Executive Summary:

Temperature and humidity – two factors that influence corrosion – are routinely monitored and controlled in museums, archives and depositories to protect the displayed or stored artefacts from deterioration. However, corrosion is dramatically accelerated by air pollutants such as nitric or sulphur oxides, organic acids and others. Since the control of the air quality might be either inadequate or excessive without the application of any monitoring technique to give rapid feedback on the air quality, information on the actual corrosivity is crucial for effective corrosion protection. There is a strong need for a simple, reliable, and real-time technique for air-quality monitoring. The main goal of the MUSECORR project was to develop electronic loggers for continuous measurement of air corrosivity, AirCorr.

AirCorr corrosion loggers allow real-time monitoring of air corrosivity towards a number of metals and alloys. The concept of the device is simple and yet highly effective: the electronic unit measures and registers the change over time in the electrical resistance (ER) of a thin metal track applied on an insulating substrate. If the metal corrodes, the cross-sectional area of the track decreases and the electrical resistance increases. A part of the metal track is protected and, thus, serves as a reference to compensate for resistivity changes due to varying temperature.

The monitoring system comprises four principal parts: an electronic logger for measuring and recording ER, a metal sensor that actually corrodes in the environment, a communication interface between the logger and computer, and a software program for interpretation of the measurements.

Three versions of AirCorr loggers were designed for specific market segments. AirCorr I is an indoor version with an exchangeable sensor well suited for e.g. showcases. AirCorr I Plus has temperature and relative humidity sensors, two exchangeable corrosion sensors and an LCD showing current corrosivity. AirCorr O is a watertight logger for heavy-duty applications.

Sensors made of copper, silver, iron, lead, zinc, bronze, brass, aluminium and tin are available in different thicknesses. Thin-film sub-micrometre sensors are designed for use in low-corrosive environments and provide extreme sensitivity. Thick-film sensors from 5 to 250 μm primarily serve for corrosion monitoring in outdoor conditions or in polluted indoor locations. The resolution varies from under 0.1 nm for the thin-film sensors to 200 nm for the robust sensors designed for highly corrosive outdoor applications.

The main advantages of the AirCorr monitoring system are:

(1) quick response time and a highly sensitive measurement achieved due to the great precision of the electronic device and the geometry of the metal track;
(2) availability of a wide range of sensors, including ultra-sensitive ones for low-corrosive environments;
(3) small size;
(4) easy replacement of sensors reducing the operational costs;
(5) non-contact data reading;
(6) long autonomy of up to five years; and

(7) user-friendly software allowing for rapid interpretation of results using available standards and recommendations.

Extensive testing in cultural heritage and industrial environments in collaboration with major European and overseas cultural heritage institutions has proven that the product is ready for market.

Besides the cultural heritage sphere, AirCorr loggers can be used for air quality monitoring in clean rooms with electronic equipment, in the transport industry, for air pollution monitoring and in research and development. AirCorr loggers are commercially available through ICO from September 2012 and through specialized distributors in the near future.

Project Context and Objectives:

A great number of both movable and stationary cultural assets are managed by cultural heritage authorities in European and other countries. Their protection against damage and degradation is achieved by many different means depending on the type of asset, customary practice of particular country and institution, available budget, education of responsible personnel and other factors. Although the deterioration of objects due to the presence of indoor pollutants is often slow, its cumulative effect is largely surpassing much more spectacular damages caused by fires, theft, earthquakes, flooding etc. combined.

It is generally accepted that the control of air quality is vital for protection of culturally significant objects stored or displayed in indoor premises. The main factors affecting air corrosivity are temperature, relative humidity, concentration of pollutants such as sulphur dioxide, nitrogen oxides, ozone, ammonia, hydrochloric acid, sulphate, dispersed chlorides, organic acids, other volatile compounds and dust particles. However, it is only the relative humidity and temperature that are usually controlled and monitored. Additional anti-corrosion measures are usually applied when valuable and often-irreplaceable historical objects have already been affected. Since control of the air without the application of any monitoring technique giving rapid feedback on the air quality might be either inadequate or excessive and thus too costly, information on the actual corrosivity of the atmosphere is crucial to effective corrosion protection.

Direct impact of atmospheres on objects is traditionally followed by exposing coupons of given materials to the environment and consequent analysis of their degradation after given period of time. For non-metallic materials, the coupon technique is rarely used, but projects on development of specific coupons or dosimeters are in progress [1]. In contrary, it is well established for metallic materials. According to current standards, a metal coupon needs to be exposed for 30 days or for 1 year in given environment. The impact of the environment on metal degradation is evaluated in a specialized laboratory based on mass loss, mass gain or coulometric reduction of corrosion products. The mass loss procedure is used for an assessment of outdoor corrosivity whereas the mass gain is measured usually on coupons exposed indoors. The coulometric reduction of corrosion products is more demanding with respect to equipment and experience, but can provide an indication of the nature of the pollution in addition to the rate of metal degradation.

However, none of the coupon techniques can be considered as real-time. Within the exposure period, valuable objects might further deteriorate if the air is contaminated. Whereas there is a relatively wide range of products for corrosion monitoring in aqueous media, the availability of means for real-time corrosion monitoring in the atmosphere is limited. Thus, there is a strong need for a tool enabling cultural heritage professionals to assess the air corrosivity in real time. Because open-air museums, artefacts of industrial activities, and even entire factories are presently recognized as important parts of cultural heritage, the need for atmospheric corrosion monitoring is not limited to indoor conditions with air quality control but must also be available for outdoor environments.

Three MUSECORR beneficiaries were involved in the project Automated corrosion sensors as on-line real time process control tools, CORRLOG, which was financed within the 6th Framework Programme [2]. Among other achievements, prototypes of loggers for continuous measurement of the corrosion rate of selected technical metals in atmospheric conditions were developed within the project. The system works on well-established and reliable electrical resistance principles. The electronic unit measures and registers the changes in the electrical resistance over time of a thin metal track applied on an insulating substrate. If the metal corrodes, the cross-sectional area of the track decreases and electrical resistance increases.

Compared to other available methods for corrosion monitoring in air, the developed concept offers several important advantages. However, although all of the objectives of the CORRLOG project were fulfilled and corrosion tests have shown that the logger concept is correct and its application might make the protection of objects of cultural heritage easier, cheaper, and more efficient, end-user testing at the end of the project showed that there were still problems to be solved before full commercialization of the product is possible in the cultural heritage sphere. The principal aim of MUSECORR was thus to finalize the process of technical development of the corrosion logger prototype and to turn it into a marketable product [3]. The main innovative objectives were as follows:

1. To develop new sensors better covering the needs of corrosion monitoring for cultural heritage, such as lead, silver, and, possibly, metal alloys more closely simulating historical materials displayed in museums.
2. Some of currently available sensors will be innovated to provide higher sensitivity below 1 nm by decreasing the metal layer thickness to 50–500 nm. Thus, highly sensitive means for corrosion monitoring in cultural heritage will be available for steel, copper, lead, silver, zinc, and eventually other metals and alloys of interest. Sensors for outdoor environments will be also developed.
3. To improve the electronic part of the logger in terms of new measurement ranges for the thinner and more sensitive sensors, a universal communication interface, and better water-tightness.
4. To adapt the electronic logger and software for single measurements on sensors exposed separately. This will make the monitoring system more economically attractive.
5. To develop completely new software providing user-friendly data handling and device operation.
6. To make the data interpretation simple by referring to available standards or recommendations.

In addition, major efforts were planned to raise awareness of the new technology through presentations to cultural heritage professionals, training of staff in cultural institutions, and promotion of the product. A standard on the monitoring of indoor air corrosivity using the electrical resistance technique would be proposed through European interest groups by C2RMF. The main goal was to finalize the product into a marketable form and ensure rapid and smooth implementation.

Project Results:

Principle

The electrical resistance (ER) technique was selected to measure the corrosion rate in real-time. The technique is described in, e.g., ASTM standard G96 [4]. The principle of the method is that the electrical resistance of a measuring element made of the material of interest increases as its effective cross-sectional area decreases due to corrosion. In practice, two such elements are built into a probe. One element is exposed to the corrosive environment and corrodes, whereas the other element is shielded and, thus, protected from corrosion. The resistances of both elements are measured at the same time and resistivity changes due to varying temperature are compensated for. Based on the initial cross-sectional area of the exposed element, the cumulative metal loss at the time of reading can be determined. The benefits of the ER technique include its versatile nature as it can be used in practically any kind of environment, robustness and ability to provide continuous measurements [5,6].

Survey on requirements for corrosion monitoring and logger concept

In first months of the project, a survey was conducted to learn about the current situation in cultural heritage institutions and the needs of professionals. Professionals in cultural heritage were interviewed in order to establish their requirements for corrosion monitoring with respect to length of monitoring, sensitivity, data presentation, evaluation of results, etc. A survey consisting of 22 questions was developed. The responses on 80 surveys were tallied and principal findings important in view of the marketing plan are listed below.

- Most of the institutions monitor and/or control temperature and relative humidity. However, the majority of respondents currently employ no corrosion-monitoring method with the exception of visual observation.
- Most of the respondents were not satisfied with their monitoring methods, although nearly all felt that monitoring was important or extremely important. Most of the respondents were concerned with the air quality inside.
- Most of the respondents would use monitoring in the interest of protecting objects. The following three choices were also chosen by about a quarter of respondents as goals of corrosion monitoring: determining corrosion rate and general corrosivity, and problem solving.
- The respondents were about equally split on whether they would like to monitor corrosivity regularly or occasionally. About half of the respondents would like to have results in weeks. Sixty-three of the respondents indicated that they would like to monitor for at least a year.
- The respondents were equally split between wanting a sensitive instrument and wanting a long service life.
- Most respondents were interested in exportable results that also yield a corrosion class or a corrosion rate.
- Over half of the respondents were also interested in ease of operation, cost and user friendliness.
- About half of the respondents would like to measure corrosivity towards two selected metals, temperature and RH.

- Thirty-two respondents would like a low-price device, while 47 indicated that they would select a more costly device.
- Remote access was desired only if inexpensive.
- The majority of respondents indicated that they would prefer to do the monitoring themselves.

In summary, respondents clearly indicated that a logger should measure for at least one year and should give results in terms of corrosivity classes and/or corrosion rate. In addition, the data should be exportable. Ease of operation and easily-understandable data were highly valued. Most respondents would like to test air corrosivity towards two metals simultaneously. Temperature and relative humidity sensors might also be desirable.

It was possible to identify two groups of end-users, one preferring cheaper loggers with no extra functions and the other one preferring more complex loggers with temperature and RH sensors and two metal sensors in parallel. In contrary to the initial anticipation, the respondents were little interested in remote data access. Thus, it was finally decided to develop the three variants of AirCorr loggers described below.

Concept of the corrosion monitoring system and corrosion sensors

The monitoring system is comprised of four principal parts: an electronic logger for measuring and recording ER, a metal sensor that actually corrodes in the environment, a communication interface between the logger and computer and a software program for interpretation of the measurement.

The concept of the measuring device is simple and yet highly effective: the electronic unit measures and registers the change over time of the electrical resistance of a thin metal track applied on an insulating substrate. The width of the measuring track is from 1 to 2 mm, depending on sensor type, and the length is over 100 mm. This geometry ensures high sensitivity to changes in the electrical resistance due to metal corrosion.

In contrast to traditional designs [7], the sensing and reference parts of AirCorr sensors are connected by an H-shaped bridge. The edge of the protective coating passes approximately through the middle of the bridge. Thus, the edge of the protective coating is neither part of the sensing nor of the reference track and the bridge serves only as a conductor for passage of the testing current. The measuring part of the track is placed a safe distance from the coating edge. This design solves a common problem of ER probes, which is corrosion of the metallic track at the interface between the sensing and reference parts underneath the protective coating, which can lead to erroneous readings [8]. A patent application has been filed to protect this unique solution.

The sensitivity and service life of the sensors depend on the thickness of the metallic track: the lower the thickness, the higher the sensitivity. On the other hand, low thickness leads to a shorter service life. The service life can be assessed as the time to consume one half of the track thickness. Therefore, sensors with different track thicknesses are available for applications in different environments.

Assuming that the electrical conductivity of the track is proportional to the remaining metal track thickness and assuming that corrosion products do not contribute to the conductivity, the corrosion depth of the metallic sensor, h, can be calculated and the calculation is based on the electrical resistances measured as a potential difference along the track through which defined currents pass. The equation has been improved compared to the earlier one in order to be valid throughout the whole service life of the sensor [5].

For indoor use, the protection of the reference track against corrosion is provided by an organic adhesive tape coated with an inorganic diffusion barrier layer. The coating is transparent to avoid differential heating of the tracks.

Corrosion loggers

The changes in electrical resistance are recorded by precise electronic loggers. Three versions of AirCorr loggers were developed for specific applications. The basic versions of the electronic logger, AirCorr I and O, are encased within a small watertight, polycarbonate box measuring 100×65×37 mm with a tightness of IP 65. For the indoor version, AirCorr I, the logger lid is provided with a connector so the sensor can be easily replaced when necessary. AirCorr O, for outdoor applications in highly corrosive environments, has an attached sensor protected with a robust polyurethane casting. The lid can be replaced when the sensor is at the end of its useful life. The devices are equipped with an LED that signals when the unit is on. AirCorr I Plus is also designed for indoor use and can measure the air corrosivity on two sensors of identical or different metals. In addition, temperature and relative humidity are registered. Current corrosivity and climatic parameters can be read on a built-in LCD display. The cadence of the measurement can be adjusted from minutes, to hours, to even days, if necessary, in order to match the sensitivity of the measurement with the anticipated corrosion rate.

Collected and stored data can be downloaded by a non-contact inductive data reader, even through showcase glass. A GPRS/GSM access unit is optional and allows remote data access and control with automatic data delivery via e-mail. The loggers are designed to be autonomous for five years. The battery itself is also replaceable. The loggers are fully independent of any power supply, any external control, and can, therefore, be placed anywhere.

WinAirCorr and data interpretation

Dedicated software, WinAirCorr, which works under the latest Windows operating systems (W7, Vista), was developed for use with the loggers. It was conceived with a view toward user friendliness and easy data interpretation. The software has several levels of user control. Three levels are designed for skilled technical users and allow for full control. A wizard mode is designed for non-technical users with a limited background in corrosion. Several wizards, virtual guides, were created to help end-users to carry out basic operations rapidly and without the need for specific knowledge. The wizards lead users through a series of simple steps to start a measurement, finish it, read and evaluate data and set up the apparatus.

Particular attention is paid to data evaluation. In addition to corrosion depth and corrosion rate, the obtained data are used to display air corrosivity classifications according to all relevant standards. Explanations are provided about the meaning and limitations of the classification in the Help section.

Three standards and a recommendation are available for air corrosivity classifications with regard to copper, silver, carbon steel, aluminium and zinc. Although the classifications are principally relevant for objects made of the corresponding metal, they are often used for general air corrosivity assessments. For example, the corrosivity classifications for silver and copper in indoor environments are widely used as general measures of the air quality.

In ISO 11844-1 [9] used to classify indoor environments, metal coupons of silver, copper, carbon steel and zinc are exposed for a period of a year. The mass lost during exposure is calculated as a difference between the initial coupon mass and the mass after removal of corrosion products. Table 2 shows corrosivity classes from IC 1 – Very low to IC 5 – Very high with corresponding mean corrosion depth in nm/year. The limits were calculated from the original standard using the densities of the pure metals. Similarly, outdoor air corrosivity is classified according to ISO 9223 [10].

Corrosivity classification according to ISA 71.04-1985 [11] and Sacchi & Muller [12] is based on the thickness of the layer of corrosion products formed within 30 days of exposure, corrosion build-up. It is calculated from the electric charge needed for electrochemical reduction of the corrosion products. Two systematic errors are introduced in the calculation:

(1) The apparent instead of real surface area is used;
(2) The density of the corrosion products is not known but only estimated.

To recalculate the thickness of corroded metal, the corrosion depth, to the thickness of a layer of corrosion products, three pieces of information are needed:

(1) density of the metal,
(2) density of the corrosion products,
(3) ratio between the mass of formed corrosion products and the mass of corroded metal.

The two latter values are not known and must be estimated. The density of the corrosion products is assumed to be about 6.0 and 7.3 for cuprous oxide, Cu2O, and silver sulphide, Ag2S, respectively [13]. These compounds are dominant on copper and silver objects exposed to indoor atmospheres [12] and they are assumed to represent the densities of entire layers of corrosion products. The ratio between the mass of formed corrosion products and the mass of corroded metal was obtained from ISO 11844-1 [9]. It is 1.5 and 1.15 for copper and silver, respectively.

Limitations of the corrosivity classification.

Corrosion depth measured by AirCorr loggers and given in nm or µm corresponds to the maximal reduction in the metal track cross-section. It thus tends to be somewhat higher than mean corrosion depth estimated from e.g. mass loss. The standards usually prescribe the minimum size of the coupons to be exposed. These are generally larger than the area of the measuring track of AirCorr sensors.

The standards define the exposure period to 30 days or 1 year. If the exposure period is shorter or longer than specified in a standard, the resulting air corrosivity classification is only indicative. This is due to the fact that corrosion processes for most metals in most environments are non-linear and any inter/extrapolation can be misleading.

Several simplifying assumptions are applied for the estimation of the corrosivity classification according to ISA 71.04-1985 and Sacchi & Muller. These must be considered indicative.

Laboratory testing – Sensitivity of measurement

The sensitivity of the thin film sensors developed for lightly-polluted indoor locations was tested in air during a cycle comprising changes in relative humidity from 30 to 85% and changes in temperature from 20 to 30 °C. An example of such a measurement is given for a copper sensor with the metal track thickness of 500 nm in Figure 8. The sensor was initially exposed to air at ambient temperature and a low relative humidity of about 33%. It was then transferred to a climatic chamber with controlled temperature and relative humidity of 20 °C and 85 %. Finally, the temperature was increased to 30 °C. As seen in Figure 8a, the changes in the air corrosivity were observable within several minutes. Figure 8b shows extrapolated curves indicating that the corrosion rate of copper increased from 0.3 nm/month (3 nm/year) in dry air to 2 nm/month (24 nm/year) in humid air at 20 °C and further to 7 nm/month (85 nm/year) at the elevated temperature of 30 °C. The rates correspond to corrosivity classifications of IC 1 – Very low, IC 2 – Low and IC 3 – Medium, respectively, according to ISO 11844-1 [9]. The standard requires 1-year exposure in a given environment to establish the classification and the obtained data are thus only indicative. Anyway, the experiment demonstrates the extreme sensitivity of the technique and the ability to assess the air corrosivity within only several hours.

The corrosion depth h can be recalculated to corrosion build-up b (thickness of the layer of corrosion products). The meanings of the symbols are explained above. The corrosivity can be classified based on the corrosion build-up under all conditions as G1-level – Mild using ANSI/ISA-71.04-1985 [11]. According to the corrosivity classification of indoor atmospheres developed by Sacchi and Muller in particular for museums and archives, the two former environments can be classified as S1, Extremely pure and the last one as S2, Pure [12].

A logger with Ag-50nm sensor was exposed to a climatic chamber with air maintained at constant temperature of 25 °C and cycling relative humidity. It started at 80% RH, then dropped to 40% and increased again to 60% and 80% RH. Two such cycles were carried out each day. At 40% RH, the corrosion rate was negligible. Corrosion rates of about 50 and 130 nm/year were recorded at 60% and 80% RH, which corresponds to IC 2 – Low and IC 3 – Medium classifications by ISO 11844-1 [9]. The Sacchi and Muller classification system marks the respective environments as

S2, Pure and S3, Clean [12]. The recording shows good reproducibility of the sensor response even after multiple cycles.

Similar measurements were performed with all sensors. It was found that at constant temperature, the precision of the resistance measurement reaches a resolution of at least 1/2000 of the initial resistance. When temperature variation is taken into account, the resolution drops to 1/1000.

The sensitivity of the measuring device with regard to corrosion may be defined as the minimum mass of corroded metal required for a reliable response of the ER measurement. For a metal film with constant thickness, the extent of corrosion can be represented as a corrosion depth assuming a homogeneous decrease of metal thickness. Such calculated corrosion depth is a mean value based on simplified model assumptions. Seemingly very small changes in corrosion depth values at sub-Ångström (<10–10 m) level can be calculated, but these do not have a direct physical meaning. Such changes can instead be associated with oxidation of a portion of an atomic layer. Localised corrosion, e.g. at grain boundaries, would obviously strongly influence the ER of a thin metallic track. Nevertheless, the simple model has proven to be successful.

Depending on the particular sensor, the corrosion sensitivity of the measuring device varies from below 0.1 nm (<10–10 m, <1 Å) for sensors developed for low-corrosive indoor environments to 200 nm for the robust 250 µm steel sensor designed for highly corrosive outdoor applications. The sub-Ångström sensitivity of the thin-film sensors is very apparent in recordings.

Laboratory testing – Reproducibility and accuracy of measurement

A series of experiments were performed in air with controlled temperature, relative humidity and concentrations of carboxylic acids, common pollutants in indoor cultural heritage premises. Formic acid and acetic acid were released to feed air at concentrations from several tens to close to 3000 ppb. The experiments are reported in detail elsewhere [8, 14, 15, 16]. In each experiment, three parallel loggers with identical sensors were exposed to assess the measurement reproducibility. The measured corrosion depths with standard deviations are shown in Figure 10. With exception of the Fe-800nm sensors in air with formic acid, the reproducibility was better than ±20%. The large scatter for parallel Fe-800nm sensors was due to non-uniform corrosion.

Because of the high sensitivity of the setup, it was not possible to compare the results to those obtained using traditional techniques after measurements in low-corrosive atmospheres. To get an idea of the accuracy of the technique, thick-film sensors for outdoor applications were tested in the ECC1 test according to Renault standard D17 2028/2002. The test is a cyclic wet/dry test performed at a constant temperature of 35 °C and comprises spraying the samples with a solution of 1 wt. % NaCl at pH 4 for 30 minutes each day. Cu-9µm, Zn-50µm, Fe-50µm and Fe-250µm sensors were exposed to the test together with corresponding 150×100-mm metal coupons of pure Cu, Zn and carbon steel. At the end of the exposure, the weight loss of the coupons was evaluated following ISO 8407. The weight loss results were re-calculated to corrosion depths assuming that the corrosion was uniform. As seen in Figure 11, good correlation between the corrosion depths measured by the AirCorr sensors and metal coupons was obtained for zinc and steel. The corrosion depth was 7% and 30–42% higher for the sensors than for the coupons for zinc and steel, respectively. The Cu-9µm copper sensors gave significantly higher corrosion depths than the coupons. Therefore, an improved sensor at higher thickness, Cu-12µm, was developed as a replacement. It showed good accuracy in further experiments, see references [14, 15].

The thick-film sensors for outdoor use (copper, iron, zinc, aluminium and brass) were also tested in air polluted with SO2. The electric resistances of the reference and sensing tracks and the corresponding corrosion depths were measured continuously using a Metricorr logger or using intermittent measurements with AirCorr loggers. In all conditions, five coupons of the corresponding metals were exposed in parallel.

The course of test consisted of three steps:

(1) Both reference and coupon parts of the sensor were protected with a masking tape. Thus, there was no corrosion within this step. Temperature was set to 40 °C and the surrounding relative humidity was 100%.
(2) Temperature and relative humidity remained unchanged but the coupon part was exposed and corrosion coupons introduced into the chamber.
(3) Temperature and relative humidity remained unchanged and 500 ml of sulphur dioxide was introduced into the chamber.

The amount of corroded metal was measured by coulometric titration or by pickling in appropriate solutions and recalculated to corrosion depth assuming uniform corrosion attack. In most cases, the corrosion depths measured by the sensors and metal coupons were comparable.

The data usually show somewhat higher corrosion depths for the AirCorr sensors than for the metal coupons. This is not surprising since the ER technique by its nature yields the maximal depth of attack, while the coupon technique provides an average corrosion depth. In addition, the edge effect is practically negligible in case of metal plates whereas it affects the reading for the sensors. In principle, the applicability of the electrical resistance technique is limited to conditions where the corrosion of a given material proceeds mostly uniformly.

Testing in real environments

In 2011 and 2012, large internal and end-user testing programmes were conducted in order to assess the performance of the AirCorr monitoring system in real environments and to obtain feedback for the last stage of development. Over 25 loggers with multiple sensors were distributed to conservators and other cultural heritage professionals around the world. The following partners participated in the testing programme:

- Swiss National Museum (Schweizerisches Nationalmuseum);
- Centre for Research and Restoration of the Museums of France (Centre de Recherche et de Restauration des Musées de France);

- National Museum of Denmark (Nationalmuseet);
- English Heritage, UK;
- Swiss National Library (Schweizerische Nationalbiblithek NB);
- Museum of Art History (Kunsthistorisches Museum), Austria;
- Australian War Memorial;
- St. Fagans: National History Museum, Wales, UK;
- The Royal Library (Det Kongelige Biblioteket), Denmark;
- Czech National Archive (Národní archiv), Czech Republic and The Mariners' Museum, USA.

The loggers were used to assess old and new storage facilities, to study the effects of supposedly corrosive factors on air corrosivity, in comparative studies of showcases, for ranking of locations and institutions, for problem solving and in fundamental studies on optimal conservation techniques. Several examples of the applications are given below.

Loan of tapestry.

A unique historical tapestry with copper threads from collection of the Louvre Museum was loaned to two galleries in Japan. A logger equipped with a Cu-500nm sensor accompanied it on its journey to monitor the air quality surrounding the tapestry. The recording plotted in Figure 14 reveals that although the relative humidity and temperature were kept close to target levels, the air corrosivity varied with time. Packing, transport to Japan in a crate, exhibition in Gallery 1 and transport to Gallery 2 were associated with only minor corrosion with the cumulative corrosion depth in 3 months reaching 1.8 nm. However, upon opening the transport box and exhibiting the tapestry in Gallery 2, the corrosivity increased significantly. During the 3-month exhibition in Gallery 2, 8.5 nm of copper corroded and the corrosion rate in the first month was 7.6 nm/30 days. Although this still corresponds to IC 2 – Low corrosivity class according to ISO 11844-1 [9], the air quality control was not ideal in Gallery 2. The record shows that aside from higher fluctuations in the relative humidity, a small amount of some pollutant had to be present in the air to accelerate the corrosion rate of copper. In particular, the increase in the corrosion depth starting on 30/06 indicates deterioration of the air quality.

Such information is indeed very valuable for future decisions on loans and the conservation measures required from partner institutions.

Assessment of a new archive building

The corrosion aggressiveness of the atmosphere within a multi-story building made of reinforced concrete which was to be used as an archive for paper documents was determined using silver and copper sensors. The building's concrete was poured during winter. The upper floors were completed at below-freezing temperatures, so an antifreeze agent containing urea was added to the concrete. Urea decomposes slowly in concrete releasing ammonia to the surrounding environment. Indeed, the air in the top floors has a typical ammonia odour. It is believed that ammonia in the air is not harmful to the documents but might be dangerous for the metallic parts of stored objects made of copper or brass. A stable temperature of 15 °C and relative humidity of 52 % is maintained in the archive.

An AirCorr I Plus logger equipped with two highly sensitive sensors, silver 50nm and copper 50nm, was installed in the archive. Initially, the logger was placed on a floor built from urea-free concrete with no ammonia odour. Then, it was moved to a floor with a strong ammonia odour. The aim was to test the effect of ammonia-type air pollutants on the air corrosivity. During the exposure in the odour-free area, the measured corrosion depth of 2.1 nm corresponds to the corrosion rate of 27 nm/year for the silver sensor. The testing period was not long enough to classify the corrosivity according to the ISO 11844-1 standard but extrapolation of the data yields the IC 2 – Low corrosivity class. The corrosion rate identified at the same location for copper was 5 nm/year (h of 0.4 nm) corresponding to the IC 1 – Very low classification. After moving the logger onto the floor with the ammonia odour, the corrosion rate of silver dropped to 16 nm/year and remained constant during whole exposure period. In the case of copper, the corrosion rate was 2 nm/year and it slowly decreased.

Surprisingly, the corrosivity on the floor with the ammonia odour was lower than in non-polluted areas. The surface of copper was analysed by XPS after the exposure. The film of corrosion products contained a significant amount (app. 50 %) of copper (II) and nitrogen bound up in an organic compound. Since urea is known for its corrosion inhibition toward copper, adsorption of urea from the atmosphere onto the metallic surface might be the reason for the reduction in the corrosion rates of copper and silver during exposure on the upper floor. The study showed that the locations made with the urea-modified concrete were safe for documents with copper and bronze parts, at least in the short term. The effect of this specific environment on other types of stored materials and its long-term effect on copper and copper-alloy materials is under study.

A quartz crystal microbalance logger was exposed alongside the AirCorr I Plus logger. It recorded a mass gain of the copper- and silver-coated crystals. The corrosion build-up after 38 days was 1.6 nm and 0.9 nm for the silver and copper sensors, respectively [17]. When the AirCorr data on corrosion depth are recalculated to corrosion build-up, the results are 3.5 and 0.8 nm, respectively. Although the build-up on silver differs by a factor of 2, identical corrosivity classification was provided and the measurements are in a reasonably good agreement.

Regular air quality monitoring of indoor premises.

The Danish Royal Library considered AirCorr loggers as a possible replacement for passive sampling, which is carried out regularly at different locations within the institution. The high cost and delay of at least 2 months between the samplers' deployment and return of the results are considered drawbacks of the passive sampling method.

Silver and copper sensors at low thicknesses, Ag-50nm and Cu-100nm, were used in an AirCorr I Plus logger. The monitoring was carried out at three locations over a total of 5 months. It started in a small room containing manuscripts with low air exchange, Location 1. Passive sampling revealed elevated concentrations of acetic and formic acids. The logger was then moved to storage with air filtration and climate control, Location 2. Acetic acid was not detected and the concentration of formic acid was very low in the second location. Finally, the monitoring was carried out in a visitor centre with low levels of organic acids but non-negligible outdoor pollution in form of SO2, NO2 and O3, Location 3. Cumulative data for the silver sensor along with the results of the accompanying passive samplers and the relative humidity record are shown in Figure 16. The corrosion depth of silver measured in the first 30 days at each of the locations reached 2.0, 0.2 and 4.8 nm, respectively. The air quality classifications according to the ISO 11844-1 standard were IC 2 – Low, IC 1 – Very low and IC 2 – Low [9]. Following the Sacchi and Muller recommendation, S1, Extremely pure class would apply to the first two premises and S2, Pure to the last one [12].

Location 2 with tight air quality control was one order of magnitude less corrosive than Location 1 with elevated levels of organic acids. The highest corrosivity was found in the visitor centre (Location 3), which was open to outdoor air containing typical urban pollutants, including sulphur dioxide, nitrogen dioxide and ozone. Although silver is not particularly sensitive to these compounds, the last two have some effect on its corrosion stability. The corrosion rate of copper was negligible in all three locations and was to be 0.3, 0.1 and 0.1 nm/year, respectively.

Study on optimal cleaning procedure of brass inlays. Optimal cleaning procedure of engraved brass inlays in valuable wooden cabinet attributed to André-Charles Boulle selected for an important exhibition was sought by restorers of the Louvre museum. The engravings in alpha-phase brass containing 35 wt.% zinc were partly damaged by previous successive cleaning. About 0.5±0.1 mm of the initial inlays' thickness was already destroyed and the restorers had to be sure that any technique used for the cleaning would be as little harmful as possible. Because brass sensors are available only at the thickness of 10 nm and thus somewhat less sensitive, it was decided to use bronze CuSn8-400nm sensor for initial measurements. Four cleaning procedures were applied and changes in corrosion depth of the sensor monitored in parallel. In addition, roughness measurements and microscopy evaluation were carried out to assess the outcome of each cleaning technique.

Good results causing limited material degradation gave the application of an animal glue with triammonium citrate (TAC) used to restore the marquetry and noticed to give a nice aspect to the surface, ivory black (a very gentle abrasive) and micromesh 12000, which is corundum-based abrasive. The corrosion depth caused by these cleaning procedures was in a range from 9 to 17 nm. On the other hand, the procedure using triethanol amine (TEA) and Pemulen gel led to material removal corresponding to 181 nm and thus cannot be considered as a gentle technique. The Roubo lacquer is a Sandarac-based resin dissolved in alcohol, named after a French cabinet maker who wrote "The Art of the carpenter" in 1769.

Obviously, the composition of the applied sensor was different to brass of the inlays. The test will be repeated with CuZn37-10nm sensors. Although the composition and microstructure is not (and cannot) be identical to that of the historical material and the material loss due to cleaning would probably somewhat differ, it is believed that the obtained data allow for relative comparison of the cleaning procedures.

Systematic classification of air quality using copper sensors. Corrosion monitoring by two types of ER loggers including AirCorr was used to assess air quality in numerous dominantly indoor cultural heritage premises with the aim to respond to questions frequently asked by conservators and curators on the appropriateness of the conservation conditions in given museum, showcase or storage. Changes in corrosion depth of Cu-500nm copper sensors were followed during a year in intermittent measurements or by continuous monitoring. Results of studies performed in twenty museums, libraries and archives situated on the French territory are presented in a paper [18]. Most premises were heated (twenty-six showcases, eleven exhibition rooms, fifteen storages, six crates), in sixteen environments the climate was not controlled, including two outdoor exposures.

The obtained data on corrosion depth of copper sensors were interpreted using the ISO 11844-1 standard [9]. Sixty per cent of the environments were very low corrosive (IC 1) and five per cent were highly corrosive (IC 5). The corrosivity was found low for two-third of the heated rooms and high for three per cent. In half of the permanent premises, the corrosivity was found to be very low (IC 1); it was low (IC 2) or medium (IC 3) for the rest.

The ER technique showed to be a very efficient tool to assess the conditions of conservation in archives, libraries and museums. It allowed for comparison of the conditions of conservation in particular premises and for assessment of applied countermeasures. A drawback of the currently available standard is the necessity to expose a probe for a year in a given environment. Due to high sensitivity of the ER measurement, reproducible results can be obtained in a shorter period. The ISO 11844-1 classification was thus compared to the Sacchi & Muller guideline based on 30-day exposures [12]. In most cases, a good correlation to the ISO 11844-1 was obtained.

Classification of air quality with lead sensors

The air quality in low-corrosive environments can be qualified by the reactivity of copper [11], copper and silver [12] or copper, silver, carbon steel and zinc [9]. Parallel exposures of more than one metal are carried out because of different sensitivity of metals to presence of specific pollutants. For example, carbon steel is particularly sensitive to chloride, silver to hydrogen sulphide and copper to sulphur dioxide [19]. However, none of these metals is very sensitive to carboxylic acids that are repeatedly reported as important pollutants in enclosed locations in indoor cultural heritage premises such showcases and cabinets. Concentrations of formic and acetic acids released from hemicellulose-containing wrapping papers and cardboards, exhibited or stored objects made of wood, paper and some plastics and conservation and preparation materials can reach from negligible to hundreds or even thousands of ppb [20–27]. The acids are harmful for metals, calcareous materials and eventually also for paper and some plastics. Particularly sensitive to the presence of vapours of carboxylic acids is lead.

Because of accelerated corrosion in air polluted with formic and acetic acid and non-negligible amount of lead objects in museums, it is of interest to use lead as an additional sensing material. Unfortunately, no current standard includes lead. Little is also known about the kinetics of lead corrosion in such environments due to low sensitivity of currently available techniques. Lead Pb-400nm and Pb-25?m sensors developed for AirCorr loggers provide unique opportunity to get valuable knowledge on lead corrosion and establish an air corrosivity classification system for this metal. The lead sensors were exposed at 15 locations within the end-user testing programme for 30 days or longer. Some of the locations were reportedly corrosive for lead objects and others were supposed to be benign. Corrosion depth registered within first 30 days of exposure varied in a very wide range from 0.1 to 107 nm. Examples of two consecutive measurements in the Australian War Memorial in a showcase where lead members of a ship model corroded are given in Figure 18. Corrosion rates of 90 and 104 nm/30 days were recorded. Although the work is still in beginning and much more corrosion and supporting data need to be obtained to establish a classification system for lead, a preliminary proposal dividing atmospheres into four classes based on the corrosion depth of lead in 30 days of exposure is outlined in Table 6. It is possible that one more class will be needed to cover extremely polluted and corrosive environments.

It is interesting to note that any classification based on exposure of copper and silver is irrelevant for lead objects. Several of the conducted experiments with lead were accompanied by parallel exposures of silver and/or copper sensors. Even in conditions where the corrosion rate of lead reached over 10 nm/30 days, i.e. Class L 3 according to the proposal in Table 6, IC 1 – Very low or IC 2 – Low classes were obtained for silver and copper.

High-corrosive environment in a paper mill

Besides the cultural heritage sphere, the monitoring technique was tested in selected highly demanding environments in order to prove its robustness. The principal corrosive factors are high concentration of 100–130 ppb of H2S, high humidity and deposition of chemically active aerosol. In first seven days of exposure, 340 and 143 nm of Cu-500nm and Ag-500nm sensors corroded, corresponding after linear extrapolation to corrosion rate of 19 and 8 nm/year and corrosion build-up of 3400 and 1100 nm/30 days, respectively. Such corrosivity is out of scale of the ISO 11844-1 standard and in the most corrosive class according to other standards and recommendations.

The actual corrosion rate responded to changes in the relative humidity (RH). When it crossed 80 %, the corrosion rate increased significantly. The corrosion rate was the lowest in a period with the RH at about 50–60 % (0.3 nm/hour). It increased above 1.5 nm/hour when the RH was over 80 %. It reached the maximum at 3.7 nm/hour when RH got over 90 %.

Potential Impact:

Main AirCorr advantages

AirCorr corrosion loggers developed within the MUSECORR project serve for real-time monitoring of air corrosivity towards a number of metals and alloys. The main advantages of the AirCorr monitoring system can be listed as follows:

- Due to the great precision of the electronic device and the geometry of the metal track, both a quick response time and a highly sensitive measurement are achieved.
- A wide range of sensors, including ultra-sensitive ones for low-corrosivity environments.
- The logger is small and can be placed virtually anywhere.
- The metal sensors are easily replaceable, which reduces the operational costs.
- Non-contact data reading allows the logger to remain in place during data reading.
- The unit is designed to be autonomous for five years.
- User-friendly software provides rapid interpretation of results with the help of existing and proposed standards and recommendations.

Application areas

Principal application areas of the AirCorr technology are cultural heritage, clean rooms for protection of electronics, transport and storage, civil engineering, pollution detection and corrosion research.

Cultural heritage

By the cultural heritage sphere, museums, archives, permanent and temporarily exhibitions, libraries and other associated premises are considered. A great number of both movable and stationary cultural assets are managed by cultural heritage authorities in European and in other countries. Their protection against damage and degradation is achieved by many different means depending on the type of asset, customary practice of particular country, region, and institution, available budget, education of responsible personnel and other factors. It is generally accepted that the control of air quality is vital for protection of valuable and culturally significant objects stored or displayed in indoor premises. However, it is only the relative humidity and temperature that are usually controlled and monitored. Additional anti-corrosion measures are usually applied when valuable and often irreplaceable historical objects have already been affected. The most common monitoring method is the exposure of passive samplers or metal coupons for a certain period of time. Within this period, valuable objects might further deteriorate. Thus, there is a strong need for a tool enabling real-time assessment of the air corrosivity from professionals active in the protection of cultural heritage.

Dominant need for corrosion monitoring in the cultural heritage is for indoor use in locations with controlled air quality at low corrosivity. Thus, mainly highly sensitive variants of AirCorr designed for low corrosive environments are considered for the application in cultural heritage. AirCorr O loggers and corresponding sensors have only minor application in this market segment.

Clean rooms for protection of electronics

Printed circuit boards used vastly in electronics and computing contain large amounts of copper. Although it is protected by lacquers and generally well corrosion resistant, it corrodes in more aggressive environments leading to costly failures. Thus, the air quality in large computer centres and computer rooms situated in aggressive environments such in ships, factories, etc. is often controlled. The air is dehumidified and special active filters are applied to absorb pollutants. Since the filtering is expensive and it is optimal to change the filters only when fully exhausted, it is already an established practice in this industry to monitor the air corrosivity. In particular, it is done regularly in pulp and paper industry where the air corrosivity is extreme and all process electronics is located in pressurized tight rooms with air quality control.

AirCorr I and AirCorr I Plus loggers can be considered for this market. In extreme conditions, also AirCorr O might be applied. However, the sensor exchangeability is crucial for this market. It may also be required to integrate the loggers into a centralized information system.

Transport and storage

Vast majority of today transport vehicles are made of metals. They are prone to corrosion deterioration, which not only decrease their aesthetic properties but threaten the safety of their operation. Thus, it is of interest to follow material degradation during vehicle lifetime.

The current AirCorr loggers are not adapted for serial use in personal cars or trucks. Their actual use can be seen in development of anticorrosion measures. They were already tested by several car makers and others plan to acquire them. AirCorr O is a typical product required by the automotive industry for its robustness, independence and small size. There is no competing product on the market.

Corrosivity at seas is high and different ship parts and equipment suffer from accelerated corrosion. Down time costs are huge as well as reparations. Thus, there is indeed an opening for real-time corrosion monitoring in this sector. AirCorr O loggers were already applied on navy ships, a container ship and passenger ships. They proved to be water tight and survive even the most aggressive exposure conditions providing valuable data for ship owners. Military bodies and navy services are seen as particularly large potential customers. If AirCorr O loggers are employed for regular monitoring at navy ships, there will be market for hundreds to thousands of units a year. Again, there is currently no competing technology available. AirCorr O is a unique tool. Because the technology is new to the sector, further dissemination activities will be necessary.

AirCorr loggers may also be applied to follow conditions during transport of goods. When valuable goods are transported, a producer, transporter or customer may be interested in verifying whether the conditions during the transport were following specifications or not. Similar applies for storage of material. In particular, advance military systems are stored for prolonged periods of time and supposed to be ready for deployment anytime. AirCorr loggers can be then used to ensure good level of anticorrosion protection.

Pollution monitoring

The sensor can be used as an early pollution detector for different pollutants such as ozone, SO2, NOx and H2S, depending on the selection of metals sensitive to these gases. The sensor would be useful if applied for on-line monitoring at locations with dangerous pollution, such as industrial plants. However, it must be noted that the response is indirect in this case. Any acceleration of corrosion rate can but does not need to be caused by presence of elevated amount of a specific pollutant. It limits the applicability of the technology for pollution monitoring. There are competing and probably more suited technologies for pollution assessment. AirCorr loggers could be successful only as a cheap alternative. It may be interesting to enter this market in case of success on the other markets discussed above that would lead to economies of scale and drop in the product cost.

Research and development

Development of corrosion tests, understanding of corrosion mechanisms and many other areas can benefit from real-time corrosion monitoring. Based on the current use of the alternative real-time monitoring techniques, it is obvious that this market will never be crucial for the AirCorr success. Anyway, it may bring some tens of additional sold units a year. Because of the limited expected size of the market, fewer efforts will be put into marketing the logger for research purposes. Anyway, the information on the developed technology was made available in scientific and technical journals and further publication activities are planned.

The project fulfilled all principal objectives and a range of three products with a number of sensors made of different metals and with varying sensitivity for corrosion monitoring in air were developed and being introduced to the market. Due to intensive publication efforts of the consortium and other dissemination measures, there is already a strong awareness about the AirCorr technology within professionals working in the cultural heritage sphere. Further marketing measures are going to be undertaken in following months. Thus, it is believed that the technology is well placed for rapid spread in the cultural heritage sphere.

The application of a simple and relatively cheap tool for monitoring the air quality and corrosivity will help in efficient protection of a huge amount of objects and buildings with immense historical and cultural value. No special knowledge is needed in order to use the unit and to interpret results. Based on obtained results, immediate countermeasures can be applied in order to make the air quality control more efficient and to protect the objects in the best possible way. Compared to the current state, the information of air corrosivity will be available significantly more rapidly (in days or weeks compared to months or a year).

It is expected that the technology will not only improve the protection of objects of cultural heritage across Europe and elsewhere, but also reduce the costs for the protection. It is known that in many cases the air quality control is excessive and thus too costly. The AirCorr technology allows for adjusting it in the most appropriate way. For example, scavengers and special filters are used for air quality control in rooms or enclosures with most valuable objects. Currently, they are changed rather randomly and often earlier than necessary because the actual air corrosivity cannot be measured. AirCorr will help in finding and maintaining correct replacement intervals.

Besides the key impact of the AirCorr technology described above, it may in addition contribute to these EU policies:

- Employment

Since the tourism industry is clearly a major employer and generator of wealth in the EU, the appropriate protection of the European cultural heritage is an important component to reinforcing competitiveness and employment in this major economic sector.

- Enterprise

Promotion of entrepreneurship and increase of competitiveness and transnational collaboration of the SMEs. NKE developed the loggers and will produce them. It adds a valuable range of products to its portfolio. Rapid return of the invested funds is foreseen.

- Protection of environment, quality of life and health

One of the applications of the corrosion monitoring system is the monitoring of pollution at high-risk plants. By giving early warning on the risk of pollution and by reducing emissions from these sources, AirCorr can contribute to an increase in the quality of life and health for European citizens by decreasing the risk of pollution.

- Sustainable development

Better corrosion protection will decrease corrosion costs and enable effective utilization of the existing resources. In specific cases, it may help saving corrosion protection consumables such as filters and scavengers and energy for heating, dehumidification and other air quality measures.

Dissemination activities:

A publication plan has been prepared by ICT with inputs from all partners and issued in December 2010. The target groups of the information addressees were specified (cultural heritage specialists, preventive conservators, air quality specialists, corrosion engineers, corrosion scientists, surface treatment specialists, specialists in other field concerned with air quality control). For each of the target groups, appropriate media has been chosen.

In total, the consortium published or prepared for publication 12 papers in scientific and professional journals, gave 11 presentations at 8 national and international conferences and participated in 2 trade fairs. Selected results were presented at 3 seminars. A brochure and web page informing general public and cultural heritage professionals about the project were published and the latter one updated. Press releases were prepared in English, German and French. In addition, information about MUSECORR and AirCorr appeared in several newspaper articles. Summary papers appeared also on web pages of InnovationSeeds, Youris, Farbe und Lack and others. A utility model application has been submitted to the Czech Industrial Property Office by ICT aiming to protect the original design of the AirCorr sensors.

In June 2012, the 10th international conference Indoor Air Quality 2012 took place in London, UK. Within this conference, five workshops were offered to the conference participants, one of them with the title Real Time Monitoring of Air Corrosivity Using AirCorr Loggers, presenting experiences of end-users of the MUSECORR project. The possibility to test AirCorr loggers directly was given, too.

The aim of the workshop was to learn about end-users experience with testing the AirCorr data loggers at their institutions and to broadcast the acquired knowledge to their peers. The workshop took place on Monday, June 18th at the conference venue of the University College, London. Moderator of the workshop was T. Prosek of ICO, co-moderators M. Taube of NATMUS, M. Dubus of C2RMF and M. Kouril of ICT. The workshop was organized by V. Hubert of SNM who was represented by M. Woerle from the same organisation.

Seven end-users were invited to talk about their experience with testing the AirCorr loggers. The overall participation was 28 persons. End-users from the following institutions presented their experience: National History Museum, Cardiff, UK; Australian War Memorial, Canberra, Australia; Institute of Chemical Process Fundamentals of the ASCR, Prague, Czech Republic; English Heritage, UK; Danish Royal Library, Copenhagen, Denmark; and Kunsthistorisches Museum Vienna, Austria. Interested persons of the following institutions were further participants: University of Applied Science, Berlin, Germany; IBM T. J. Watson Research Center, New York, U.S.; Camfil Ltd., UK; British Museum, London, UK; Archaeological Service of the Canton Berne, Switzerland; University of Antwerp, Netherlands; National Museum, Czech Republic; Microwise System, Ltd., China; Politecnico di Milano, Italy; Institute of Atmospheric Sciences and Climate, Italy; National Library of Wales, UK; Historic Royal Palaces, London, UK; National Museum Wales, UK.

In the beginning of the workshop, consortium members gave an overview of techniques in corrosion monitoring. The AirCorr monitoring system was then explained in detail, followed by a demonstration of different AirCorr loggers. Another talk was given about possibilities to establish a classification system for the corrosion of lead, which is not yet available, a topic that has been discussed a lot among the consortium due to recurring demands of the end-users and other interested persons especially from museums. After another demonstration of the loggers a concrete example of the application of AirCorr loggers in finding an optimal cleaning procedure of brass marquetry was given. In the second part of the workshop the end-users were talking about their experience with testing the AirCorr loggers. Further demonstration was done and the workshop concluded with an open discussion.

The workshop was successful and many participants indicated that they were ready to buy the loggers when commercially available. The outcome of the workshop was clearly positive. It is believed to facilitate further dissemination and rapid commercial success of the AirCorr technology.

The final publication efforts significantly exceeded the original plan due to a large amount of attractive results obtained in course of the project.

Exploitation of results:

The developed technology proved to provide extreme sensitivity at a sub-Ångström (<10–10 m) level allowing for real-time corrosion monitoring even in low-corrosive indoor cultural heritage premises. Due to short response times, immediate countermeasures can be applied in case of an increase in the atmospheric corrosivity.

It was shown that the technique is reproducible with standard deviation of parallel measurements up to ±20 % for metals corroding in a given environment mostly uniformly. The response is close to the maximal depth of corrosion attack and thus somewhat higher compared to methods measuring the average corrosion depth.

Wide testing programme in partner museums, archives, libraries and other institutions was conducted to demonstrate the potential of the real time reactivity monitoring by the ER technique. AirCorr loggers were successfully applied for qualification and comparison of air quality control in indoor premises, assessment of new buildings and storage facilities, air quality control during transport and temporary exhibitions and fundamental studies of optimal conservation and storage procedures. Unique sensors made of lead and some alloy materials can provide useful insight into corrosion of these materials that was difficult or even impossible to get earlier. A first outline of a classification system for lead, which is particularly sensitive to presence of carboxylic acids, was proposed.

It is believed that the technique has a large potential as an independent method of air quality monitoring in facilities displaying and storing valuable objects of cultural heritage.

Because of the encouraging results, AirCorr monitoring system in versions AirCorr I, AirCorr I Plus and AirCorr O with sensors listed in Table 1 is currently being introduced to the market. First units were sold in September 2012 but full commercialization on the cultural heritage market starts in October 2012.

The consortium prepared a marketing plan as deliverable D17. The market size is expected to be from 40 to hundreds of units a year in 2013–2014. The long-term market potential to be reached in about ten years is estimated to be between 1300 to over 7000 units a year. However, it will necessitate further development for the market of clean air industrial solutions.

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