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Development of passive controlled atmosphere display cases for the conservation of cultural assets

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Keywords

Oxygen-free atmosphere, display cases, cultural assets, mummies, conservation.

Abstract

This work expands the study of the conservation of organic specimens of historical and artistic interest, assessing both biological and physical-chemical conservation requirements, in order to arrive at the tangible solution, set out herein. The results of the experiment carried out on the prototype demonstrated the performance in terms of gas tightness achieved by the system, as well as the ability to maintain stable storage parameters for a very long period of time. During the course of the study, the chemical compounds emitted by the materials used in construction were taken into consideration, and the effect of the climatic variations present in museum exhibition areas, archives or churches on the physical properties was monitored. This study saw the development of two innovative patented technologies (IT-1398645 and IT-1425729) applied to the construction of two cases, designed to conserve and display the mummies of Rosalia Lombardo (1920 AD) in Palermo, Italy and Princess Anna of Bavaria (1319 AD) in Kastl, Germany.

1.1 Introduction

It has been known for several years, and is confirmed by the scientific literature, the degradation of historically-artistically significant organic specimens is principally attributable to either biological, chemical or physical factors [1].

The degradation phenomena are governed by chemical-physical parameters and directly affect biological processes. Among the most influential factors are the temperature and the water activity (a_w) [2]. Further, the equilibrium relative humidity (ERH) is fundamentally important to the conservation of organic materials and is closely linked to the concept of water activity (a_w) [3, 4]. Examples of non-microbial degradation include loss of solubility , coagulation of proteins, and oxidation of lipids. Proteins are principally subject to the following transformations: denaturation; proteolysis; rotting [5]. Some biological-molecular studies show that collagen, for example in mummy tissues [6], as well as in ancient parchments [7], is a surprisingly resistant protein that, if stored in the right climatic conditions, only undergoes minor alterations even over thousands of years. One of the mechanisms that causes the greatest amount of degradation in organic specimens is chemical. It is the result of chemical reactions, principally oxidation, but may also be caused by other undesirable reactions catalyzed by enzymes, proteolysis or lipolysis, isomerization and photodegradation. The degenerative processes in the organic compounds lead to the formation of products that are more stable than the initial compounds. The speed at which these transformations take place may differ, depending on the parameters of the system and the environment. The strong presence of airborne chemical compounds, such as NO_2, SO_2 and O_3 in the urban environment, in addition to the numerous volatile organic compounds (VOCs) emitted into the atmosphere as a result of normal anthropogenic activity, have been well-known for years [8], as are the acidic compounds resulting from secondary reactions occurring between such substances and the humidity in the air, such as nitric acid (HNO_3) and sulphuric acid (H_2SO_3). Clearly, such factors also result in the degradation of cultural assets, as well as of organic materials [9].

The presence of oxygen is essential for all forms of aerobic organisms: insects and microbial flora are directly influenced by the presence of oxygen. By reducing the oxygen concentration to a value below 0.1 %, under certain thermo-hygrometric conditions, it is possible to guarantee the total elimination of such insect pests [10]. The effects of oxidative activity resulting from contact between oxygen and materials of all types are well-known and documented [11]. Thus, the presence of an acidic environment, i.e. having a low pH, inhibits the proliferation of harmful microorganisms. The presence of oxygen in sufficient amount can favour the development of microorganisms that, by metabolizing acids, shift the pH towards neutrality, thereby decreasing its inhibitory potential. It is therefore necessary, in cases where pH is the main conservation factor, that the specimens be stored in environments with a reduced O_2 concentration [12]. Lastly, it is also necessary to consider the phenomenon of photo oxidation, which is a degradative process triggered by the presence of light. Chemical reactions only occur when a molecule is provided with sufficient "activation energy" to break the covalent bonds along the macromolecules of natural polymers [13].

With regard to the choice of the physical and chemical parameters to be adopted when conserving organic cultural assets, we refer to Samadelli *et al.* [4], as summarized in Table 1, which took into account the main causes of degradation, indicating the reasons for the choice.

When designing display cases for the conservation and exhibition of cultural assets, modern construction methods take into account the fundamental necessity of working in a modified, low-oxygen (ideally oxygen-free) atmosphere. Display cases for the above applications are classified into two main categories: active-type cases and passive-type cases. In the case of an active-type construction, the main conservation parameters are guaranteed by a conditioning system based on an inert gas generator (normally N_2) which is usually located inside the display stand, or remotely-installed and automated to manage several such displays within the same museum. The method typically consists of the construction of a poor gas-tightness system, which has a relatively high air exchange rate ($AER \geq 0.1$ vol day^{-1}) between the interior volume of the display case and the external environment.

This construction method may be found in applications such as the System Q solution, produced by Goppion S.p.A., for the display case that houses Leonardo da Vinci's Mona Lisa in the Louvre in Paris (2004), and the two display cases produced for the Rijksmuseum in Amsterdam (2013), where gas tightness is achieved by means of silicone sealants and magnetic seals on the doors.

The passive-type construction consists of an, ideally, air-tight display case, which is saturated with inert gases that have been conditioned (humidified) accordingly. This construction method is known as "passive", not only because it contains an internal relative humidity (RH) buffer, such as silica gel, but also because it is able to independently balance the internal pressure variations, which occur inevitably in the event of temperature variations. It is also distinguished by that fact that it operates without the need for an electrical power supply. In order to be effective, the gas tightness rating of the passive-type display case must be such as to guarantee an ultra-low air exchange rate ($AER \leq 1\ 10^{-5}$ vol day^{-1}). In order to obtain an accurate measurement of the gas tightness for this type of display case, a method which takes into account the oxygen leak rate (LR-O_2) over a 24-hour period is often used. This method measures the amount of oxygen, here expressed in parts per million (ppm), which leaks from the display case over a 24-hour period (ppm day^{-1}).

The first prototype of passive-type, oxygen-free, display case was introduced in the early 1990s by Shin Maekawa of the Paul Getty Conservation Institute in Los Angeles [14]. It involved the construction of a glass case with extruded aluminum profiles, sealed with Viton® gaskets, which guaranteed a LR-$O_2 \leq 100$ ppm day^{-1}. Some important applications of the Maekawa prototype included the fifteen Royal mummies of the Egyptian Museum of Cairo (1994), the Egyptian mummy of a five-year-old child, Nesi, on display at the Biblioteca-Museu Victor Balaguer in Vilanova i la Geltrú, Spain (1992), the Original Documents of the Constitution of India (1994) [14], the world's first photograph, Joseph Nicéphore Niépce's View from the Window at Le Gras (2003) [15] and the Declaration of Arbroath, a fourteenth-century document of Scottish Independence (2005) [16].

2.1 Research aim

When designing a display case for the conservation of cultural assets, some standards and guidelines exist [17, 18]. However, they are quite general in scope and, thus, not always directly applicable to specific conservation cases. In reality, a display case should represent the result of a compromise between the conservation issues and the display aspects. It should isolate the displayed items completely from the outside environment and be designed so that it is possible to modify the chemical-physical parameters in order to provide the ideal environment for a specific specimen to be conserved, maintaining it stable for very long periods of time. At the same time, it should be aesthetically pleasing, while guaranteeing high visibility, mechanical security and easy access to the specimen.

3.1 Material and methods

3.1.1 Design of passive leak-free display cases

All of these aspects were taken into careful consideration when designing and manufacturing the described prototype, proposed by Eurac Research, which is based on a passive-type display case, featuring an oxygen-free internal environment, but differing from the method proposed by Maekawa [14] in terms of both construction criteria, which were selected in order obtain a higher degree of gas tightness, and layout, which guarantees access to the specimen. It also places greater attention on the aspect of conservation, focusing on a targeted chemical-physical analysis of all the components used in the construction, in order to avoid any damage to, or contamination of the conserved specimen in the long run. Another significant benefit of this innovative design is the absence of structural metal supports for the glass panels, since it consists of a single-body stainless steel tank, on which a single glass plate is mounted, which may be either curved or flat (Fig. 1). However, the most important innovation lies in the method used to seal the glass/steel interface, which uses a special hydro-carbon based wax formula, as described at a later stage in this work.

The case design uses exclusively TIG-welded AISI 316L stainless steel, chosen for its high resistance to all types of pollutants and corrosive agents and further polished as an additional measure to reduce the risk of microbiological aggression. To ensure maximum static gas tightness, all fittings and connectors are made of AISI 316L stainless steel based on Swagelok® VCR series metal gasket fittings.

The glass represents one of the fundamental elements of the system. It must guarantee the safety of the specimen, without compromising its visibility. According to the Italian national standards, objects of historical and artistic significance must be protected by P4A class, anti-vandalism laminated glass, with minimum thickness of 5 mm + 5 mm, and 1.52 mm of polyvinylbutyral (PVB); whereas the use of tempered, monolithic glass is not permitted [19, 20]. The choice of laminated glass is determined by the fact that it does not splinter into multiple pieces when fractured. In the event of breakage, an intermediate layer, typically PVB, will hold the surrounding glass layers together. The PVB layer also provides UV filtering. This feature is obtained by applying materials such as CeO_2-TiO_2 directly to the polymer [21]. The Eurac Research prototype goes beyond the scope of these guidelines by making use of metal oxide-free glass plates, which guarantee high light transmission and exceptional color rendering, as well as anti-reflective glass. It is even possible to obtain anti-reflective glass by applying a coating consisting of nano pigments which eliminate reflections almost entirely [22].

3.1.2 Patents

The highly innovative aspects of the Eurac Research project led to the registration of two patents. The first, entitled "Exhibition Display Case" [23] describes in detail the realization of a display case for the conservation of organic artefacts of historical-artistic interest. It consists basically of a metallic steel part with a glass cover. The two parts are sealed by means of an organic hydrocarbon wax. The main feature lies in the very high degree of gas tightness that may be achieved by using this method. The second patent, entitled: "Pressure Compensator (Bellows)" [24] was designed to be connected to the display case for the purpose of compensating for the difference in pressure that occurs between it and the surrounding environment due to temperature variations and prevents the display glass breakage. The volume of the bellows is determined during the design stage, depending on the historical climate series at the exhibition site. It consists of a rigid AISI 316L stainless steel plate, to which the fittings necessary for the connections to the display case are TIG-welded, and a movable part, consisting of a thin sheet of flexible multi-layered material made up of several layers of polyethylene, aluminum and nylon (Marvelseal 360, Ludlow Corp.). The bellows minimum differential pressure sensitivity is equivalent to 10 Pa. The fundamental constructional feature of the bellows, however, lies in the material used to form the joint between the rigid and movable parts, which consists of the same organic wax used to seal the display case [23].

4.1 Theory

4.1.1 The importance of water

Air humidity is by far the most important factor in conservation because it influences the variations in both the size and shape of the tissues that constitute the organic materials, as well as the chemical and biological processes involved [25]. In particular, water-absorbing organic materials swell when the humidity increases and shrinks when it decreases, resulting in weight variations, deformation, damage to fibres, and micro cracks. This behaviour is known as physical deterioration mechanism. Over time, any object will adapt itself to the surrounding environment, by first entering into a thermal equilibrium, and then into a hygrometric equilibrium. The process is described through the so-called sorption isotherms between the equilibrium moisture content (EMC) and the equilibrium relative humidity (ERH). It is above all the magnitude and speed of the shift away from this equilibrium that accentuate the deterioration processes in progress [26]. Abrupt variations or short-term fluctuations, over a period of days, if not hours, can cause irreversible alterations [27]. RH changes should not exceeded the permitted tolerance range by more than 5 %rh for a total period not exceeding one hour per day; this definition identifies the so-called Shift Index (IS) [17].

In a confined space, such as a sealed display case with constant water vapour concentration, RH fluctuations are closely correlated to the temperature change [28]. In order to maintain the RH constant, a display case must be equipped with a suitable buffer material capable of acting as a passive compensator. The scientific literature on conservation and restoration of cultural assets suggests the use of silica gel, a term commonly used to denote colloidal silica $(SiO_2)_n$. This is an inert silicon dioxide polymer, which contains no volatile compounds. There are various types of silica gel available, depending on its hygroscopic capacity (symbol M_H) to absorb/adsorb water from the surrounding environment [29]. Conventionally, the studies carried out by Weintraub and Tétreault [30] are used as the reference works when evaluating the quantity of silica gel to be introduced in a given display case.

However, Weintraub's formula [30] is not applicable in the case of this prototype display case which uses a passive-type approach and a fully air-tight design, as there is no exchange of air between the interior and the exterior. In this case, in order to quantify the required quantity of silica gel, it is important to estimate the interval of air temperature (Δt) that the display case may be subject to, by taking into account the historical climate temperature series at the exhibition site.

It is assumed that good quality silica gel ($M_H \geq 8$), at a temperature of 25 °C, and within a working range of 40 %rh to 55 %rh, has a water absorption/adsorption capacity of about 15 % of its weight (i.e., about 150 g of H_2O per 1 kg of silica gel). Thus, once the maximum temperature range inside the display case has been defined, at constant RH, it is also possible to estimate the absolute humidity change (symbol AH, in grams of water per cubic meter of air). Once the amount of H_2O has been established, it is easy to determine the amount of silica gel required, with respect to the total volume of the display case.

For an example of this calculation, let us consider the prototype display case developed for the mummy of Princess Anna of Bavaria (1319 AD), in Kastl, Germany, which is described at a later point in this document and has a volume of approximately 1 m^2. The annual temperature excursion in the church where this artefact is displayed was monitored and found to range between -3 °C and 27 °C (Δt = 30 °C). Under these conditions, assuming an ideal value of ERH of 45 %, the maximum annual change in the AH would be approximately 13 g m^{-3}. It was thus estimated that > 100 g of silica gel, pre-conditioned at 45 %rh, were needed to maintain a stable RH in the confined space of the display case. In order to ensure that the mummy of Princess Anna of Bavaria was conserved correctly, once the desired RH to be maintained within the display case was established, also the N_2 gas used to fill the internal environment was pre-conditioned accordingly, as well as the mummy itself, which had already been stabilized separately in a period of about six months.

4.1.2 Choice of sealing materials

When selecting the substances used to construct a display case, including the sealant for the glass parts, it is important to prevent any emission of VOCs, which, if present, would expose the artefact to a serious risk of chemical aggression [31]. Silicones and epoxy adhesives, which have high VOCs emission, have to be avoided. Viton®, which features low VOCs emission and is supposed inert, is frequently used to seal the cases. Initially, it guarantees an excellent degree of gas tightness, but this decreases over time due to the inevitable physical deformation it is subjected to. The search for a suitable inert, non-deformable product, offering very low VOCs emission, led us to consider the W100 wax produced by Apiezon®. This is an inert, semi-solid hydrocarbon wax that presents a degree of softening at temperatures above 50 °C, maintains a fairly constant viscosity at temperatures between -10 °C and 45 °C, and guarantees very low VOCs emission at room temperature (vapour pressure <6 10^{-7} Pa at 20 °C). The wax was tested to analyze its emission and stringent physical tests to evaluate its gas tightness.

5.1 Results

5.1.1 HS SPME – GC/MS analysis of the W100 Apiezon® wax

For many applications, bitumen is a sufficiently durable and adhesive binder for the aggregate. For some applications, however, additives may be added to the bitumen in order to improve its mechanical properties. Various additives have been proposed for this purpose, including polymers such as ethylene and vinyl acetate copolymers, random or block copolymers of styrene and conjugated dienes (e.g. SBS copolymers). More recently, synthetic waxes comprising blends of synthetic aliphatic hydrocarbons have also been used in bitumen blends. Such blends tend to be more resistant as sealing agents, compared to their corresponding wax-free counterpart [32]. The application of headspace solid phase microextraction (HS-SPME) coupled with gas chromatography/mass spectrometry (GC/MS) was developed at the University of Camerino for the analysis of the VOCs released by the W100 Apiezon® wax used as sealant. Solid phase microextraction (SPME/GC-MS) [33] is a new fast, selective, low cost and environmentally friendly sample preparation technique. SPME involves the extraction of volatile compounds out of liquid samples or out of the headspace of solid or liquid samples onto a fused-silica fiber coated with a polymeric phase, a polydimethylsiloxane (PDMS) extraction fiber. Hence the selection of the fiber and SPME extraction conditions can affect the sensitivity and accuracy of SPME analysis. As the HS-SPME mechanism is based on the equilibrium of analytes among three phases (fiber coating, headspace and sample), the analysis of headspace volatile compounds by HS-SPME is greatly influenced by the vapour pressure of flavour volatiles in the vial. The main variables that influence the vapour pressure and equilibrium of the volatile components in the headspace have been reported to be extraction temperature, equilibrium time and extraction time. The goal of the present study is to determine the feasibility of an entire system of conservation for high relevance cultural properties. The analyses were carried out using a gray SPME fiber, 100 μm and 30 μm polydimethylsiloxane (PDMS) (Supelco), together with a manual holder. According to recommendations from the supplier, the PDMS fiber was conditioned in the GC injection port at 250 °C for one hour before being used. Due to the properties of the bituminous sealants, headspace mode (HS-SPME) was applied. This grey fiber is very useful as it makes possible to perform a very wide range of analyses and absorptions of volatile and semi-volatile components. The analysis was carried out in steel cylinders at 25 °C that faithfully reproduce the environment conservation avoiding contamination and performing a progressive exposure in the order of time, i.e., the fiber was subjected to exposure with different amounts of wax for different exposure times (24 h, 72 h and 120 h). After sampling, the fiber was redrawn into the SPME needle, ready for GC-MS analysis. Blank injections were performed routinely to ensure no carry-over from the previous test. GC-MS spectra have led to identify a bituminous wax that has few volatile substances, mostly low molecular weight alkyl chains and other organic compounds, mainly long alkyl chains of waxy source. It was not possible to properly identify all molecules due to the complexity of the mixture, but it was possible to highlight the presence of decane, undecane, dodecane, decene, dodecene, 1-methyl-2-methylenecyclohexane, n-decanoic acid, 2-hydroxycyclopentadecanone, 3,8-dimethyldecane, undecanoic acid, 1,2,3-trimethylcyclopentane, 8-methyl-9-tetradecanoic acid, 1-dodecanol, 1-tridecanol as the most visible chemicals.

Furthermore, the nature of the W100 Apiezon® wax was identified performing an FT-IR analysis, which was carried out using a Perkin Elmer Frontier FTIR spectrometer. The wavelength range of the instrument is from 485 cm^{-1} to 4500 cm^{-1}, with resolution better than 0.7 cm^{-1}. The spectrum is shown in Fig. 2. It is possible to predict from the spectrum the bitumen/wax nature of the compound, being essentially present the characteristic peaks of stretching of the alkyl C-C and C-H bonds at 2900-3000 cm^{-1}, and the peaks at 1400-1500 cm^{-1}, mainly due to the bending of these bonds [34].

Therefore, these results strongly indicate the presence of substances that most likely do not have a harmful impact on the remains of biological origin contained in the showcase. Therefore, to the best of our present knowledge, it is possible to define the real goodness of the W100 Apiezon® wax used as sealant agent.

Internal pollutants in the display case include volatile gases slowly emitted from the displayed objects, or from construction materials, or from infiltration through minute leaks over the years. Even though the composition and quantity of these internal pollutants have not been thoroughly investigated, pollution sorbent such as activated carbons are the best preventive solution [35]. Activated carbon is capable of absorbing the pollutants of NOx, SO_2, CO, CO_2, O_3, and hydrocarbons at a level of approximately 50 ppb. The quantity to be used is calculated from the display case size.

5.1.2 Physical tests on the prototypes

Several different methods can be used for measuring the gas tightness of a display case, with varying degrees of measurement sensitivity; some of these methods are described in technical standards, such as the pressure drop test [36] which involves the introduction of an inert gas into the system until a pressure of at least 100 mbar above the atmospheric pressure is reached, and the evaluation of the rate of decay over a period of 15 minutes; a similar method is the loss-of-volume test [37] estimates the leak rate in terms of gas volume loss over time. However, neither of these tests are applicable in the developed prototype display case, both due to the inherent low measurement sensitivity of the above methods and because the wax seal cannot withstand the mechanical stress caused by the above differential pressure.

A more refined quantitative gas tightness test can be carried out using tracer gases. The display case is saturated with a "tracer gas"; often sulphur hexafluoride (SF_6) is used, but it is also possible to use argon (Ar), nitrogen (N), or helium (He), together with a dedicated leak detector. Ultrasonic leak testing can also be used to assess whether a display case or a metal weld is sealed correctly. It involves scanning an ultrasonic source along the welds to identify any interruptions in the seal by analyzing a so-called “signature” return signal.

Within our study, the gas tightness of the prototype display case was assessed by setting up a dedicated analysis system able to detect the LR-O_2 with a sensitivity in the order of several ppm (Fig. 3). In order to ensure reliable and accurate measurements, a number of factors were taken into account. Particular attention was paid to the study of the variations in temperature, gas flow, the system pressure in relation to the instrumental response of the O_2 detection system. The oxygen detector was a Ntron® N3100 partial pressure oxygen analyzer with a specified measurement accuracy 1 % in the 1000-ppm range. Periodic calibration was carried out using a certified mixture with (524 ± 5) ppm of O_2 in N_2. The prototype display case was connected to the analysis system via a closed-circuit configuration (Fig. 4) to quantify the leak rate by means of partial O_2 pressure measurements. A Senior-Aerospace® MB118E bellows pump was used to provide gas flow in the analyzer circuit.

Because of the expected low LR-O_2 it was necessary to carry out continuous measurements over an extended period of time. The process involved performing week-long measurements over a period of about two months, while sampling the gas mixture in the display case at intervals of 6 hours. The upper plot in the Figure 5 shows the O_2 concentration over the test period, while the lower plot shows the display case temperature over the same interval.

As expected, the correlation between variations in temperature and partial oxygen pressure shows up in Figure 5. To estimate the real leak rate via the O_2 partial pressure measurements, the latter must be corrected with respect to the variations of its absolute temperature, based on the following gas law equation:

$$dP = \frac{\partial P}{\partial \mathrm{T}} dT + \frac{\partial P}{\partial n} dn = \frac{nR}{\mathrm{V}} dT + \frac{\partial P}{\partial n} dn$$

where

P is the O_2 partial pressure (in Pa)
T is the absolute temperature (in kelvin)
n is the number of moles of O_2
R is the gas constant
V is the volume of the display case.

The term $\frac{\partial P}{\partial \mathrm{T}}$ represents the dependence of pressure from the temperature, at a constant concentration, whereas the term $\frac{\partial P}{\partial n}$ represents the pressure variation caused by oxygen leaking from the display case.

The graph in Figure 6 plots the O_2 concentration after the compensation for the temperature effect. It can be seen that the non-compensated LR-O_2 is about 0.26 ppm day-1, whereas the compensated residual term is approximately 0.18 ppm day-1, which is well below the instrumental sensitivity of the analyzer.

5.1.3 Case studies

The passive-type display case prototype developed in this project has been successfully implemented to conserve and display the two exhibits: the mummy of Rosalia Lombardo (1920 AD) in Palermo, Italy in 2011, [38] and the mummy of Princess Anna of Bavaria (1319 AD) in Kastl, Germany in 2013 [39] (Fig. 7). Since both mummies are those of young girls, the interior volume of the display cases was relatively small, whereas the only difference in the construction of the two cases was the shape of the glass, the former had a curvature radius of 40 cm, whereas the latter was flat and laid at a 45° angle. Both mummies were anthropogenic in origin, and another similarity lay in the fact that both were exhibited in ancient Christian places of worship. Neither site is equipped with an electrical power supply, or any kind of air conditioning system, which means the passive-type display case represented the most suitable solution.

6.1 Conclusions

A display case designed and constructed using the described passive-type approach may provide the ideal parameters for storing the exhibits and guarantee that these conditions are maintained over a very long period of time.

The aim of the project was to develop a gas-tight system capable of achieving a very low gas leak rate, possibly below 1 ppm day-1; i.e., by assuming a display case having a volume of 1 m^2, at a LR-O_2 leak rate equal to or lower than 1 ppm day-1, the equivalent AER would be 5 10^{-6} vol/day.

It would take more than 500 years for a complete air exchange in the display case. The goal of the project has been both met and exceeded, with an estimated LR-O_2 ≤ 0.18 ppm day-1.

While this approach has the added advantage of virtually eliminating servicing and maintenance costs, it is clear that such display cases are comparatively more expensive to construct, to ensure the fundamental design criteria are observed and an accurate and meticulous set-up procedure is required.

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Table 1 Physical-chemical parametersforthecorrectconservationoforganicculturalassets

Quantity	**Interval**
Air temperature	14 °C to 16 °C
Relative humidity	25 % to 60 % (*)
O_2 concentration	0 % to 0.01 % (**)
O_3, SO_2, NO_2, CO_2, VOC concentration	0 μg m^{-3}
Illuminance	50 lm m^{-2}
UV irradiance	0 μW lm^{-1} to 10 μW lm^{-1}
UV irradiance	0 μW cm^{-2} to 0.05 μW cm^{-2}
Spectral irradiance (λ = 0.4 μm to 4 μm)	1 W m^{-2}
Maximum light dose per year	0.015 Mlx h yr^{-1}

* Materials of plant origin (linen, paper, wood) prefer a relative humidity between 40 % and 65 %, where the Shift Index (IS) is 5 % [17].

** Before applying this condition, it is essential to verify the absence of possible metabolic activity of anaerobic bacteria on the object to preserve.

Fig. 1. Display case prototype for the mummy of Rosalia Lombardo (1918–1920AD), Palermo, Italy

Fig. 2. Display caseprototypeconnectedtotheO2 analyzer during the leak rate tests.

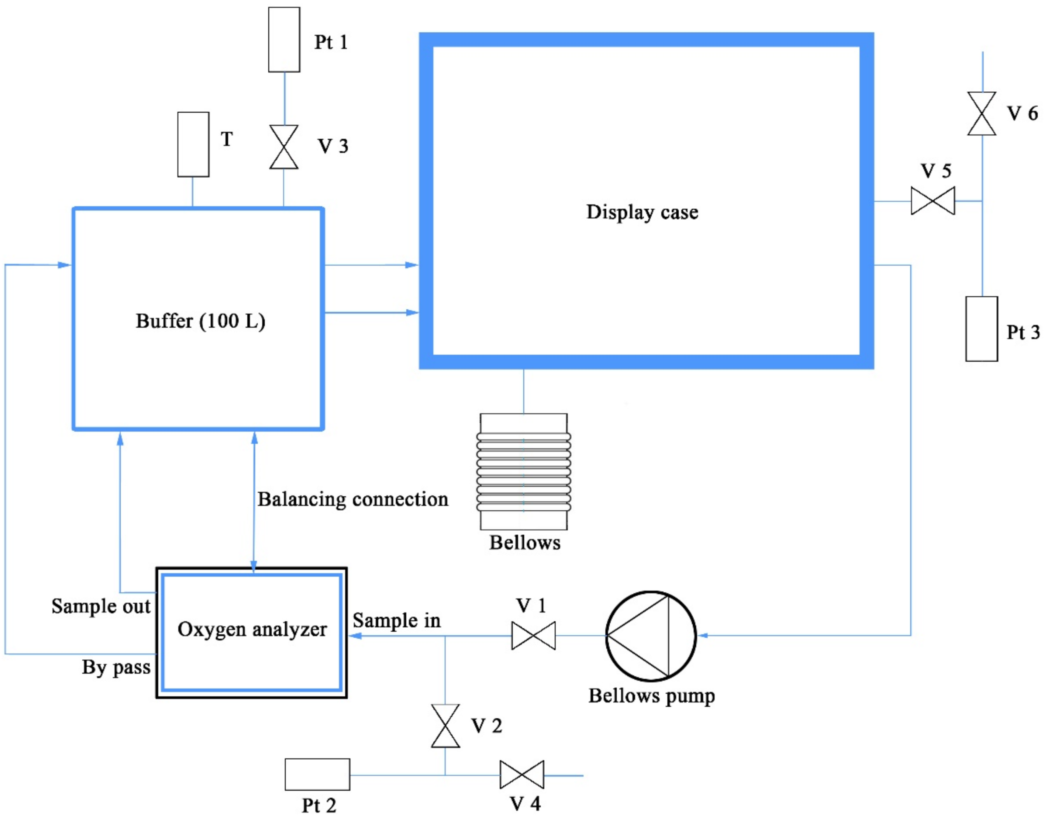

Fig. 3. Leak rate test set-up. Ptx=Pressure transducers; T=thermometer; Vx=valves.

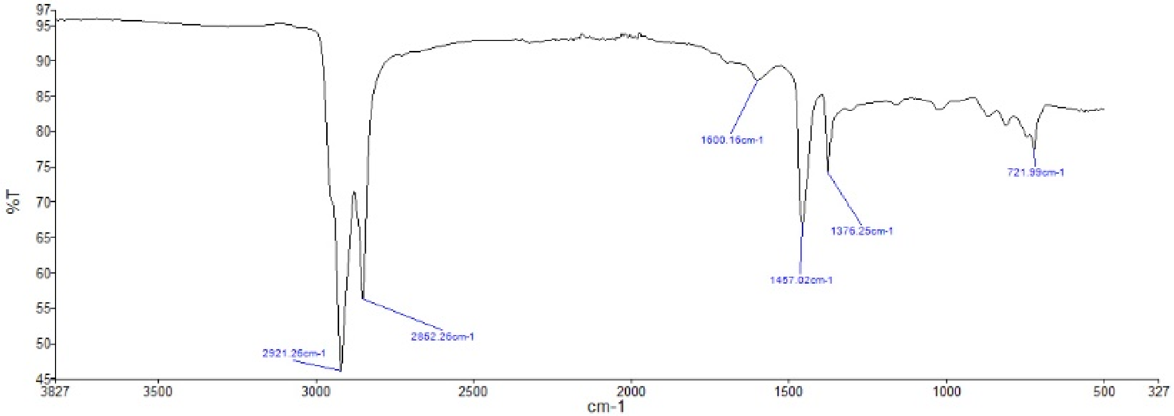

Fig. 4. FT-IR ATR spectrum of the bitumen wax W100 Apiezon® .

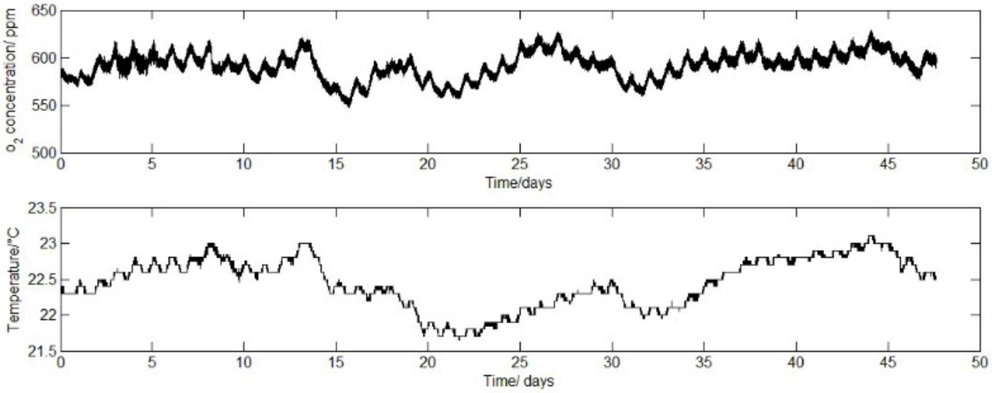

Fig. 5. Detected O2 concentration (upper plot) and temperature changes (lower plot) overtime.

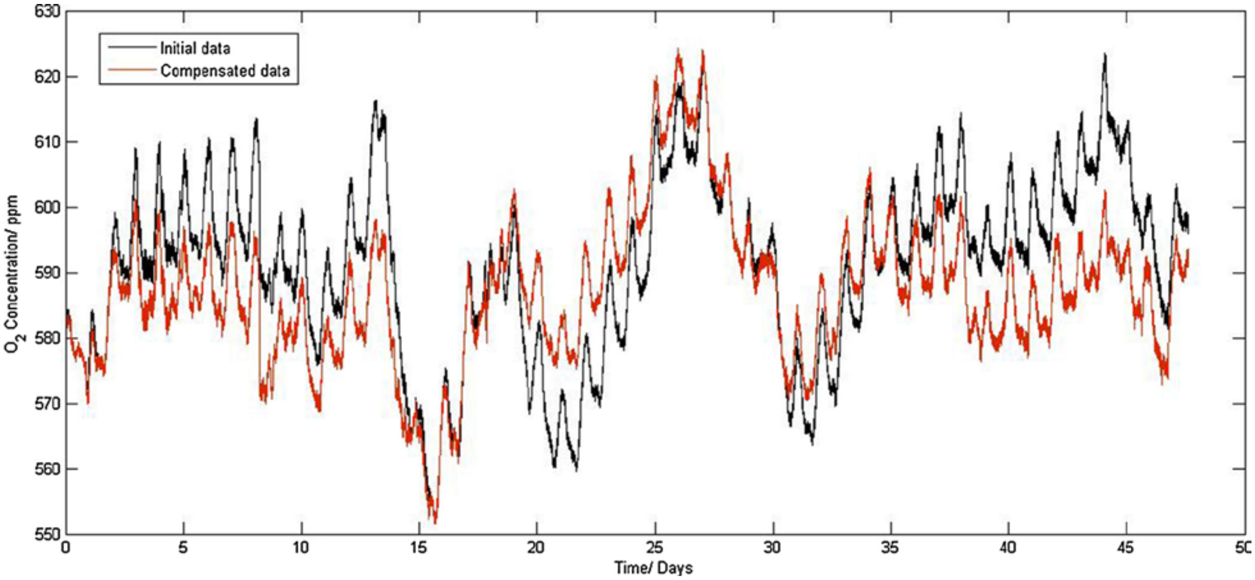

Fig. 6. Corrected O2 concentration inside the display case prototype over a fifty-day period.

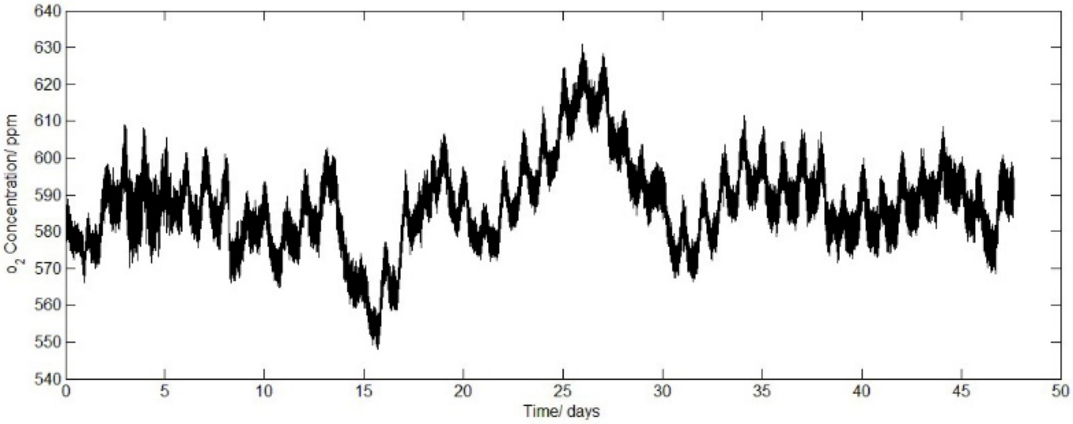

Fig. 7. The slope of the fitting line represents the average leak rate inside the display case prototype over a fifty-day period.

Fig. 8. The mummy of Princess Anna of Bavaria (1319AD), Kastl, Germany.