



AIR QUALITY ASSESSMENT IN CULTURAL HERITAGE INSTITUTIONS USING EWO DOSIMETERS

FULL PAPER

Susana Lopez-Aparicio*, Terje Grøntoft, Elin Dahlin

This paper is based on a presentation at the 9th Indoor Air Quality meeting (IAQ) in Chalon-sur-Saône, France, 21-23 April 2010.

Guest editor:
Dr. Christian Degryny.

NILU – Norwegian Institute for Air Research, Instituttveien 18, Kjeller N-2027, Norway

corresponding author:
sla@nilu.no

Since its development, the Early Warning dosimeter for Organic materials (EWO dosimeter) has been used as both a research and general measurement tool for the evaluation of indoor air quality for preservation of cultural heritage artefacts. The EWO dosimeter measures the integrated degradation impact of the environment, comparable to that observed on organic materials due to the synergistic effects of gases (NO₂ and O₃) and climate (temperature / RH, UV-light).

Measurements of impacts of air pollution on EWO dosimeters were performed in different cultural heritage locations as part of EU projects, other types of international projects and as a service to individual institutions. In this study, the indoor air quality in different microenvironments or locations is assessed based on the results obtained by EWO dosimetry. Correlation between the type of location and the dosimeter results has been observed. Indoor locations in highly polluted cities showed higher dosimeter response than more rural locations probably due to more infiltration of outdoor generated pollutants such as NO₂ and O₃. In contrast, measurements performed inside enclosures (e.g. showcases / microclimate frames) showed low response of the dosimeter and hence low photo-oxidizing effects.

1 Introduction

Air pollution has become a main concern of our society due to its adverse effects on health, materials and ecosystems. The study of the effects of indoor air pollution on cultural heritage objects is receiving an increasing interest that has over the last decade focussed on the protection of items both in exhibition and storage. However, the evaluation of the environment and the risk assessment for the preventive conservation of cultural heritage objects are complex exercises. Damage observed on objects depends partly on the material which the object is made from and partly on the indoor environment. Indoor air contains a mixture of different types of gases which may vary in

received: 22.04.2010
accepted: 24.07.2010

key words:
Cultural heritage, dosimetry, photo-oxidizing effects, indoor environment, outdoor pollutants

space and time, as do values for climate parameters such as temperature and relative humidity. In addition, pollutants and climate parameters can act in synergy to enhance the harmful effects on the objects.

The selection of measurements to be performed is one of the primary steps and main concerns for the evaluation of air quality. In addition, cultural heritage locations have specific needs compared with other types of indoor locations. User friendly techniques, aesthetically non invasive, reduced size and low cost are some of the most common requirements from cultural heritage professionals interested in indoor air quality.

Measurement techniques can be divided between those measuring single parameters such as temperature, relative humidity or the concentration of specific pollutants and those which measure the impact of the environment. Concentrations of single pollutants can be measured by passive diffusion gas samplers,¹ monitors or other types of devices / sensors. In contrast, dosimeters or impact sensors² measure the degradation effects of the total or parts of the total environment on the objects of interest. For that reason, dosimeter materials are often similar to the objects of study, but should be more sensitive to provide quick measurement (e.g. some months) of possible degradation risks. However, museum collections include different types of materials which respond differently to the environment. A general division into organic (i.e., paper, some types of pigments, leather, textile, varnishes) versus inorganic materials (i.e. metals, some pigments, mineral specimens) can be made based on the chemical composition.

A wide variety of dosimeters made from different materials and analysed according to different methodologies are available. Metals are commonly used as dosimeters (i.e. lead, copper, silver) due to their quick response to the environment and their sensitivity to compounds which are also harmful for cultural heritage objects.³⁻⁴ Other materials that are used are synthetic polymers, glass, varnishes and pigments (see ref. 5-7).

The objective of this study is to evaluate the indoor air quality in different cultural heritage locations based on the results of the Early Warning Organic (EWO) dosimeter developed by the Norwegian Institute for Air Research (NILU), in the EU project MASTER⁸ and applied in the EU PROPAIN project⁹ and other projects. The EWO dosimeter was developed as a tool for assessing indoor air quality in museum, archives or historic buildings, to give guidance in the work to protect organic cul-

tural heritage items. Results from measurements with the EWO dosimeter in different types of cultural heritage locations (e.g. historic building, enclosure, storeroom or archive) and geographical location (e.g. urban or rural environments) are compared and evaluated.

2 Methodology

2.1 The EWO Dosimeter

The EWO dosimeter is a synthetic polymer sensitive to climate parameters (i.e. temperature, RH and UV Light) and NO₂ and O₃, which are usually emitted outdoors and ventilated or infiltrate into the indoor environment. The environmental effect on the dosimeter polymer film is measured by spectrophotometry as the change in UV absorption at 340 nm from before to after exposure. The relation between the EWO-response and the environment is based on a non linear dose response function found from the statistical analysis of the results obtained in a measurement campaign performed in the MASTER project.⁸⁻⁹ Two dose response functions for indoor locations outside (Equations 1) and inside enclosures (i.e. showcases; Equation 2) were defined⁹ as it follows:

$$EWO \times 1000 = 8.7 + \sqrt{UV} + \sqrt{T} (0.11[NO_2] + 0.1[O_3]) \quad \text{Equation 1}$$

$$EWO \times 1000 = 4.5 + \sqrt{T} (0.16[NO_2] + 0.052[O_3]) \quad \text{Equation 2}$$

where *UV* represents ultraviolet radiation (mW m⁻²), *T* represents temperature as °C, and the gas concentration is expressed as µg m⁻³.

An evaluation of recommended response levels for the EWO as compared to effects on organic cultural heritage objects was performed based on existing knowledge in conservation science about the effects of the single environmental parameters on the heritage objects.¹⁰ The results from measurements with the dosimeter are reported as values of increasing environmental impact ranging from one to five. The evaluation of the indoor air quality is performed for five different locations with different degree of protection, from archive to external store with no control.

2.2 Data sources

This paper reports data from measurements with the EWO in research projects and as services offered to Cultural Heritage professionals by the Norwegian Institute for Air Research (NILU) between 2008 and 2009. Table 1 shows the sites, types of locations (e.g. historic building, enclosure), geographical situation and types of environment (i.e. rural / urban). A total of 207 results from EWO dosimeter measurements were analysed in

#	Geographical Location	Location Type	Urban / Rural
23	Oslo, NO	Historic Building, enclosure	Urban
2	Akerhus, NO	New building	Rural
5	Copenhagen, DK	Historic Building, enclosure	Urban
16	Haslach, GE	Historic Building, enclosure	Rural
13	Heraklion, GR	Historic Building, enclosure	Urban
20	Krakow, PO	Historic Building, enclosure	Urban
24	London, UK	Historic Building, enclosure, Storeroom, Archive	Urban
7	Madrid, ES	Workshop, enclosure	Urban
2	Mexico City, MX	Historic Building, enclosure	Urban
16	Norfolk, UK	Historic Building, enclosure	Rural
2	Nurberg, GE	Historic Building, enclosure	Urban
10	Prague, CR	Historic Building, Storeroom, Archive	Urban
16	Rabat, ML	Historic Building, enclosure	Rural
16	Stuttgart, GE	New building, enclosure	Urban
16	Trondheim, NO	Historic Building, enclosure	Urban
2	Valencia, ES	Historic Building, enclosure	Urban
16	Zakopane, PO	Historic Building, enclosure	Rural
1	Tokyo, JP	Storeroom	Urban
207	Total EWO dosimeter measurements		

Table 1: Overview of the EWO results analysed in this study.

this study to evaluate the response of the EWO dosimeters in different locations with different environments. The results obtained in workshops were left out (i.e. three EWO results) and the remaining 204 EWO results were divided according to types of Cultural Heritage locations, as “Historic Buildings”, “Storeroom / Archives”, “New Buildings” and “Enclosures”, understanding for enclosures as containers with relative small volume of air such as showcases or microclimate frames. The highest number of EWO results belongs to the class of measurements performed inside enclosures followed by those performed in historic buildings (Table 1; Figure 1).

3 Results and discussion

The EWO measurements were, on average, found to be lower in locations classified as “Enclosures” (EN) than those classified as “Historic Buildings” (HB; Figure 1). These results indicate that enclosures protect objects against degradation that can be caused by the synergistic effects of outdoor generated pollutants (i.e. NO₂ and O₃) and climate parameters (i.e. temperature, RH and UV-light). The protective effects of enclosures against externally generated pollutants such as NO₂ and O₃ has been previously established based on the results obtained by different types of dosimeters⁹ and the evaluation of pollutant concentration measurements.¹¹

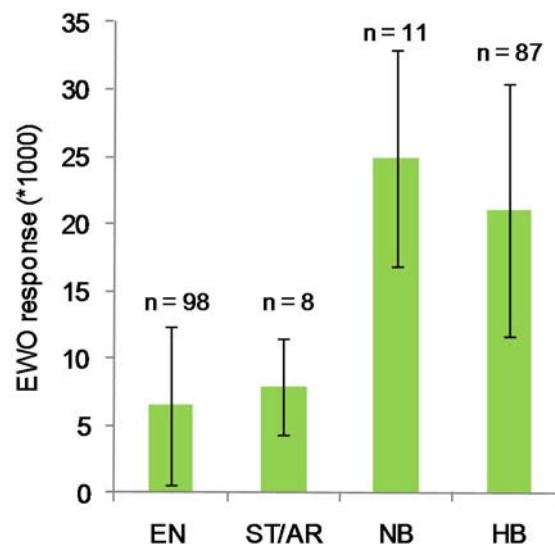


Figure 1: Average EWO response (*1000) in different heritage institutions. EN: enclosure (i.e. showcase and / or microclimate frame), ST/AR: Storeroom and archives, NB: new building, HB: historical building. Vertical bars indicate standard deviation. n: number of measurements.

The average of the measurements results for the class of “Storeroom / Archive” (ST/AR) was also very low, similar to the result obtained inside enclosures (Figure 1). Some of the storerooms and archives were air conditioned with low light levels and low number of visitors. This may explain the low EWO results values. The average of the results obtained for the class “New Buildings” (NB) is very similar to the average obtained for the class “Historic Buildings” (Figure 1). However, the results for the classes “New Buildings” and “Storeroom / Archives” may be less representative due to the low number of measurements (i.e. ST/AR = 8; NB = 11; Figure 1).

The EWO results obtained in the different types of indoor locations and in different geographical areas were compared with punctual measurements of NO₂, O₃ and acetic acid performed in the same locations, where information was available. The measurements of the pollutant gases were performed simultaneously or following the EWO measurements for some of the enclosures. NO₂ and organic acids (acetic and formic acids) concentrations were measured by passive diffusion gas samplers¹² from the Norwegian Institute for Air Research (NILU) and from Swedish Environmental Institute (IVL) in the case of ozone concentration. The linear correlations between the EWO response and the concentration of NO₂ and O₃ are low as expected, with R² values equal to 0.38 and 0.29, respectively (Figure 2), as the EWO response correlates with multiple parameters. The R² value for the multiple regression (Equation 1) is 0.73,⁵ showing the value of the EWO dosimeter for

the assessment of the combined effects of outdoor pollutants (i.e. NO₂ and O₃) and climate parameters (i.e. temperature, UV light). The correlations of the EWO measurements with the NO₂ and O₃ concentrations show that the EWO dosimeter is a good indicator for the presence of outdoor generated pollutants (Equation 1; Figure 2). The lack of sensitivity and thus of correlation of the EWO dosimeter with acetic acid (Figure 2) is one of the disadvantages of the dosimeter since organic acids are common in indoor locations and may be harmful for some items. Thus, in the EU project PROPAINT a method for dosimetry combining the EWO with another dosimeter sensitive to organic acids was developed.⁶

The relation between the EWO response and the NO₂ concentration was used to illustrate and evaluate the EWO response in the different types of locations (Figure 3). The category called historic buildings shows the highest variance in NO₂ concentration and EWO response (Figure 2). This large variance may be explained by larger variability of the environmental parameters between locations in this class, which may be due to different regimes for the indoor climate and / or different degrees of protection by the building against infiltration of outdoor generated pollutants (i.e. NO₂ and O₃). The climate control and effect of building protection will depend on factors such as type of ventilation systems, presence / absence of filtration systems for gases and particles, general maintenance of the building, indoor activities (i.e. cooking / coffee activities) or on the geographical location of the building (i.e. urban, traffic or rural locations), among others.

Few measurements have been performed inside storerooms and / or archives (i.e., n=8; Figure 3). The concentrations of NO₂ measured in these locations and the EWO responses were low, indicating low photo-oxidant effects and low infiltration of outdoor generated pollutants.

The class named “Enclosures” includes a wide variety of enclosure locations with different dimensions, construction materials, objects within the enclosures and air exchange rates. Some show-cases were exclusively made of glass or wood whereas glass was combined with wood, metal and / or cloth in other enclosures. Microclimate frame enclosures are made from wood, glass, metal and / or polycarbonate as the main construction materials. Some of the enclosures were empty whereas others included objects such as paintings, textiles or wood items. Differences in the size and the air exchange rate between the enclosures are among the most significant. The volumes vary from 0.01 to 70 m³, and air exchange

rate varies from 0.2 to 15 day⁻¹. The different sizes and air exchange rates of the enclosures will strongly influence the amount of pollutants that are

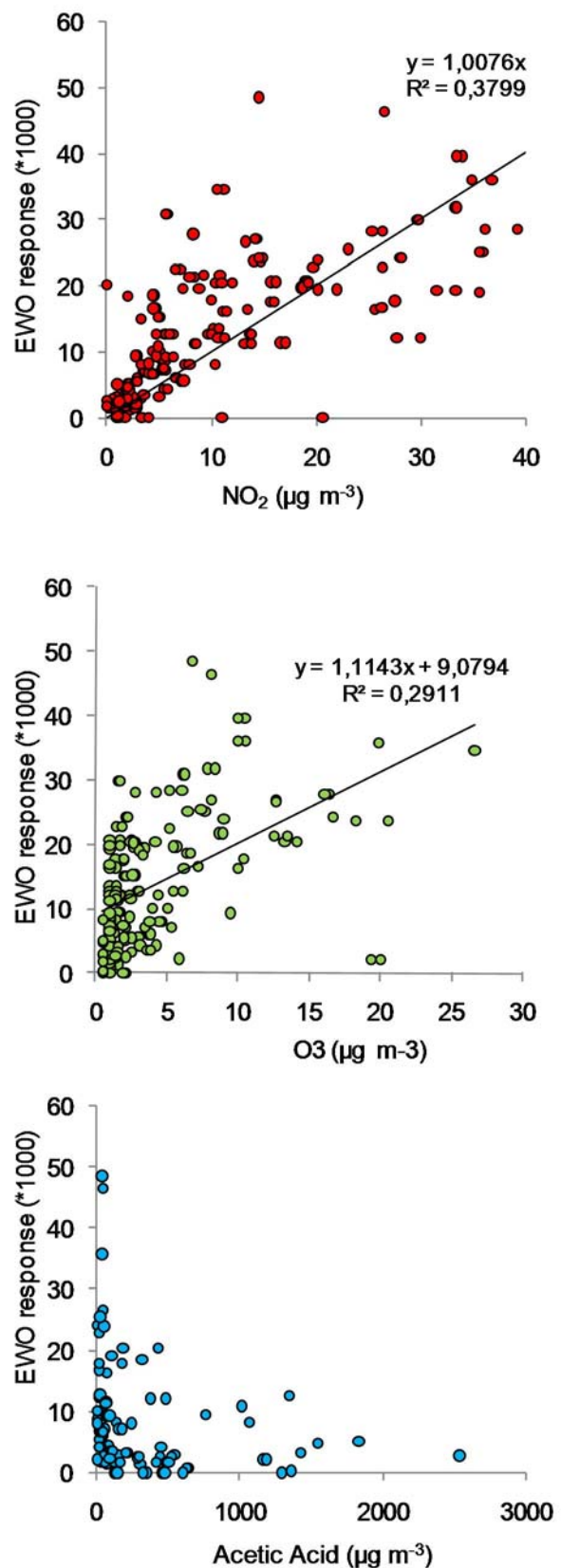


Figure 2: EWO dosimeter responses versus NO₂, O₃ and acetic acid measured with passive diffusion gas samplers.

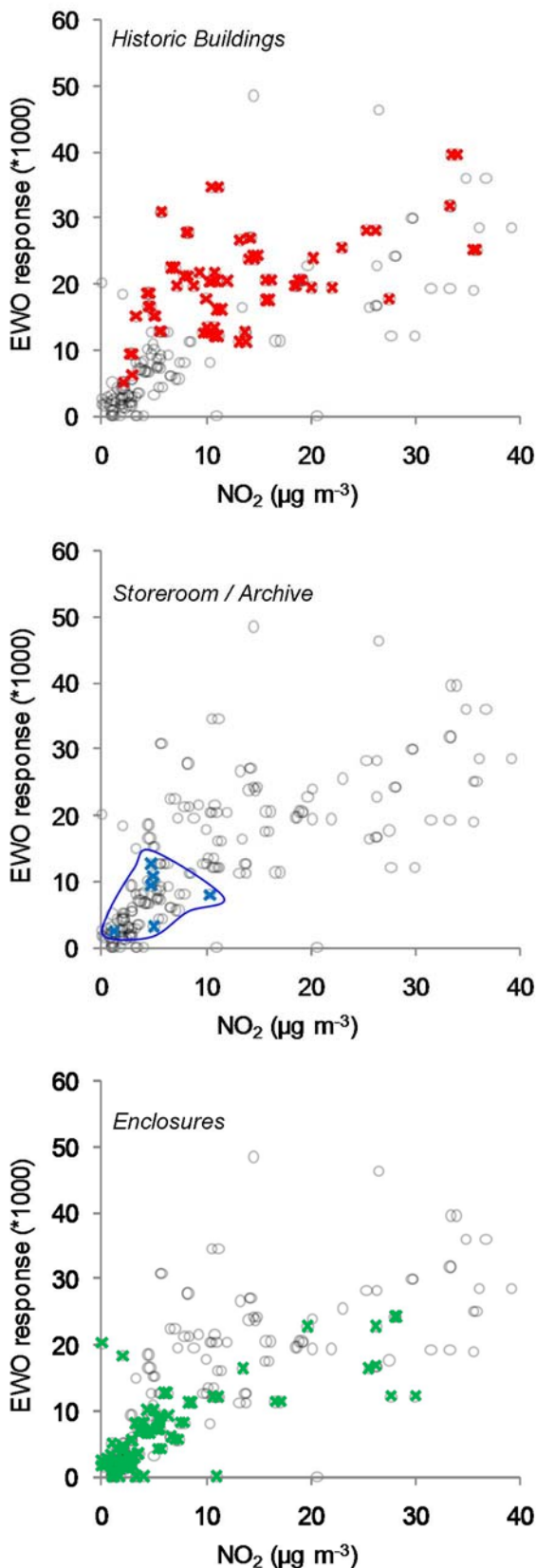


Figure 3: EWO response (*1000) versus NO₂ concentration measured by passive diffusion gas samplers in different types of indoor locations. Open circles: total EWO dosimeter results. Crosses: EWO measurement results for the class indicated on each graph.

infiltrated into the enclosures and the dilution and ventilation of internally generated pollutants. These are important factors in explaining the variability observed in the EWO dosimeter results (Figure 3). Lower EWO response than expected seems to be observed in enclosures (Figure 3). There is reason to believe that the lack of UV radiation inside the enclosures considered in our study explains a lower EWO response.

The properties of the emission sources of the pollutants are a main factor influencing level of air pollution at a geographical location. Emissions of primary pollutants such as nitrogen dioxide are related to combustion processes such as industry and traffic, and they are usually higher in urban areas than in rural environments.¹³ Therefore, buildings without climate and pollution control that are located in urban areas are usually more exposed to outdoor generated pollutants (e.g. NO₂) and their effects. Figure 4 shows some of the measurement results obtained in historic buildings in rural areas in Norfolk (UK) and Zakopane (Poland), at the small town of Rabat (Malta), and measurement results obtained in historic buildings in urban areas in London (UK), Mexico City (Mexico) and Valencia (Spain). The measured EWO responses and indoor NO₂ concentrations are generally higher in the urban areas than in the more rural areas. One of the measurements from London in Figure 4 (green dot close to the origin) deviates from the pattern. This value was obtained in Tate Store, which has climate and pollution control, low light levels and restricted personnel access. The measurement indicates very low infiltration of outdoor generated pollutants and low photo-oxidizing effects (i.e. low EWO response).

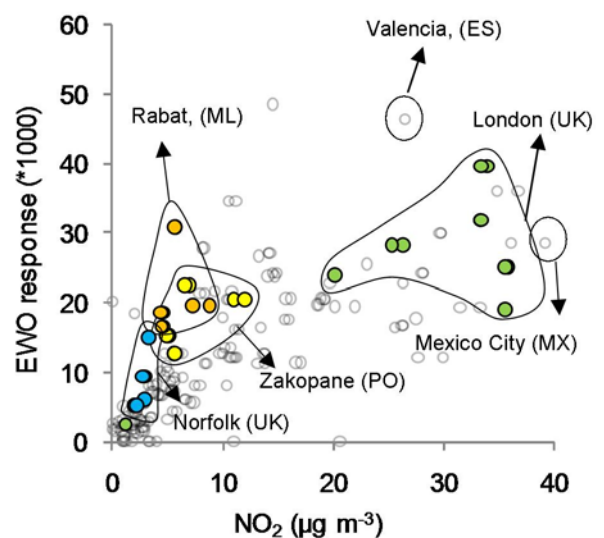


Figure 4: EWO response (*1000) versus NO₂ concentration in historic buildings locations placed in urban and rural environments. Green dot close to the origin represent a storeroom (see text for explanation).

The results from the EWO dosimeter and their comparison allow us to establish that indoor air quality in buildings without climate and pollution control, which in addition are located in highly polluted environments, may constitute a risk for the preservation of cultural heritage assets in exhibition or storage.

4 Conclusions

The EWO measures the impact on organic materials of pollutants that are usually generated outdoors (i.e. NO₂ and O₃) and act in synergy with climate parameters (i.e. temperature / RH and UV Light).

The analysis of a large number of EWO measurement results obtained from different studies, according to the types of locations where the measurements were performed, shows clear correlation between the EWO results and more (i.e. enclosures, storerooms / archives) or less (i.e. new buildings, historical buildings) protected locations. This shows that the type of indoor location and its characteristics (i.e. type of ventilation system, air exchange rate, etc) are important factors for the indoor air quality and for possible implementation of climate and pollution control.

The EWO results showed that the risk of degradation of indoor cultural heritage due to air pollutants is higher in buildings located in more polluted urban environments than in less polluted rural environments when the building does not provide the needed climate and pollution protection. These results are supported by measurement results for NO₂ concentrations obtained by passive diffusion gas samplers. NO₂ concentrations are in most instances a good indicator of outdoor generated pollutants subsequently infiltrated to the indoors.

This study shows the usefulness of the EWO for indoor air quality screening studies in cultural heritage locations. If the EWO measurements show non acceptable environments it is recommended to do measurements of specific parameters (e.g. temperature, relative humidity, light and / or single pollutant concentration levels) to identify the problem and to decide the most effective abatement strategies.

5 Conflict of Interest Statement

The authors have no commercial interest in the subject matter under consideration in the manuscript.

6 Literature

1. C.M. Grzywacz, *Monitoring for Gaseous Pollutants in Museum Environments (Tools for Conservation)*, Getty Conservation Institute, Los Angeles, 2006.
2. M. Bacci, C. Cucci, A. Azelio Mencaglia, A.G. Mignani, *Innovative Sensors for Environmental Monitoring in Museums*, *Sensors*, 2008, **8**, 1984-2005.
3. W.A. Oddy, *An unsuspected danger in display*, *Museums J.*, 1973, **73**, 27-28.
4. M. Ryhl-Svendsen, *Corrosivity measurements of indoor museum environments using lead coupons as dosimeters*, *J. Cult. Herit.*, 2008, **9**, 285-293.
5. M. Bacci; M. Picollo, S. Porcinai, B. Radicati, *Tempera-painted dosimeters for environmental indoor monitoring: a spectroscopic and chemometric approach*, *Environ. Sci. Technol.*, 2000, **34**, 2859–2865.
6. E. Dahlin, T. Grøntoft, S. López-Aparicio, M. Odlyha, M. Scharff, T. Larsen, A. Tabuenca García, A. Ortega, G. Andrade, P. Mottner, M. Obarzanowski, J. Czop, R. Kozłowski, M. P. Colombini, I. Bonaduce, M. Ryhl-Svendsen, D. Thickett, S. Hackney, J. Wadum, A. Haack Christensen, S. Jakiela, 2010 PROPAIN; Improved Protection of Paintings During Exhibition, Storage And Transit. *PROPAIN Final Publishable Report*. NILU report OR42/2010, Kjeller, Norway.
7. M. Odlyha, C. Theodorakopoulos, D. Thickett, M. Ryhl-Svendsen, J.M. Slater, R. Campana, *Dosimeters for indoor microclimate monitoring for cultural heritage*. In: T. Padfield, K. Borchersen (eds), *Museum Microclimates*. Proc. Conference, Copenhagen, 19-23/11/2007, National Museum of Denmark, 2007, 73-79.
8. T. Grøntoft, E. Dahlin, J. Henriksen, S. Rentmeister, M. Hanko, J. Heinze, J. Taylor, N. Blades, M. Cassar, *An Early Warning system for organic materials in museums, historic buildings and archives*, in: M. Drdácý, M. Chapuis (Eds.), *Proceedings of the 7th European Conference "SAUVEUR, Safeguarded Cultural Heritage" 2006*, Prague, Czech Republic, 2007, **2**, 41-50.
9. T. Grøntoft, M. Odlyha, P. Mottner, E. Dahlin, S. Lopez-Aparicio, S. Jakiela, M. Scharff, G. Andrade, M. Obarzanowski, M. Ryhl-Svendsen, D. Thickett, S. Hackney, J. Wadum, *Pollution monitoring by dosimetry and passive diffusion sampling for evaluation of environmental conditions for paintings in microclimate frames*, *J. Cult. Herit.*, in press, <http://dx.doi.org/10.1016/j.culher.2010.02.004>.
10. J. Tétrault, *Airborne Pollutants in Museums, Galleries, and Archives: Risk Assessment, Control Strategies and Preservation Management*, Ottawa, Canadian Conservation Institute, 2003.
11. S. López-Aparicio, T. Grøntoft, M. Odlyha, E. Dahlin, P. Mottner, D. Thickett, M. Ryhl-Svendsen, N. Schmidbauer, M. Scharff, *Measurement of organic and inorganic pollutants in microclimate frames for paintings*, *e-Preserv. Sci.*, 2010, **7**, 59-70.
12. M. Ferm, *A sensitive diffusional sampler*, Swedish Environmental Research Institute, Publ. IVL B-1020, 1991.
13. EIONET, 2010, AirBase, <http://air-climate.eionet.europa.eu/databases/airbase/>