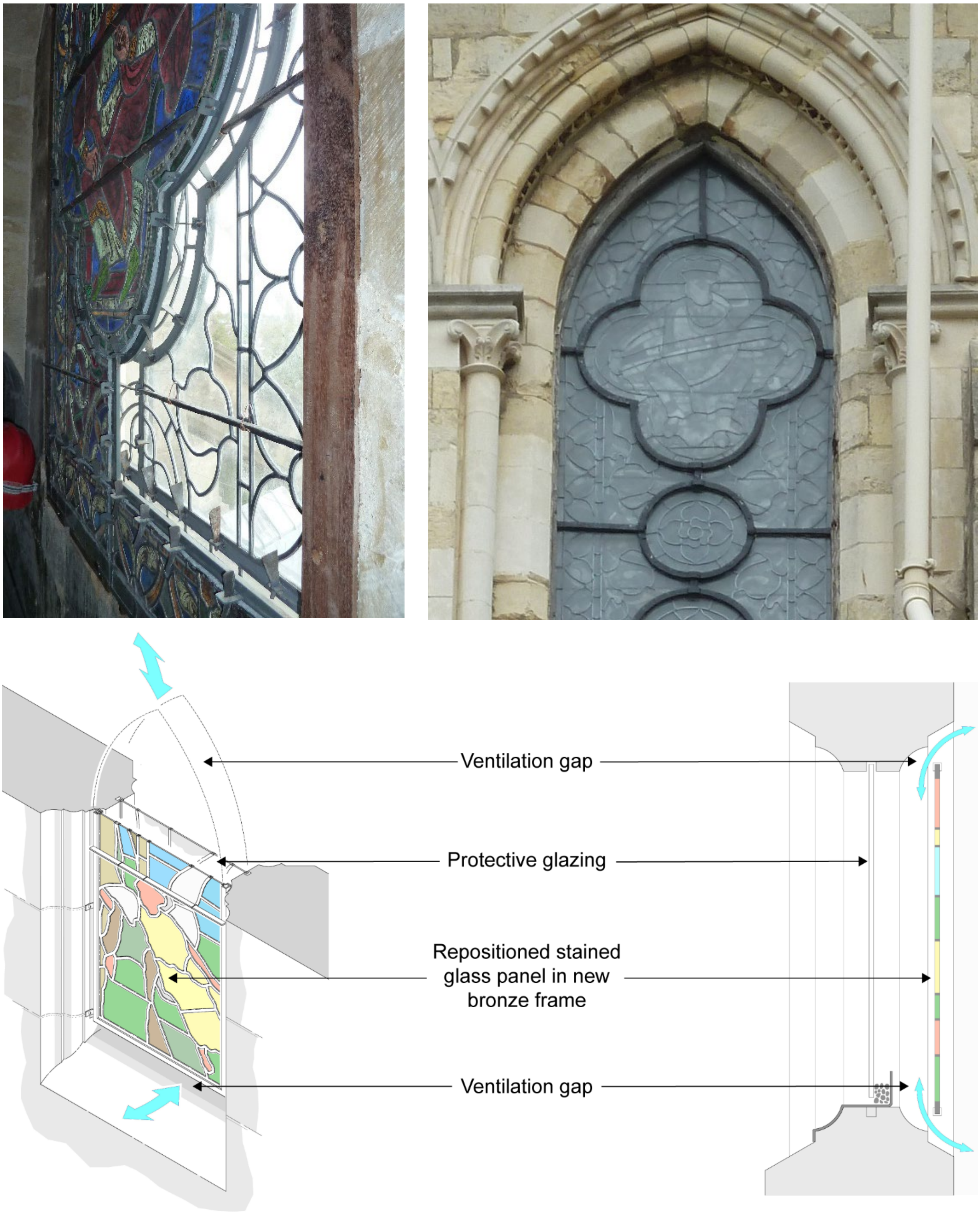
Installing EPG involves the addition of a layer of modern glass to the outside of historic glazing. An air gap is left between the two panels, which is generally ventilated at the top and bottom to the inside. This increases thermal buffering between internal and external conditions. When the external conditions are colder than those inside, this air gap stops the minimum temperature of the historic glass dropping to a level where condensation might occur. This risk is, instead, transferred to the EPG panel, which acts as the new interface with the external environment.



Figures 5 to 7: Diagrams showing the basic method by which EPG controls condensation.

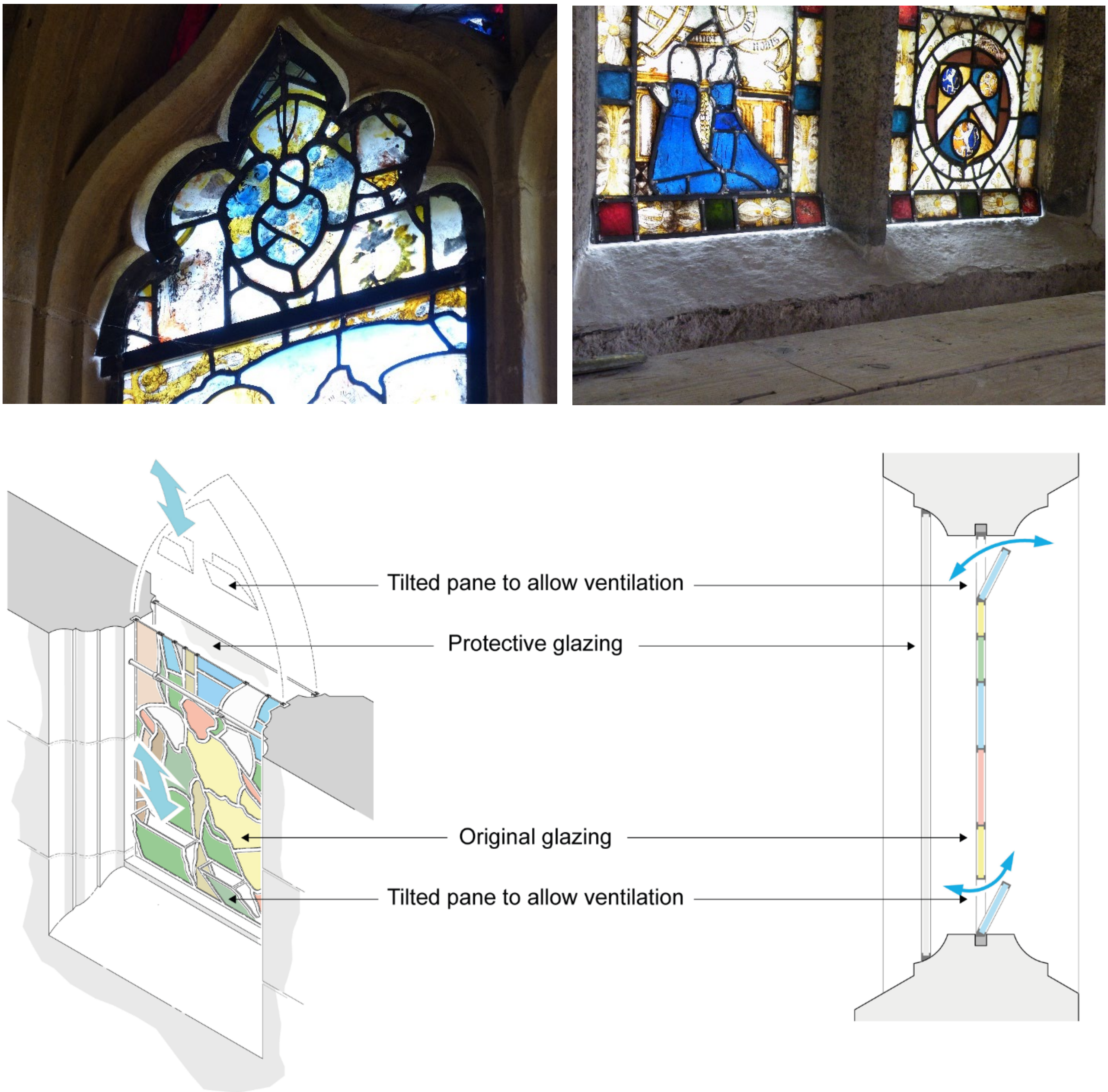
A number of ventilation systems have been used since secondary glazing was first introduced, but most common today is the internally ventilated design. In this system, the historic glass is moved inside the building, usually on a frame, with ventilation gaps at the top and bottom. Protective glazing is then placed in the original glazing grooves, thereby allowing internal air to circulate between the two layers.

When the air in the interspace is warmer and more buoyant than the air in the building (when external conditions are significantly warmer than internal ones), the air flows upwards, drawing in more air through the bottom vent and expelling it through the top vent. This mechanism is commonly known as ‘stack effect’. When the air in the interspace is cooler and less buoyant (when external conditions are colder than internal ones), the opposite flow pattern occurs.



Figures 8 to 11: Internally ventilated EPG, with the new glass in the original glazing grooves and the historic glass moved forward into the building. [Figures 10 and 11 © Historic England]

If the historic glass is too delicate to be moved, the stained glass can sometimes remain in the original glazing grooves, with modern glazing added to the exterior within the depth of the tracery, with a lead skirt dressed tightly to the stonework to minimise air leakage. Openings are made in the historic glazing, or sections are tilted forward, to allow airflow through the interspace.



Figures 12 to 15: Internally ventilated EPG, with the historic glass remaining in the glazing grooves and the new glass mounted externally within the depth of the tracery. Images and illustrations show a number of different approaches to creating ventilation openings. [Figures 14 and 15 © Historic England]

In both EPG designs, the modern glazing forms the interface between internal and external conditions, so that condensation will form on the modern glass rather than the historic glazing. Despite the fact that the interspace is a semi-enclosed space, the condensation on the new glazing should evaporate quickly, as long as there is sufficient air flow to allow exchange of humidity with the drier internal air.

The exact design of any EPG installation has a significant impact on its performance. The depth of the interspace and the design of the ventilation openings are of particular importance. Modelling and field tests during the 2017 research demonstrated that the optimal design was vents that were no less than 30% of the depth of the interspace. For example, vents of 20mm would be optimal for a 60mm interspace.

In an ideal model, the interspace should have no irregularities. The vents should be linear and full width to allow unrestricted laminar airflow. However, the ideal model is almost never achievable in real applications, and the performance of the system is limited by certain factors. These include:

- insufficient interspace depth
- restricted airflow caused by elements such as stone tracery, historic ferramenta and modern metalwork supports
- deformed historic glass
- poorly designed/sized vents

Despite this, as a system, EPG is relatively robust and it can tolerate a number of imperfections, while still providing significant protection.

Historically, systems with external ventilation were widely used and are still employed in some applications today. However, monitoring has demonstrated that while such systems offer a level of protection, they don’t function as well as well-designed, internally ventilated EPG.

EPG not only modifies the microclimatic conditions to which the historic glass is exposed, but it also stops direct rainfall and wind loading from damaging or promoting corrosion of the external glass surface. If the EPG is ventilated to the outside, there is a risk of some rainfall entering via the vents. In addition, outside air is generally more polluted than internal air. External ventilation may not, therefore, reduce the effect of pollutants on the external historic glass surface to the same extent as an internally ventilated system. On the plus side, installing an externally ventilated system may require a lower level of intervention on the historic glazing itself. Consequently, the overall risks and benefits of internally and externally ventilated systems need to be carefully evaluated in each individual case.

2.2. General building environment

The effectiveness of EPG in controlling condensation is reduced by poor environmental conditions within the building itself. If a building is in poor condition and suffers from water ingress, the relative humidity (RH) and dew point temperature (DPT) will be higher, and the basic risk of condensation will, therefore, be greater. To prevent condensation occurring, the EPG will need to perform more efficiently than if the building were dry and the DPT were lower. For this reason, ensuring that the building is in good condition and that the environmental conditions are controlled are essential to any EPG project.

3. The tracery and partial EPG project

Constructed in the late 13th century, the east window of the Chapel of St Gabriel at Exeter Cathedral has five principal lancet lights. Above these, there are ornate tracery lights, including quatrefoils and sexfoils, separated by small triangular sections.

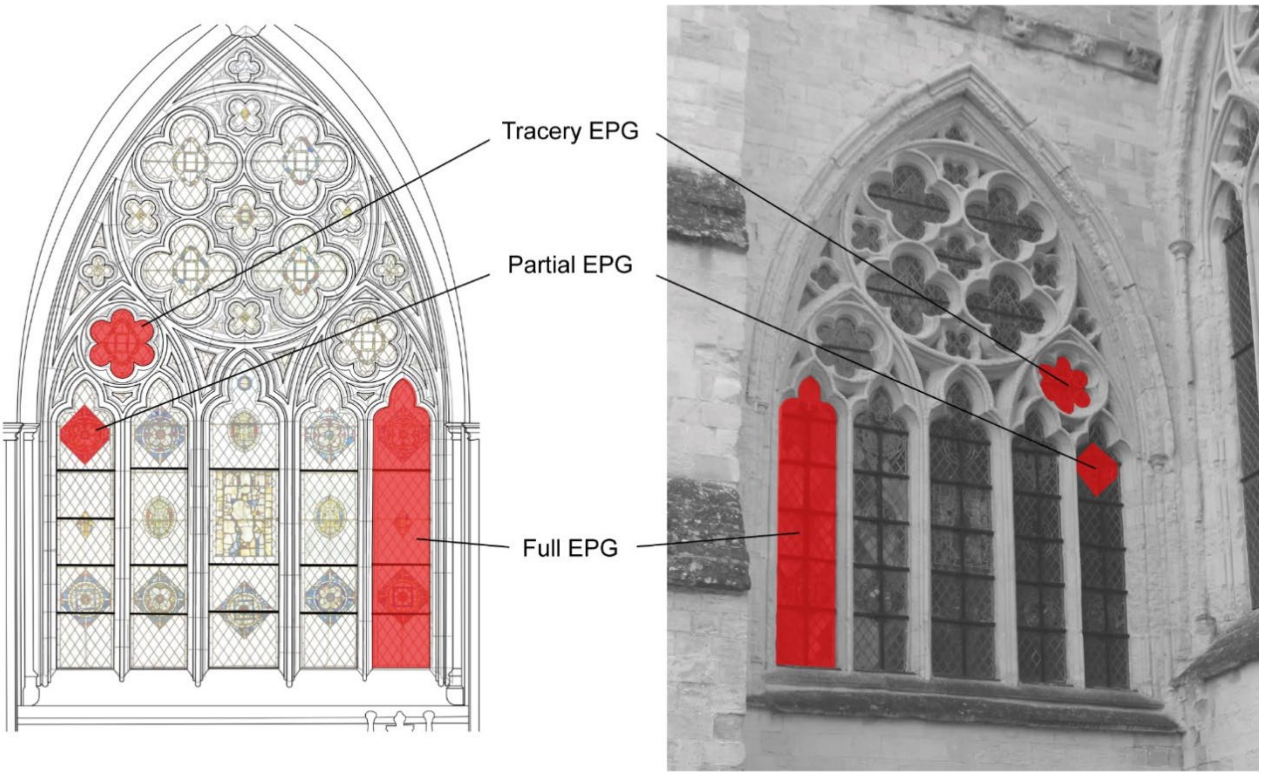
Figures 16 and 17: The east window of the Chapel of St Gabriel at Exeter Cathedral.

Much of the glazing is plain quarry glass, into which sections of highly significant medieval glass – both decorative and figurative – have been set. Holy Well Glass carried out condition surveys, which demonstrated that the historic glass was deteriorating with the dissolution of the soluble fraction of the body glass, and the delamination and flaking of the glass paint. It was determined that the only way the stained glass could be conserved *in situ* would be to install a system of EPG.

Given the small size of the tracery lights, using EPG to protect the full tracery section was the only practical approach. For the lancet lights, however, the sections of decorative glass were in clearly defined diamonds, rectangles or roundels, which were visually separated from the main areas of plain glazing. In this case, it made better sense – in terms of EPG design – to limit the intervention to each section of the stained glass itself, rather than to provide EPG to an entire lancet.

Data from the environmental monitoring of the cathedral which has been carried out by the author since 2013 demonstrated that the ambient conditions were relatively benign and that well-designed EPG should perform effectively.[4]

Three EPG designs were evaluated on the east window: a full light on the right side (viewed internally), and tracery and partial light on the left side (viewed internally).

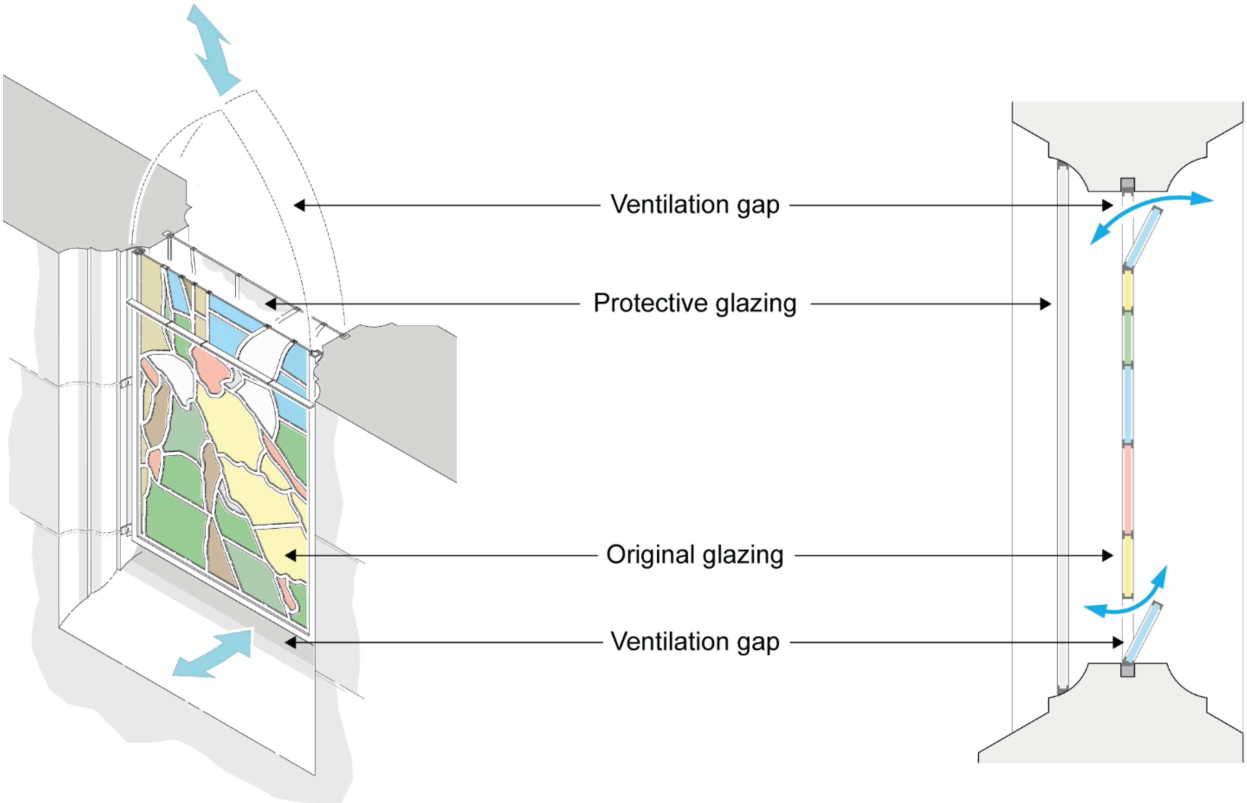


Figures 18 and 19: The east window of the Chapel of St Gabriel, showing the location of the tests. [Figure 18 © Acanthus Clews Architects]

3.1. Full EPG

The full lancet installation had ventilation gaps at the top and bottom formed by the removal of small sections of clear glazing, and a 50mm interspace. The historic glass remained in the original grooves, with a Perspex glazing panel mounted on the outside and a lead skirt dressed back to the stonework to minimise air leakage. The Perspex EPG was installed only for the period of the trials and was subsequently removed.

Figures 20 and 21: Layout of the full EPG control trial.

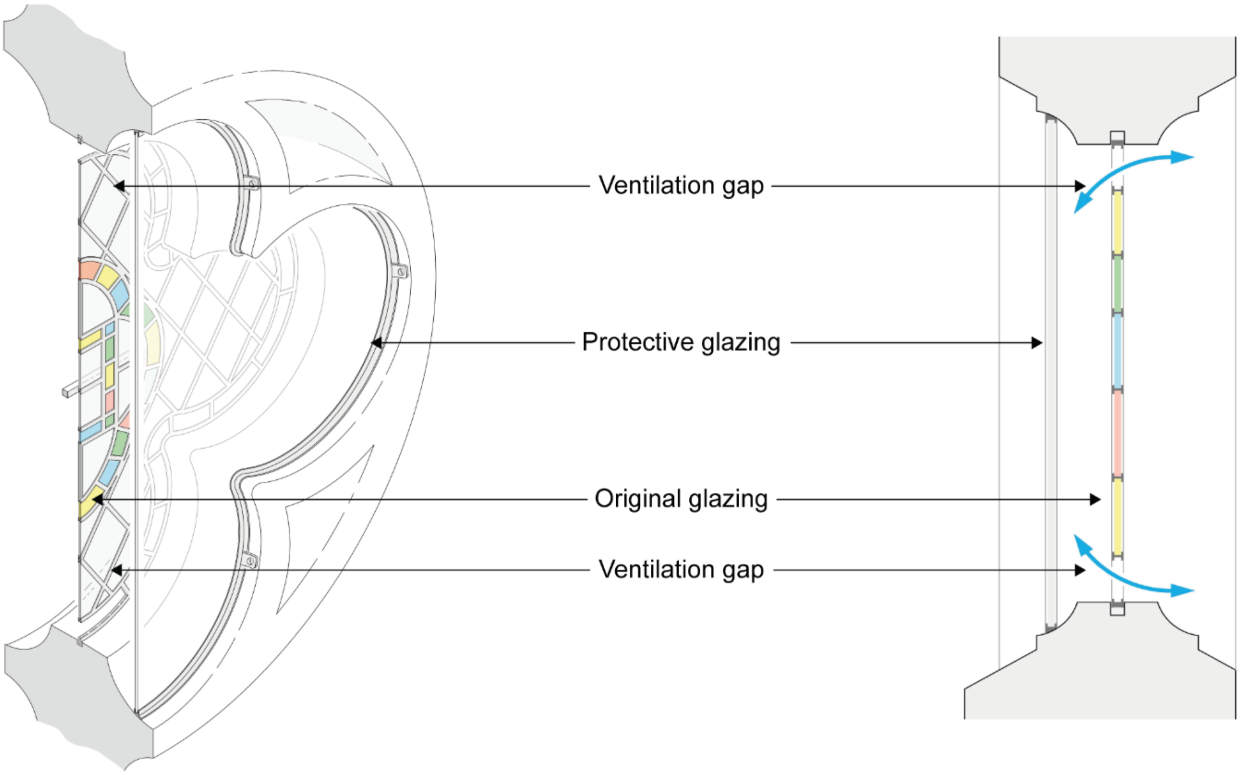


Figures 22 and 23: Functional principles for the full EPG control trial. [© Historic England]

3.2. Tracery EPG

For the tracery EPG installation, some of the clear glass pieces at the top and bottom edges of the historic glazing were removed to allow ventilation. The Perspex glazing was mounted on the outside, leaving a <50mm interspace, with a lead skirt dressed back to the stonework to minimise air leakage. The Perspex EPG was installed only for the period of the trials and was subsequently removed.

Figures 24 and 25: Layout for the tracery EPG trial.

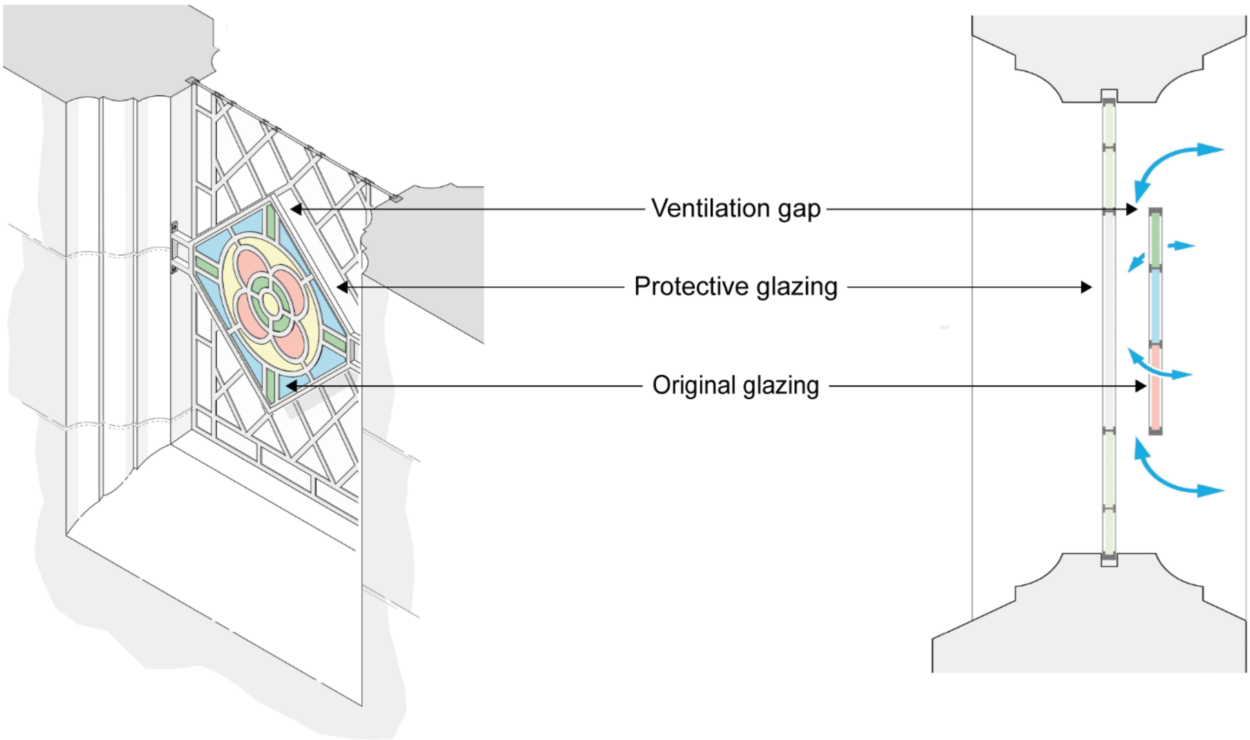


Figures 26 and 27: Functional principles for the tracery EPG trial. [© Historic England]

3.3. Partial EPG

For the partial EPG installation (small stained-glass panels within plain glazing) the historic glass was removed from the quarry glazing and set forward on a bronze frame, with the resulting opening filled with a section of modern glazing. The bronze-framed historic glass had open sides, to allow internal ventilation, and a <20mm interspace. The EPG glazing system for the panels was a permanent installation.

Figures 28 and 29: Layout for the partial EPG trial.

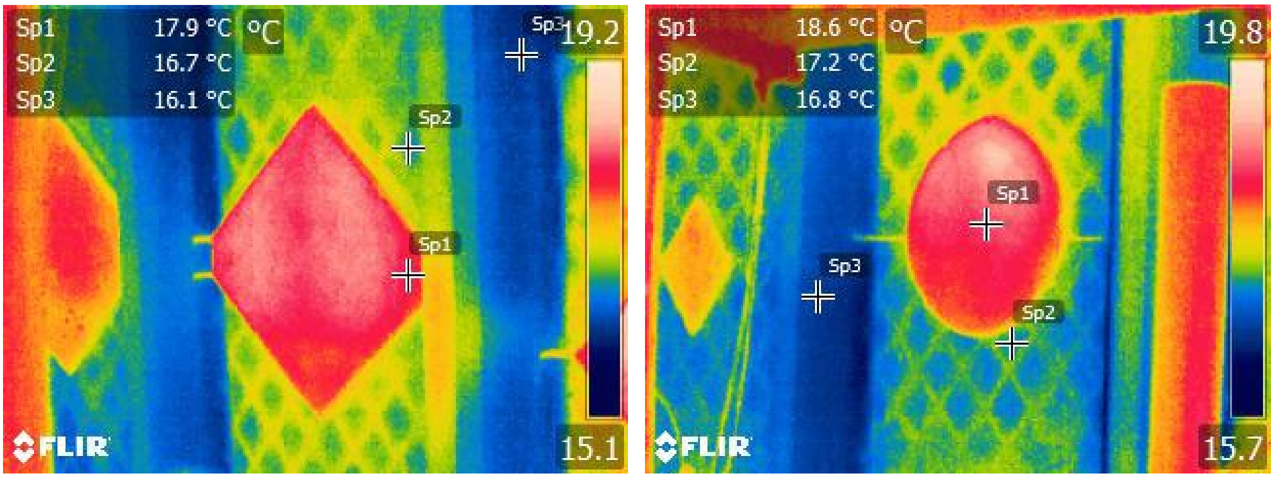


Figures 30 and 31: Functional principles for the partial EPG trial. [© Historic England]

4. Environmental survey and monitoring

4.1. Thermal imaging

Following the partial EPG installation, thermal imaging demonstrated that there was a variation of almost 2°C, between the historic glass mounted in the bronze frame and the original external glazing, demonstrating the immediate increase in thermal buffering.



Figures 32 and 33: Functional principles for the partial EPG trial.

4.2. Environmental monitoring

Monitoring was carried out using an Eltek RX250 telemetric system. The data were logged at 15-minute intervals. They were then downloaded and analysed every four weeks, using Eltek Darca Heritage software. Relative humidity and ambient temperature were measured using RHT10-D combined probes, and surface temperature was measured using EU-U-V2 thermistors.

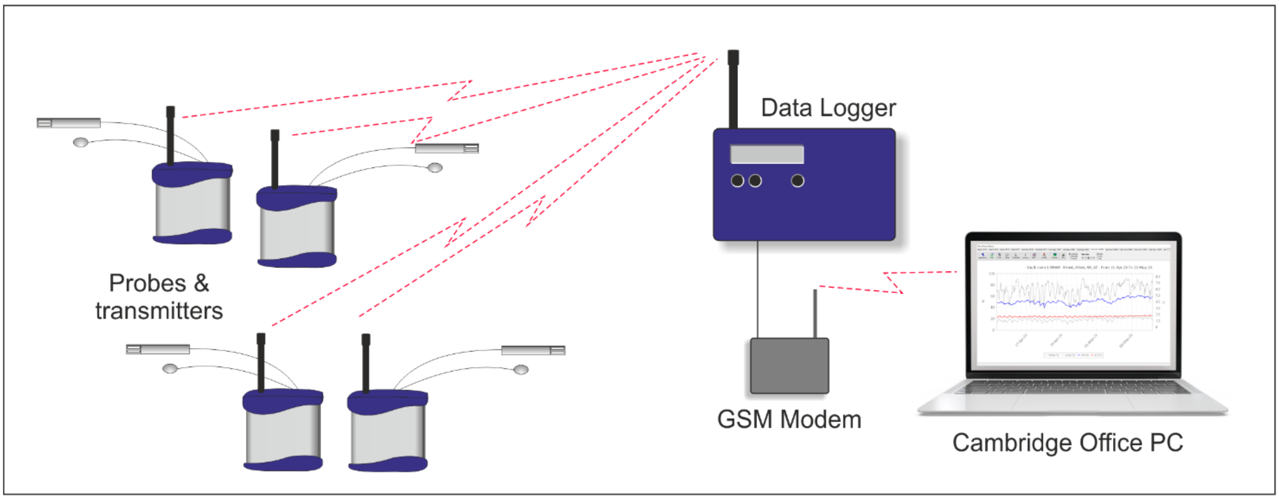


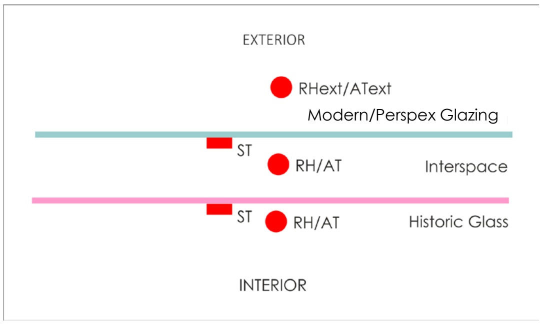
Figure 34: Schematic diagram showing layout of the telemetric system.

Internal RH/AT probes were suspended from available fixing points on the ferramenta. Surface temperature probes on the historic glass were attached to the surface using Paraloid B-72 adhesive. A block of Plastazote foam was used to thermally insulate the back of the sensors. Surface temperature probes on the Perspex and modern glazing were attached using epoxy resin.

On the historic glazing and the EPG, the parameters that were monitored were relative humidity (RH), ambient temperature (AT) and surface temperature (ST). Calculated parameters were dew point temperature (DPT) and absolute humidity (AH). External RH (RHext) and ambient temperature (AText) were monitored to provide control data. Sensor locations are shown in Table 1.

Figures 35 and 36: Relative humidity/ambient temperature and surface temperature sensors, attached to the stained glass (left) and modern glazing (right).

Table 1: Sensor locations

Serial	**Location**	
21023	External	
38270	South light, full EPG (interspace)	
38268	South light, full EPG (internal)	
38267	North light, tracery EPG (interspace)	
38269	North light, tracery EPG (internal)	
38266	North light, partial EPG (interspace)	
38265	North light, partial EPG (internal)	

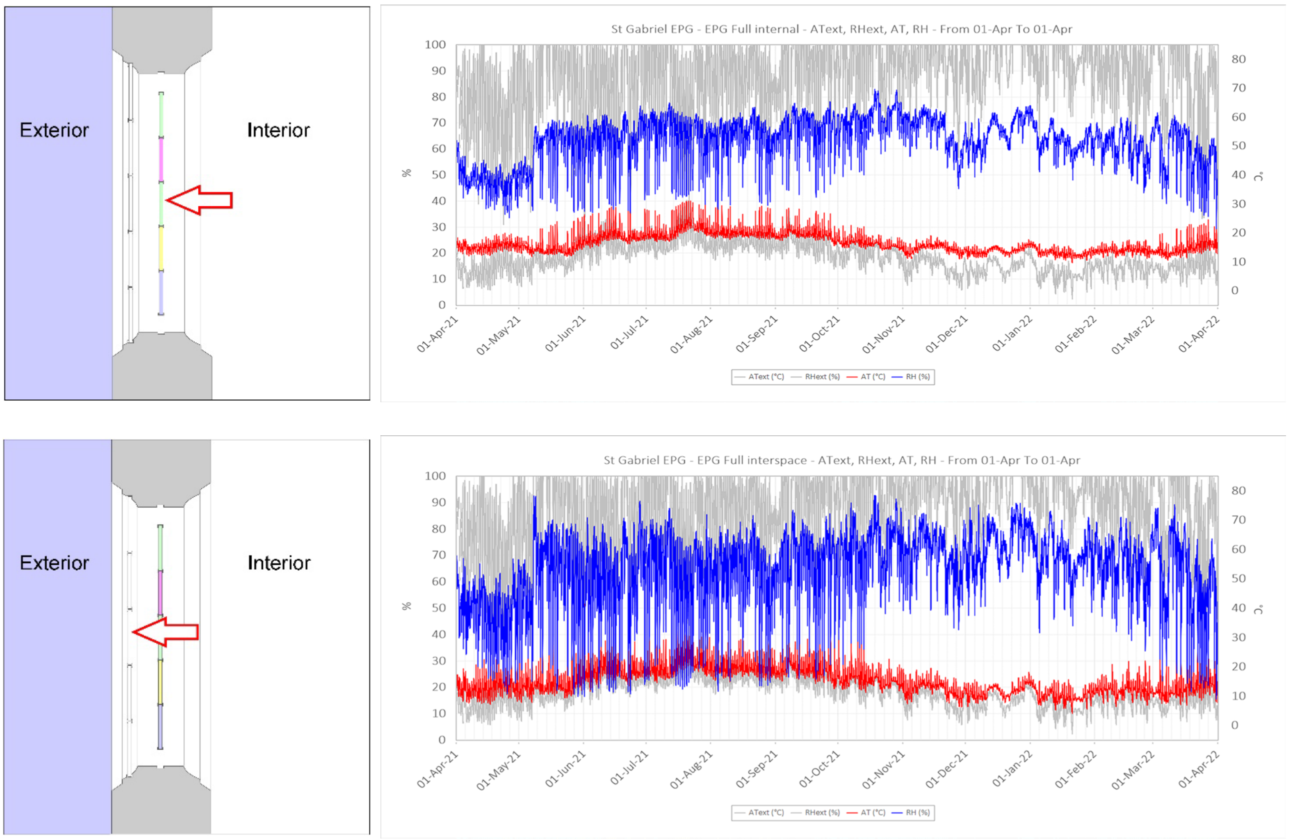
Tobit Curteis Associates, in conjunction with Holy Well Glass and the cathedral team, installed sensors on 31 March 2021. The monitoring period spanned 1 April 2021 to 1 April 2022.

4.3. Environmental monitoring results

Background data showed that the general microclimate was normal for a medieval cathedral. Average annual values in the Lady Chapel, which is adjacent to the Chapel of St Gabriel, were 16°C and 67% RH and well within the range that would allow EPG to function effectively.

4.4. Full EPG test

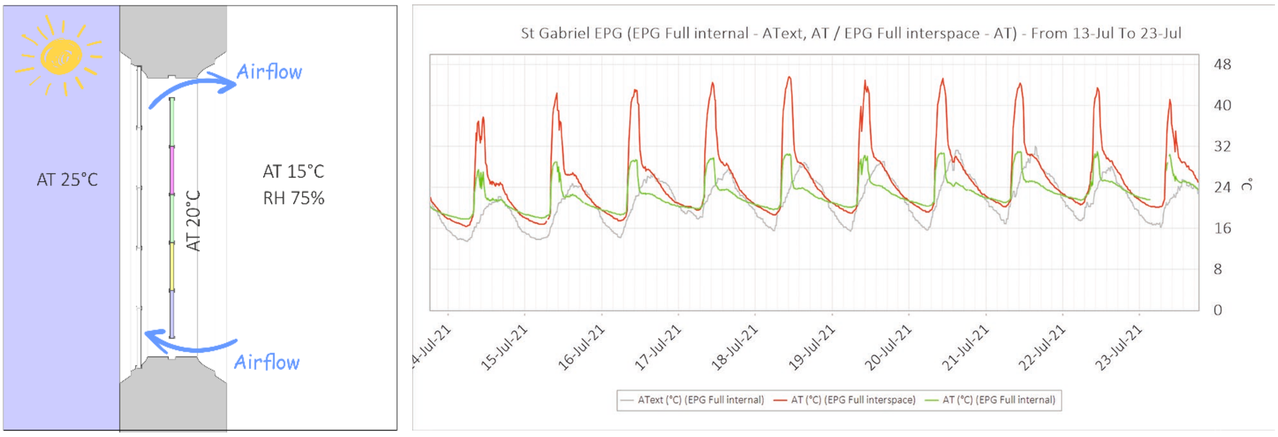
Data from the full EPG test demonstrated that the conditions by the east window were typically unstable due to the limited thermal buffering provided by the glazing (in comparison to masonry) and, in particular, the effect of solar gain when the window was exposed to direct sunlight in the mornings.



Figures 37 to 40: Charts showing the RH/AT conditions on the historic glass (top) and in the interspace (bottom).

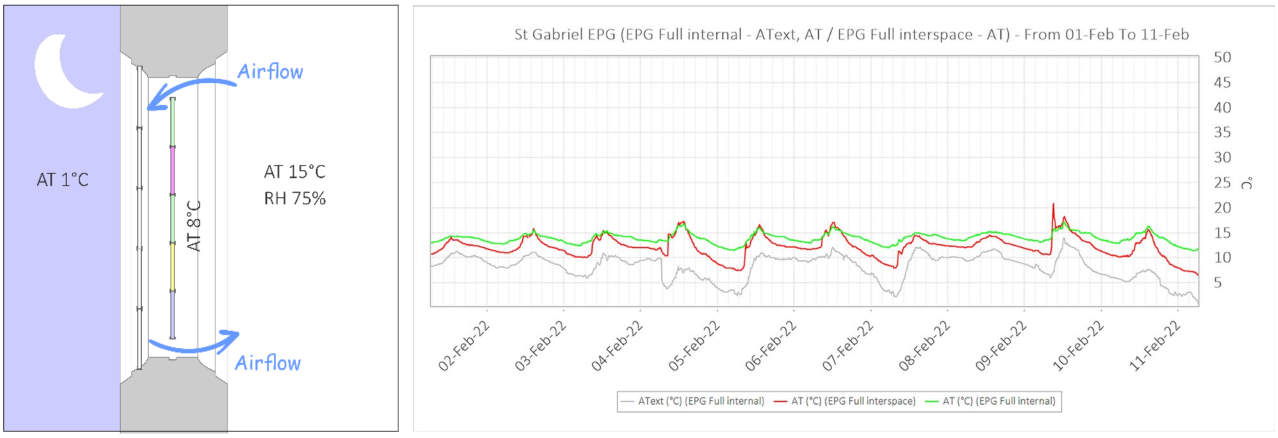
As a result, the AT and ST fluctuated sharply, with temperature increases (in the summer months) of more than 10°C. These were reflected by decreases in RH of more than 30% over a period of four hours, before the sun moved to the south and the window fell into shade. Conditions in the interspace were even more unstable. Temperatures increased by more than 25°C, resulting in decreases in RH of more than 50%.

During the daytime, in the summer, when the external air was hotter than the internal air, and when the window was exposed to direct sun, the temperature of the air in the interspace was higher than that inside the chapel. The resulting buoyancy would have caused the air to rise, escaping the interspace via the top vent and drawing in internal air via the vent at the base.



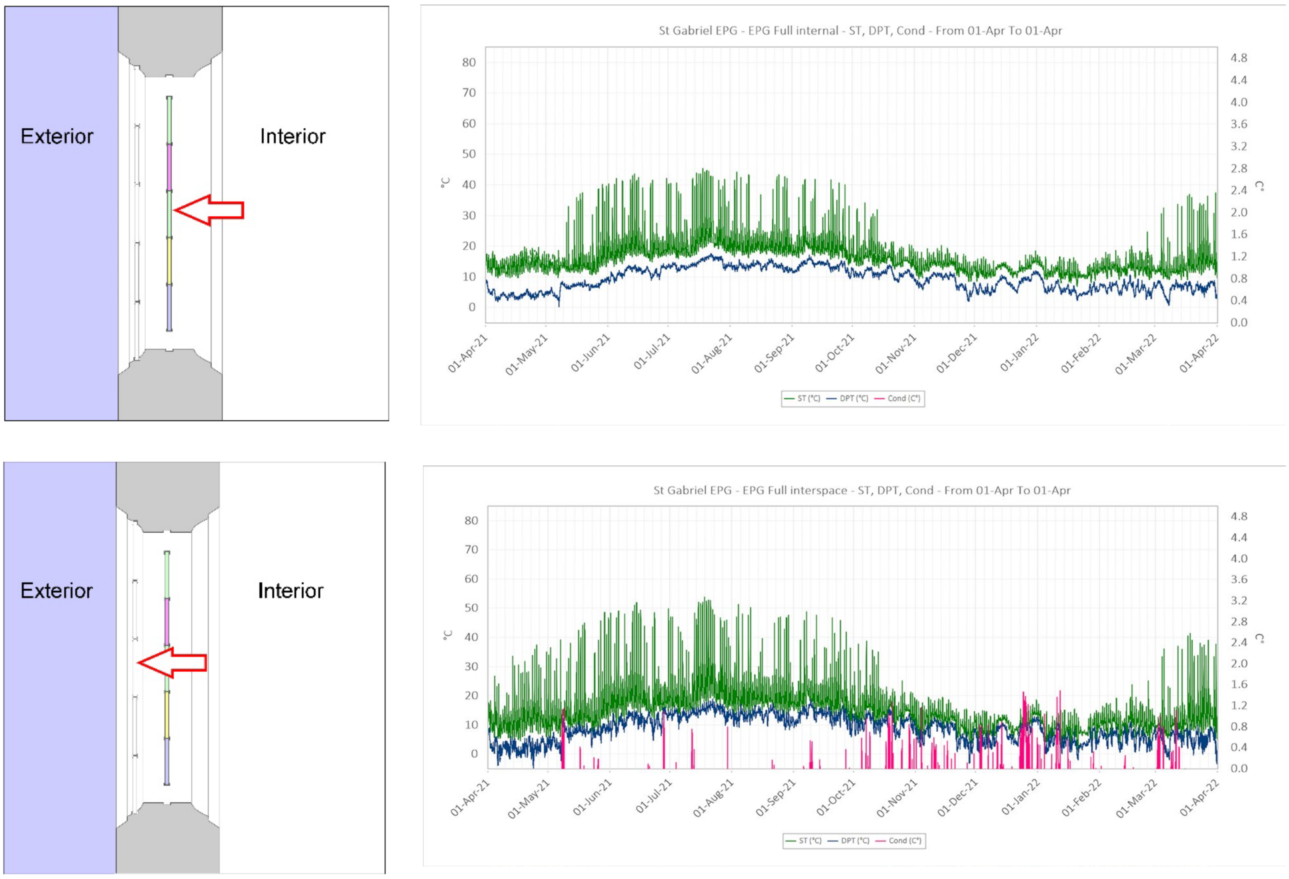
Figures 41 and 42: During the summer, the interspace temperature (red) is far higher than the internal temperature (green), causing air to rise.

At night, and on cold and cloudy days in winter, the interspace AT was lower than the internal AT, resulting in the opposite effect. The interspace air would have become less buoyant and descended, escaping at the base and drawing in internal air at the top.



Figures 43 and 44: During the winter, the interspace temperature (red) is lower than the internal temperature (green), causing air to descend.

The ventilation of the interspace with internal air, increased the thermal buffering so that the ST remained above the DPT and condensation would not have occurred on the historic glass. By contrast, the ST on the Perspex glazing regularly fell below DPT, and condensation would have occurred frequently, especially during winter. The level of condensation recorded on the Perspex glazing is likely to be similar to that which would have occurred on the historic glass before the EPG was installed, demonstrating the severity of the deterioration issue.



Figures 45 to 48: Charts show no condensation occurring on the protected historic glass (top) and regular condensation occurring on the Perspex glazing (bottom).

4.5. Tracery and partial EPG tests

The environmental conditions observed in the tracery EPG and partial EPG were generally similar to the full EPG, demonstrating that both designs were largely effective. Some differences were observed in the interspace AT in the three installations, particularly during the summer, due both to variations in levels of shading but also the difference in the ventilation designs. For example, a lower peak temperature was observed in the partial EPG, likely caused by more effective ventilation with internal (cooler) air facilitated by the open design which allowed more unhindered airflow, in comparison to the more restricted airflow through the vents on the full EPG and tracery EPG designs.

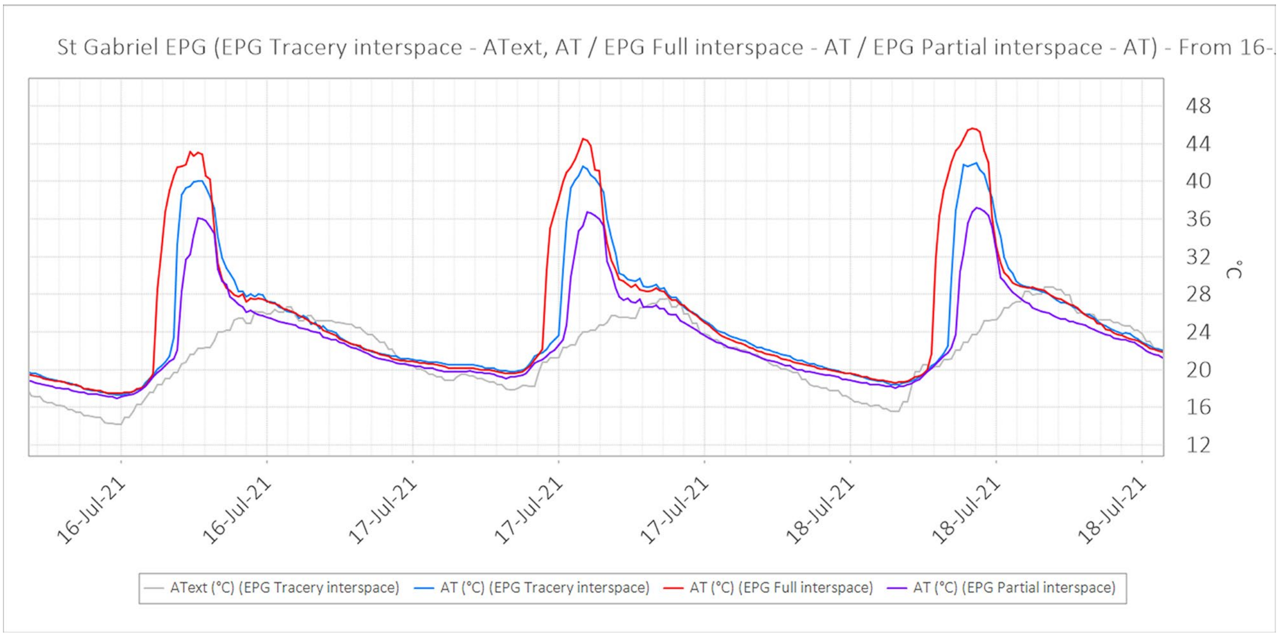


Figure 49: Differences in temperature in the full, tracery and partial interspaces due to system design and sensor location.

Minor but significant AH differences were also observed between the three tests. Data showed that for the partial EPG, the interspace AH was similar to the interior value while for the full EPG and tracery EPG the interspace AH was more significantly influenced by the exterior values. This appears due largely to the higher level of external air leakage around the edges of the externally mounted EPG systems. While these systems still functioned well, this demonstrates the importance of ensuring that the lead skirt is well dressed into the stone tracery, to minimise air leakage.

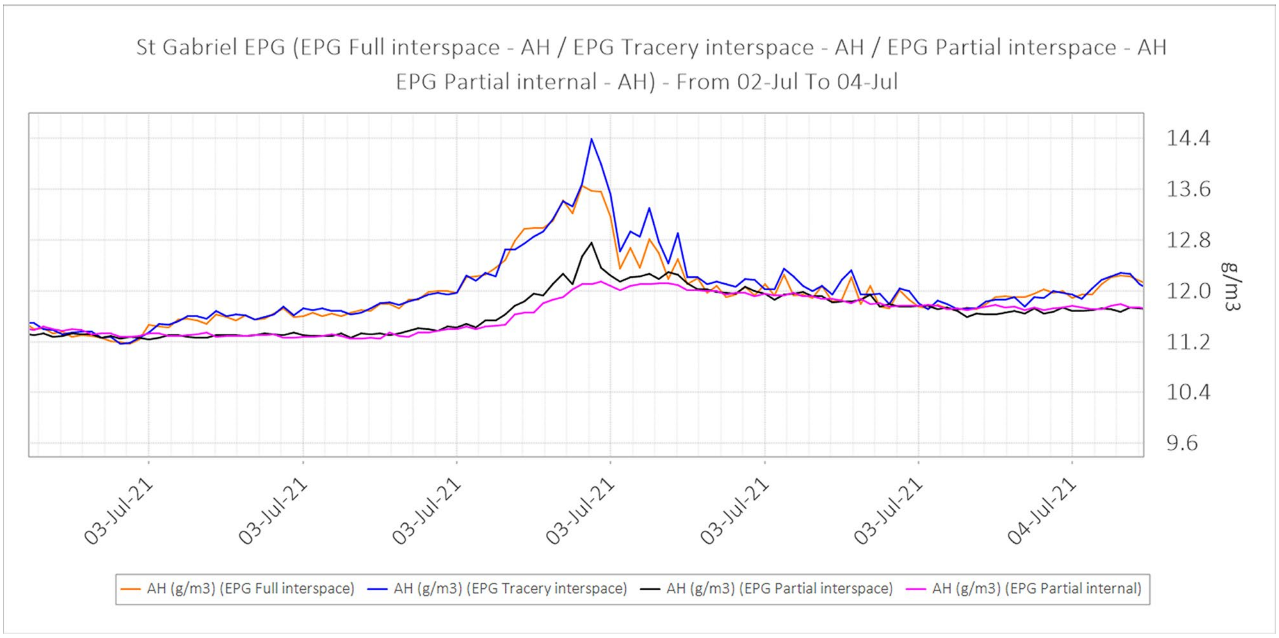
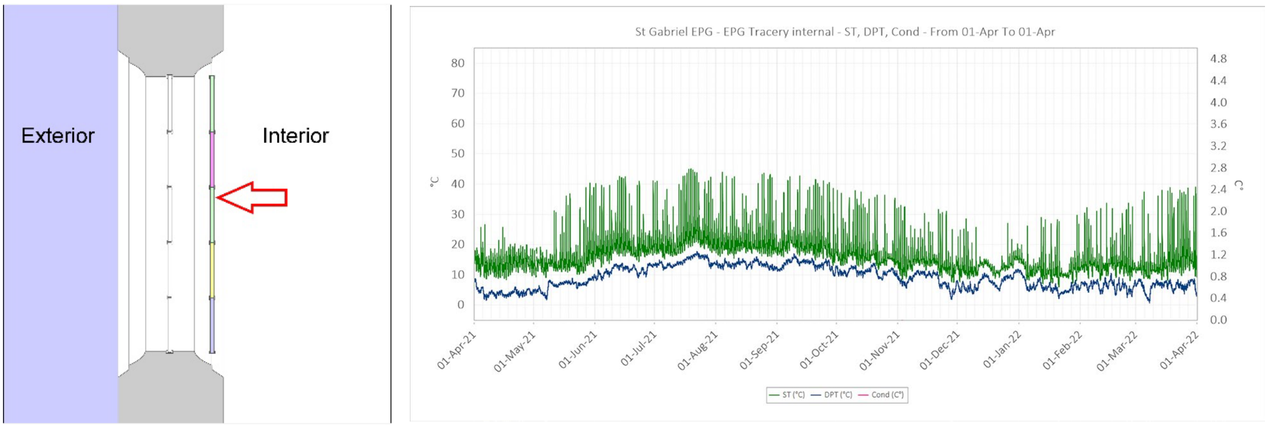
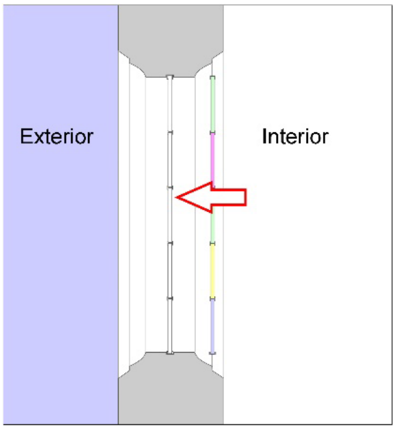
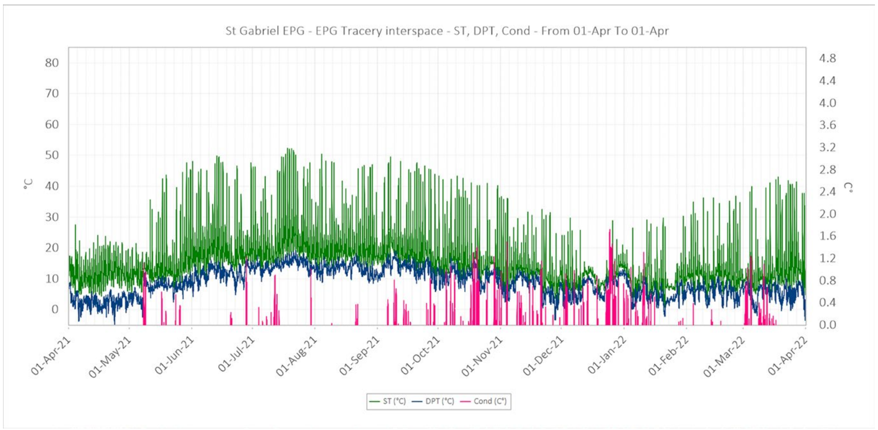


Figure 50: Differences in AH in the interspaces – full EPG test (orange), tracery EPG test (blue) and partial EPG test (black) – compared with the internal value (pink).

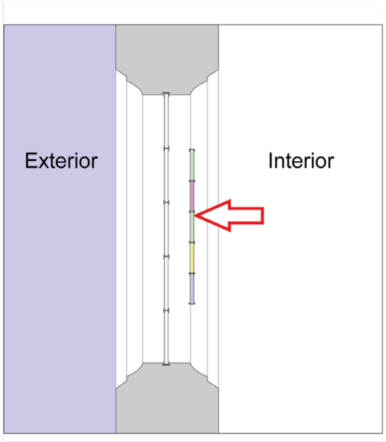
Because the average interior AH is higher than the external value, this resulted in a slightly elevated AH for the partial EPG interspace than for the other two designs and a slightly greater number of condensation events on the modern glazing, although the periods over which it occurred were more limited. However, there appeared to be no additional risk of condensation on the historic glass.

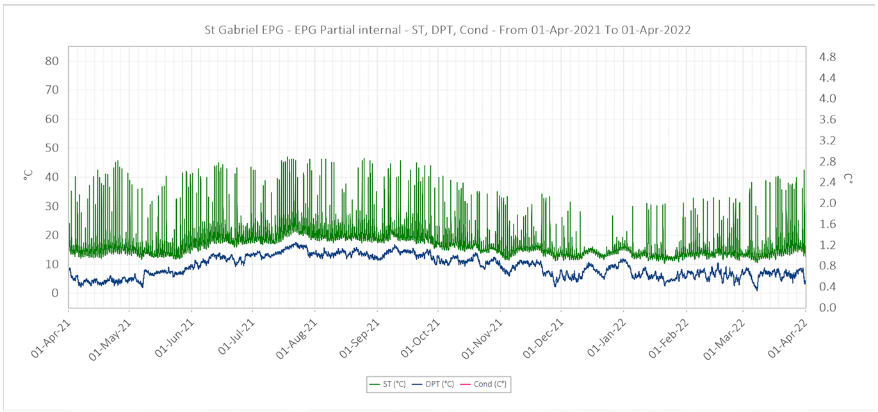


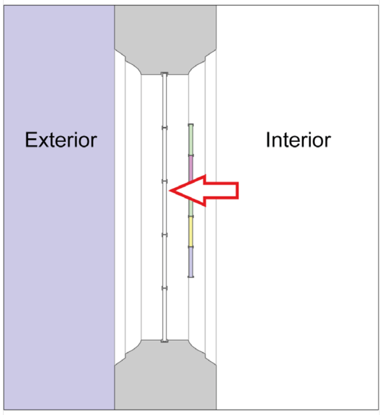


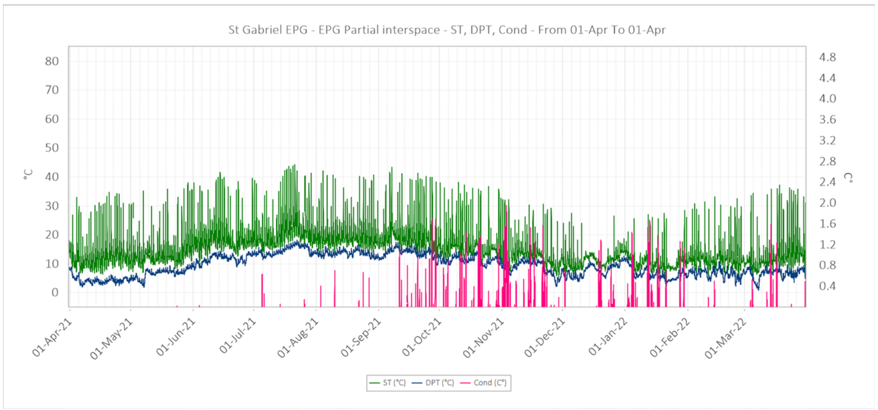


Figures 51 to 54: Charts for the tracery EPG test, showing no condensation occurring on the protected historic glass (top) and regular condensation occurring on the Perspex glazing.









Figures 55 to 58: Charts for the partial EPG test, showing no condensation occurring on the protected historic glass (top) and regular condensation occurring on the modern glazing.

5. Conclusions

The test data demonstrated that the partial EPG and the tracery EPG performed effectively. They significantly improved the thermal buffering of the historic glass and prevented condensation, with results that were comparable to the full EPG. By contrast, condensation occurred throughout the year on the Perspex and modern glazing in all three areas.

Some limited variations in performance occurred, apparently caused by air leakage in the externally mounted Perspex glazing. The different geometry of the three tests, such as the relationship between interspace depth and the size and shape of the ventilation gap, may also have affected performance. However, the fact that all three tests worked at a similar level indicates that EPG as a system is tolerant of some variation.

Despite these small differences in performance, the adverse conditions to which the historic glass was exposed were significantly reduced in all three EPG trials, with the risk of condensation minimised. This would be expected to have a direct and immediate beneficial impact on the long-term conservation of the vulnerable elements of the historic glass.

It was noted that the environmental conditions in Exeter Cathedral are relatively benign and, therefore, do not hamper the functioning of the EPG. In a church with significantly worse environmental conditions, full, tracery and partial EPG would perform less effectively.

6. Glossary

Absolute humidity (AH) – The actual amount of water vapour molecules in the air, irrespective of temperature (g/m3). AH is not directly affected by temperature (the AH of a volume of air with a fixed water content will stay the same if the temperature changes). However, an increase in air temperature can cause water vapour to evaporate from damp fabric, resulting in an increase in the AH value.

Ambient temperature (AT) – The temperature of the air.

Dew point temperature (DPT) – The temperature at which the air reaches saturation and water vapour will condense. This often occurs when air touches a cold surface and the relative humidity rises to 100%, at which point it can no longer hold the current water vapour load. On a non-porous surface (such as glass), water may be visible; on a porous surface (such as stone and plaster), water may be immediately absorbed and, therefore, not visible.

Condensation – Liquid water that forms, often on a surface, when the air becomes saturated and can no longer support the existing water vapour load, due to an increase in water vapour (AH) or a reduction in ambient temperature (AT).

Environmental monitoring – The recording and comparison of environmental conditions such as temperature and humidity over time to evaluate the influence or one space on another (for instance the influence of external conditions on those in an EPG interspace).

Environmental protective glazing (EPG) – A system of secondary glazing in which a new glazing panel is added to the outside of the historic glazing, leaving an air gap between the two, generally ventilated at the top and bottom of the panel, which increases thermal buffering between internal and external conditions, thereby reducing or preventing condensation.

Externally ventilated – Protective glazing that is open to the outside, providing external air to ventilate the space (interspace) between the stained glass and the protective glass.

Internally ventilated – Protective glazing that is open to the inside, providing internal air to ventilate the space (interspace) between the stained glass and the protective glass.

Interspace – The space between the stained glass and the protective glazing layer.

Isothermal glazing – A term previously used to describe environmental protective glazing.

Partial environmental protective glazing – EPG for a small section of stained glass within a larger plain-glazed window.

Protective glazing – A generic term applied to a secondary glazing system that is designed to prevent further deterioration of stained glass.

Relative humidity (RH) – The amount of water vapour molecules that the air is holding, as a percentage of the number it could be holding at that temperature. RH is affected both by temperature and water vapour (that is, warm air can hold more water so that, in the absence of additional vapour, an increase in temperature will cause the RH to fall and vice versa). RH is the parameter we cite when referring in general to humidity.

Stack effect – Air movement driven by differences in temperature, leading to changes in air density and buoyancy. In an enclosed vertical space (such as a chimney) warm air rises, reducing the pressure at the base and drawing in colder air, whereas cold air will sink. In protective glazing systems, the stack effect ensures air circulates through the interspace.

Surface temperature (ST) – The temperature of a surface (in this case glass).

Tracery environmental protective glazing – EPG for stained glass within stone tracery.

Vents or ventilation openings – Spaces at the edge of the glass, often top and bottom. which allows air to enter the interspace and provide ventilation.

7. End notes

1 The different types of stained glass and the deterioration processes are discussed in detail in Curteis T. Seliger L., Luxford N., Slater S., Manning T. and Pender R. 2017 *Conserving Stained Glass Using Environmental Protective Glazing*. Swindon. Historic England ISSN 2059-4453 (Online)

2 Ibid

3 Pender R., Manning T., Curteis T. and Seliger L.2020 *Stained Glass Windows: Managing Environmental Deterioration*. Swindon. Historic England

4 Tobit Curteis Associates 2016 *Environmental Survey and Monitoring at Exeter Cathedral: Phase II, A Report for the Dean and Chapter*

Historic England's Research Reports

ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)