Indoor measurements of microclimate parameters in the Mithraeum in the Baths of Caracalla (Rome, Italy)

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1. Introduction
Although in the last decade a growing number of studies on environmental conditions of museums and buildings housing artifacts have shown that a stable microclimate is beneficial for their conservation [Camuffo, 1998, 1-432; Camuffo, 2001, S127-S140; Pavlogeorgatos, 2003, 1457-1462], this is not always put into practice. The continuous monitoring of the microclimate to assess the artifacts own historic microclimate and to develop a preventive control program for the best conditions of preservation, is becoming a common procedure [Camuffo, 1998, 1-432; Corgnati et al., 2009, 1253-1260]. The building, as envelope, can be considered a filter for the outdoor environmental conditions and sometimes this can be sufficient to ensure adequate microclimate and air quality [Strada, 2002, 89-92]. When the indoor environment is strongly affected by external forcing, this requires to be studied carefully.

The Mithraeum was built in the early third century A.D. in an underground corridor of the North-West exedra of the Baths with an independent access from the Baths complex. The Mithraeum consists of five communicating rooms (Fig.1): two rooms (δ and η) adjacent to the entrance (ε) with two wall openings of about 1.0 x 1.5 meters (F2 and F3); room (ε) with no ceiling adjacent to the Central Hall (h) thus precipitation and sunlight reach the Mithraeum continuously. The Central Hall still preserves a mosaic floor and on the wall on the North-West side (P1B) a fresco of Mithras.

The site has been closed to the public for the last 10 years. Different decay processes occurred in the Central Hall. Green and dark patinas on the wall P1A were probably due to biological colonization. The high porosity and the mobilization of salts, together with the humidity in the inner layers of the wall, could have facilitated the colonization and growth of such organisms [Macedo et al., 2009, 3476-3490]. The fresco has suffered from exfoliation and flaking that could be caused by salt crystallization [Zehender, 2007, 353-367].

In this paper we performed the analysis of the indoor/outdoor exchange of air mixing ratio and of temperature, of the impact of natural lighting, and of fungal growth, to prevent the decay processes and to suggest solutions to improve the microclimate conditions.

2. Methodologies
The following parameters were monitored from December 14, 2010 to May 3, 2011 before the beginning of the restoration:
• Indoor air temperature (T2in and T3in);
• Outdoor air temperature (T1out);
• Indoor Relative Humidity (RH2in, RH3in);
• Outdoor Relative Humidity (RH1out);
• Surface temperature (Tc);
• Intensity of lighting per unit area (E).

The instrumental system installed in the Mithraeum (shown in Table 1 and Fig.1) consisted of three electronic thermo-hygrometers, one contact thermometer and one photo-radiometer. The technical features are summarized in Table 2.

All sensors were connected to the GRILLO MMTS data logger with remote transmission of data. The unit used the GSM/GPRS (Global System for Mobile Communications/General Packet Radio System) technology for the data transmission to the server allowing the visualization of the data set and their download. For this study the acquisition time was set to 30 min and the processing time was set to 60 min, providing the minimum, maximum and the average of the recorded parameters.

<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>SENSOR HEIGHT</th>
<th>LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor sensor (URT1)</td>
<td>1.80 m</td>
<td>Near the entrance</td>
</tr>
<tr>
<td>Surface temperature (Tc)</td>
<td>1.70 m</td>
<td>On the South-East and North-West walls (Fig.1)</td>
</tr>
<tr>
<td>Indoor sensors (URT2 and URT3)</td>
<td>2.00 m</td>
<td>Four instrumental configurations (Fig.1)</td>
</tr>
</tbody>
</table>

Table 1

<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>PARAMETER</th>
<th>MEASUREMENT RANGE</th>
<th>ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-thermometer (thermistor)</td>
<td>Surface temperature (°C)</td>
<td>-30°C / +50 °C</td>
<td>±0.1 °C</td>
</tr>
<tr>
<td>Thermo-hygrometer: platinum resistance sensor</td>
<td>Air temperature (°C)</td>
<td>-40°C/+60 °C</td>
<td>±0.3 °C</td>
</tr>
<tr>
<td>Capacitive hygrometer</td>
<td>Relative Humidity (%)</td>
<td>0-100%</td>
<td>±1.5%</td>
</tr>
<tr>
<td>Photo-radiometer</td>
<td>Intensity of lighting on the unit area (lx)</td>
<td>0-1000 W/m²</td>
<td>±0.5% of reading value</td>
</tr>
</tbody>
</table>

Table 2

The following analyses were performed:
- Indoor/outdoor air temperature and water vapor exchanges to evaluate the influence of weather systems (external air fluxes and daily accumulated precipitation) on indoor conditions;
- The trends of differences between surface walls (P1A and P4B) temperature and air temperature to evaluate the heat fluxes over time;
- The germination time curves for material type II (non-biologically recyclable materials with porous structure) to estimate the best thermo-hygrometric conditions limiting fungal growth. In addition the Time Of Wetness (TOW) was determined to predict fungal growth [Sedlbauer, 2001].
- The daily intensity of lighting (E in lx) and its frequency to evaluate the illuminance limit for high responsivity objects and the limit of the total annual light exposure, according to the standard CIE 157:2004.

Daily accumulated precipitation and wind direction data were provided by the University of Rome Tor Vergata, Department of Environmental Technical Physics.
3. Results

The Box-plots (Fig. 2) show that there are no significant differences among indoor air temperature and relative humidity values in the different configurations. Therefore the following analysis was carried out considering the collected data as homogenous.

3.1. The thermo-hygrometric conditions and indoor/outdoor exchanges

Fig. 3 shows a linear relationship between indoor and outdoor air temperature (coefficient of determination $R^2=0.9$). The intercept of indoor temperature is $2.9^\circ$C and the slope is 0.7 indicating that almost 70% of indoor air temperatures is related to the exchanges with the outdoors. In Fig. 4, the trend of air and surface temperature difference $\Delta (T_{3in}-T_c)$ is shown. It is to be noticed clearly the increasing influence of the daily cycle. In fact the air temperature is higher than the surface temperature during the day. During the night the air cools faster than the wall probably due to its thermal inertia.

The mixing ratio (MR) values were then determined and analyzed to evaluate the water vapour exchange. We found that the indoor MRs (MR2in and MR3in) are higher than the outdoors (MR1out). Moreover the difference between the indoor and the outdoor MR shows a larger exchange between MR1out and MR2in (the air in the Mithraeum), than MR3in (the wall) (Fig. 5).

The MR data were related to both the outdoor wind direction and the daily accumulated precipitation. It can be noticed an increase of indoor MR (higher than 6g/kg) during precipitations occurrences and during cases of warm and humid wind (e.g. from South sector). During the North wind occurrences (cold
and dry wind) MR decreases (lower than 6g/kg) were experienced. Indoor mixing ratios against outdoor values is plotted in Fig.6. A linear relationship was found (R²=0.96) with the intercept equal to 1.03 g/Kg and a slope of 0.90. This means that 90% of indoor MR is related to exchanges with the outdoors.

The spore germination time curves were taken into account in the case of wall P1A where the biodeterioration was observed, in order to evaluate whether the thermo-hygrometric conditions are favourable to spore’s growth. If the values are above the threshold (the lower germination limit), the spores become active fungi [Sedlbauer, 2001]. The time of germination is specified by the curves under which the values occur (from 16 to 1 day of germination time). The data were divided into two periods: winter (from December to February) and spring (from March to April). A germination range time, from 16 to 1 day, was found. Furthermore the TOW (Time Of Wetness) was considered, for a TOW below 0.5 the fungal growth is negligible. Instead, TOW=0.5 in winter and TOW=0.8 in spring were found. It should also be noticed that the RH3in values mostly determined spore germination (Fig.7).

3.2. Lighting analysis
The frequency distribution of the intensity of lighting per unit area E was calculated at 3 hours intervals, showing maximum values between 13:00 and
Fig. 5 - The difference between the indoor and the outdoor MR data related to daily accumulated precipitation (from 14/12/2010 to 3/5/2011).

Fig. 6 - The linear relationship between indoor mixing ratios and outdoor values (from 14/12/2010 to 3/5/2011); Fig. 7 - The spore germination time curves for the thermo-hygrometric values of the wall P1A. The time of germination is specified by the curves under which the values occur (from 16 days to 1 day of germination time) (from 14/12/2010 to 3/5/2011).
15:00 during the period from 14/12/2010 to 16/02/2011 (the first and second configuration). While from 16/02/2011 to 16/03/2011 (the second and third configurations), no significant values were found and the data were omitted. The standard CIE157: 2004 gives a threshold for the E value lower than 50 lx for high responsivity materials. It was found that many occurrences of E values during 12:00-15:00 were above the threshold (Fig.8).

4. Discussion
The analysis of indoor/outdoor air temperature and mixing ratios shows that the Mithraeum is characterized by high air temperature and water vapour exchanges.
The wall surfaces have a rapid daily heat exchanges with air, due to its thermal inertia and its adjacency to the ground. Moreover precipitation in the room with no ceiling continues to store a water reserve which soaks the walls and the stamped earth floor. As a result the wall against the ground and the stamped earth floor contribute probably to maintain the volume of indoor water vapour.
The analysis of the wind direction and MR values indicates an increase of MR due to South sector wind (warm and humid wind), while with North wind (cold and dry air fluxes) there is a decrease. As a result the air is directly exchanged through the openings.
Furthermore the thermo-hygrometric conditions strongly support the fungal growth, one day suffices to activate the spores. To prevent fungal growth in a hypogeum site, the parameters should be maintained approximately at a temperature below 15 °C and a relative humidity below 77.6%.
The lighting analysis shows a high frequency of E values over the 50lx threshold (from 14/12/2010 to 16/02/2011), due to the direct sunlight incoming from room ε without the ceiling. According to the standard CIE 157: 2004 a total annual light exposure of 15000 (lux-hours per year) should not be exceeded.
These results indicate the necessity to improve microclimate conditions. Our suggested solutions to better preserve the Mithraeum are:
- to close the openings and build a ceiling in the room near the Central Hall to reduce indoor wind speed and air mixing, and to avoid solar irradiation and precipitation.
- to build an interspace on the South-East side of the Mithraeum between the ground and the wall, to reduce salt and water exchange.
- to use a lighting system not exceeding the total annual light exposure of 15000 (lux·hours per year).

During the restoration, room ε was rebuilt. The great arch (Arc1) was covered with a special tissue to reduce air fluxes in the Central hall. The opening F1 and the entrance were partially closed with polycarbonate panels which diminish the air exchange. However the openings F2 and F3 are still open. To verify whether the quality of the indoor microclimate after restoration has improved, another cycle of microclimate monitoring has begun in February 2013.

Acknowledgements
We are grateful to Dr. Piranomonte of the Soprintendenza Speciale per i Beni Archeologici di Roma that provided informations and access for this study and to University of Rome Tor Vergata, Department of Environmental Technical Physics, to have provided precipitation and wind data.

References
Abstract
The Mithraeum in the Baths of Caracalla was discovered during the archaeological
evacuation carried out in 1912. It was built in the early third century A.D., in an un-
derground corridor of the North-West exedra with an access independent from the
Baths complex. The Mithraeum consists of five communicating rooms. The two rooms
adjacent to the entrance have two wall openings (about 1 x 1.5 meters). The floor was
made of stamped earth (terra battuta) while the Central Hall still preserves a mosaic
floor and a fresco of Mithras on the North-West side. The room adjacent to the Central
Hall has no ceiling thus precipitation and sunlight affect it continuously.
The Mithraeum site suffered from heavy damage and the site has been closed to the
public for the last 10 years. Several weathering processes were observed in the Cen-
tral Hall. On the South-East side, almost at ground level, a compact deposit covered
the entire surface of the wall changing the morphology of the stone surface with green
and dark patina, probably a sign of biological colonization. On the North-West side,
the fresco surface suffered from exfoliation, flaking and swelling. These deterioration
processes are sensitive to microclimate factors (high humidity, temperature changes
and aerodynamic features), salt weathering, and microbiological factors.
In 2010, before the beginning of restoration, the Soprintendenza Speciale per i Beni
Archeologici di Roma decided to monitor the microclimate of the Mithraeum to search
for the causes of the deterioration and design proper conservation measures.
Indoor and outdoor thermo-hygrometric parameters were monitored from December
2010 to March 2011 to characterize environmental conditions. Moisture exchanges
between indoors and outdoors were evaluated taking into account the mixing ratios,
the outdoor wind direction and the intensity of precipitations whereas the difference
between air and surface temperatures was taken into account as indicator of heat fluc-
tuations. Indoor lighting measurements were performed in accordance with the European
Standards CIE 157:2004. In addition the germination time curves for materials with
porous structure were considered to evaluate the risk of occurrence of fungal growth.
The results show that the indoor microclimate conditions need to be improved to li-
mit the observed decay and to better preserve the materials (fresco and mosaic), in
particular the fresco of Mithras. Possible solutions to protect the Central Hall against
outdoor climate can be to close the openings in the walls and to build a ceiling in the
room near the Central Hall.