*Indoor Air Quality in the Museum Environment*

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# Introduction

## I. A. Preventive conservation

For as long as humans have regarded objects as worthy of preservation, there have been attempts to maintain and protect these objects. The field of conservation research has emerged as a way of understanding the composition and structure of these objects, as well as how they deteriorate. As analytical techniques have become more and more sophisticated, so too has the field. A growing body of research now focuses on understanding past mechanisms of material degradation and applying that knowledge to determine what techniques can be used to limit the amount of future damage — a sub-field known as preventive conservation. Preventive conservation focuses on interactions between cultural heritage objects and the materials and environments in which they are displayed, stored, and transported, understanding the best ways to preserve culturally significant objects so that they may be enjoyed for generations to come.

The field of conservation science is technically advanced and multi-disciplinary: it combines aspects of materials science, atmospheric chemistry, engineering, and even biology. These fields inform the decisions that cultural heritage institutions must make about the correct way to store and display their collections. Conservation scientists, however, work under an all-important constraint: cultural heritage objects are, by definition, of great historic and cultural significance, and any research done on these objects must be as minimally invasive as possible with the understanding that the unique and idiosyncratic history of each object also makes it challenging to apply methods and treatments from one object to another.

Preventive conservation research becomes even more important when these considerations are taken into account. A growing proportion of this research is focused on the role that air pollution plays in degrading cultural heritage objects. In fact, when considering environmental factors, air pollution is the third most common cause of damage to objects in museums, according to a large-scale survey of 115 European cultural heritage sites conducted as part of the MEMORI project.[1] Pollutants ranked only behind inappropriate humidity and temperature controls in terms of environmental factors that cause visible damage to objects in 2 years or less.

Scores of different types of objects are affected by atmospheric pollutants in diverse ways (Figure 1). The types of art that are typically of highest concern are metals, plastics, paint, pigments, calcareous, and cellulosic materials such as papers, fabric, and wood. Of course, the risks vary from museum to museum depending on their collections and environments.

Figure 1.  Examples of disfiguring surface damage from indoor air pollutants[2]

## I. B. Indoor air quality

In the mid-twentieth century, air quality research began to flourish as scientists investigated the processes generating smog and poor air quality in major cities around the world. Most of this research, however, focused on outdoor chemicals and reactions and the potential impacts on the environment and human health. In recent years, researchers have turned their focus to studying indoor air quality in homes and offices with a continued focus on human health.

Indoor air is made up of thousands upon thousands of organic compounds in both the gas and condensed phases. These compounds vary widely in concentration over time and from environment to environment; they can also react with each other to form even more diverse compounds. Despite most spending the vast majority of our lives indoors, this research area has been largely understudied in the atmospheric chemistry community. As a result, many of these compounds and their effects on humans are unknown and unquantified — to say nothing of their effects on the preservation of cultural heritage objects. The effects of indoor air pollutants are a burgeoning area of interest for the cultural heritage preservation community.

## I. C. Indoor air in the museum context

The enclosures used to store or house art objects and artifacts each create their own unique microclimates. Just as trace compounds can accumulate in homes and other indoor spaces, display cases in museums can reach much higher concentrations of pollutants than are found in the outdoor air. This phenomenon is not limited to display cases, either — organic and inorganic compounds have been found at very high concentrations within enclosed frames, in the protective crates used to ship artworks, and even within the enclosures that pieces are stored in when not on display. Depending on the dynamics of airflow within a case, pieces within a storage or display unit can also have differing exposure to certain pollutants, akin to the idea of “peri-human” air quality.

The objects themselves add multiple further layers of complexity. Pollutants that degrade one material may have no effect on another. In addition to an object’s as-found composition, historical preservation treatments may promote the chemical transformations that occur on the surfaces of objects. And seemingly minor variations in objects and their environments may have out-sized impacts on preservation. Indeed, collections of seemingly similar objects have been found to degrade in vastly different ways under the same conditions.

Due to the complexities of indoor air, attempts to model or forecast chemical transformations that occur must take a multi-scale approach, similar to the Modelling Consortium for Chemistry in Indoor Environments (MOCCIE),[3] which uses models at a variety of scales to understand the complex chemical processes of indoor air in a home-like environment. At the smallest scale, molecular simulations can provide insight into the physical and chemical processes that occur when specific pollutants adsorb onto surfaces. Parameters derived from this type of modeling can be fed into kinetic multi-layer models that approximate the envelopes of air around specific objects. These mass transports and reaction rates can then be parameterized in computational fluid dynamics models that provide insight into how pollutants move within a case or a building as a whole.

Both inorganic and organic pollutants can be significant contributors to degradation of cultural heritage objects. The most prominent inorganic pollutants, such as nitrogen dioxide, hydrogen sulfide, ozone, and nitric and hydrochloric acids, are introduced to the museum environment in a variety of ways, including the oxidation of other trace gases, off-gassing from sealants and vulcanized rubber, and the use of equipment. Major pathways of volatile organic compound formation in museums include the evaporation of solvents, off-gassing from construction or furnishing materials and objects in the museum, and byproducts of degradation from museum objects. Museum staff and visitors, and the personal care products they use, can also be considerable chemical sources. In addition, compounds that are technically classified as volatile may act differently indoors due to the high surface-area-to-volume ratios found inside as compared to outside. The high concentrations of water and the wide array of organic surfaces indoors can help these volatile compounds partition into non-gaseous phases, react, and deposit more readily than they would outdoors.

The "Indoor Air Quality in the Museum Environment" workshop brought together leading experts in both the indoor air quality and the art conservation fields at the Metropolitan Museum of Art in New York City on 13–14 February 2020. Presentations on research and challenges were interspersed with discussions that brought together the diverse perspectives from both the academic and museum communities. The goals of the workshop were to share the research that is being done between the two communities, determine the research priorities for the growing field, and forge new connections at the interface of conservation and indoor air quality research. Each community brought with it perspectives and needs that helped shape the following document.

This whitepaper summarizes the three main challenges identified in the workshop: identifying and characterizing pollutants; understanding the chemical transformations occurring on art objects and other artifacts; and developing better methods for assessment of the environment and mitigation of damage. The following sections will provide an overview of each of these areas, specific research themes, and advances needed by the field. The report will also provide a series of recommendations for how to broaden the impacts of conservation research and educate the general public about its importance.

## I. Grand challenge I: Pollutants

### II. A. Overview

The foundation of indoor air quality research is understanding volatile pollutants and the reactions that they undergo. In museums, these pollutants can both come from and interact with art objects, leading to a highly complex series of problems, which may destabilize or disfigure the original materials. Semi-volatile compounds can also be directly emitted or off-gassed from a variety of both construction materials and human sources indoors. These compounds can react with each other and with art objects in myriad unknown ways.

All told, thousands of trace compounds make up the air around us; museums lack the capabilities to both qualitatively and quantitatively assess many of these chemicals. In order to protect against degradation, museums must have a solid understanding of what chemicals are present, where they are coming from, and at what levels they are capable of causing lasting damage.

It is clear that with the abundance of chemicals found in indoor environments, measuring and modeling each of them individually would be a Sisyphean task. Instead, the community must be systematic and strategic in establishing research priorities, as outlined below.

## II. B. Research themes

### *II. B. i. What chemicals are present?*

The first challenge is to understand each environment the art is housed: determining what chemicals are present at every scale — from the individualized storage container and vitrine, to the exhibition gallery and museum building as a whole. Pollutants can come from myriad sources, as is explored in Section II.B.iii. Determining the concentration of pollutants in a case, gallery, or building is also critical to damage prevention and depends not just on the sources of pollutants but also the air flow and exchange rates for each separate situation. Modern display cases, for example, are typically well-sealed to allow for tighter control of humidity and dust within the case. But this comes at a cost — minimizing the exchange of fresh air into and out of the case allows for the build up of pollutants that off-gas from the art and the case itself.

Current research into the presence of chemicals in museums is generally done on small scales. Museum scientists commonly detect the presence of certain compounds like nitrogen dioxide using passive samplers like diffusion tubes. Some of these, such as Dräger tubes, change colors as they absorb a desired pollutant. This method, of course, has its limitations: its accuracy and precision are much lower than higher-tech (and higher-cost) solutions such as gas chromatography and mass spectrometry (GC/MS). Other types of diffusion tubes are sent away for instrumental analysis after sample collection — a much more accurate but more expensive option.

Active sampling and other continuous sensors can provide a more complete picture of the chemicals present in a case, but these tools are expensive and require technical expertise to both operate and interpret the resulting data.

Major interdisciplinary projects looked at indoor air quality but not specifically in a museum environment. The HOMEChem (House Observations of Microbial and Environmental Chemistry)[4] campaign of 2018 outfitted a model house with a variety of sensors to identify the chemicals present in the air and on surfaces as it was put through a variety of typical home activities (e.g., cooking and cleaning). A museum corollary could prove to be a watershed project for the art conservation community.

### *II. B. ii. At what levels are pollutants harmful?*

More than 40 individual compounds have been identified as causing damage to certain types of objects with the list continually expanding. These chemicals are identified mostly by observations in museum settings, leading, in only a few cases to rigorous experimental determination of cause and effect.[5,6]

Establishing which chemicals at what amounts cause damage is paramount to allow the rapid and accurate assessment of risk from measurements, to date, lengthier and less reliable tests have been used to sift out unsuitable materials before construction or installation. Where possible, in a laboratory setting, damage-causing compounds are typically identified and examined for their chemical similarity to other compounds known to cause problems in the museum environment. These chemicals are tested for their effects at a high concentration; if damage is found, the tests are performed again at more realistic concentrations and at varying levels of relative humidity. But only a short list of chemicals have undergone the systematic studies described above: acetic acid, formic acid, nitrogen dioxide, ozone and formaldehyde. Publications are scant for other suspected pollutants, where only a few conditions were applied to very limited materials.

These compounds are often classified by two metrics: NOAEL and LOAED. NOAEL, the No Observable Adverse Effect Level, is the highest concentration of a pollutant at which no damage was observed. LOAED is the Lowest Observable Adverse Effect Dose, or the lowest concentration at which damage was observed. These are commonly used concepts in risk assessment in the museum environment, but there is much variation in the gray literature as to what these levels are for different compounds.

### *II. B. iii. What are the sources of the pollutants?*

There are many sources of pollutants that one must consider in the museum space. Each source may introduce different types of compounds at varying concentrations and over a range of time periods, but they all potentially play a significant role in the chemistry that affects cultural heritage objects.

One source of pollutants is simply outdoor air, brought into the museum environment through HVAC systems or exchange through doors and other openings. Once inside the museum, pollutants can be altered in both abundance and form. The concentrations and types of pollutants will vary considerably depending on a museum’s location — urban or rural, coastal or land-locked, etc. These are factors that the atmospheric chemistry community are keenly aware of when it comes to outdoor air quality but have not been fully considered in many cultural heritage institutions.

The construction of exhibits and display cases often introduces additional pollutants into a museum. Many institutions attempt to minimize potential for damaging interactions by choosing materials that are low in emissions, but low emissions can also be damaging. Volatile and semi-volatile compounds from construction materials can build within display cases that have low air exchange rates.[7] Art objects themselves, often complex and multilayered in their fabrication, may also emit chemicals that can be damaging, interacting with their own materials and other objects in the same case.

Lastly, the museum staff and visitors who enter museums daily introduce their own chemicals to an exhibition. Recent research on the effects of third-hand smoke, for example, show that many compounds that are hazardous to human health can be introduced into non-smoking environments via smokers' clothing and skin.[8] Fragrances, lotions, and other personal-care products can all act as sources of novel chemicals to the museum environment.

## II. C. Advances needed

First and foremost, a thorough understanding of the chemicals present in any given space is needed. But as noted above, the thousands of compounds present at once make it impractical to measure and quantify them all. Rather, the compounds that are causing or have the potential to cause damage must continue to be identified. The sources and presence of these chemicals must be considered in a temporal sense, too — construction of an exhibition space may introduce a new suite of compounds into a museum over a short period of time. Determining the suitable materials for construction, then, must take into account when the objects will be displayed relative to when the construction occurs both in the new gallery and in adjacent spaces with shared HVAC systems.

Another temporal aspect to consider is the length of an exhibition. Because many construction materials off-gas the highest volatile pollutant load when new, objects that are on display for shorter periods of time may be exposed to higher concentrations of potentially harmful pollutants than those on longer-term display. Understanding what chemicals are present over what timescales will help conservators plan for different lengths of exhibition. Wrapped into this is the idea that hazard potential is not a single quantity, akin to the difference between acute and chronic doses of pollutants that are harmful to human health.

Many attempts have already been made to define acceptable levels of pollutants for some of the most commonly occurring and most abundant compounds, such as acetic and formic acids. But the standards by which these are measured — and thus the advice offered — vary greatly from one set of guidelines to another. Standardized, objective measures of degradation for the most commonly used art media and construction materials will help provide more clear guidance to museum decision-makers.

But in addition to defining standards for acceptable levels of pollutants, museums must consider acceptable levels of damage. At what concentrations do certain compounds begin causing damage? And what amount of damage is permissible for different types of objects? This is understandably a sensitive subject for museum conservators. In an ideal world, cultural heritage objects would be preserved and displayed pristinely for an indefinite length of time, but this is simply not feasible.

An oft-cited approach to studying atmospheric chemistry is the “three-legged stool” — the idea that modeling studies, laboratory (or chamber) experiments, and field campaigns all contribute to a greater and complimentary understanding of the atmospheric system. A similar approach could be applied to museum indoor air chemistry. Here, modeling could help elucidate the chemical transformations occurring within a case and whether there are gradients or stratification of temperature or other key factors that must be considered. Laboratory experiments would help identify the compounds being emitted from specific materials or objects and assess the damage that these compounds can impart. And a large-scale experiment like a MuseumChem (modeled after the aforementioned HOMEChem study) could put all of this knowledge in a broader context.

Another aspect of the field that is ripe for scientific advancement is the improvement of detection levels. This avenue is not unique to the indoor air quality or museum communities: manufacturers are continually pushing the boundaries of detection limits for all sorts of applications. However, the inexpensive, real-time sensors that currently exist are often not sensitive or specific enough to be useful in the museum environment.

## II. Grand challenge II: Chemical transformations

### III. A. Overview

Indoor environments are inherently complex, being composed of a wide array of both inorganic and organic pollutants and surfaces. They also provide a high surface-area-to-volume ratio, which lends itself to multiphase and surface chemistries that can produce secondary organic compounds, further complicating matters. Indoor oxidant loadings tend to be much lower than outdoor environments, but many trace gases are highly concentrated indoors as compared to outdoors. The reactions among these volatile and semi-volatile organic compounds leads to the tendency to develop organic films on indoor surfaces. Organic films can act as both reservoirs and sources of gas-phase pollutants such as organic acids. And further reactions can be carried out within these films, affecting both their lifetimes and the potential degradation of the objects on which they form.

The chemical transformations that occur within an exhibition space or a display case can produce secondary organic compounds that complicate the already-complex chemistry occurring indoors. Further transformations that occur on the surface or within art objects have the potential to cause lasting damage. The degradation products that are generated as a consequence of these reactions can also react further with the compounds in a particular space. Thus, chemical transformations must be understood in both spatial and temporal contexts in order to give a complete picture of the chemistry affecting cultural heritage objects in museums.

Ultimately, volatility may not be the most important factor for understanding the mechanisms of transformation and degradation. The relative importance of volatility and reactivity in determining how hazardous a pollutant can be remains an open question within both the atmospheric and museum chemistry communities.

## III. B. Research themes

### *III. B. i. Degradation effects on cultural heritage materials*

The main way that damage and chemical transformations are studied and understood within the museum context is by accelerated corrosion testing on art surrogates, typically some form of the Oddy test.[9,10] In this test, a construction or preservation material of interest is placed in a sealed container at a fixed temperature and relative humidity with coupons of reactive metals, typically copper, silver, and lead (Figure 2). After a given length of time, the coupons are inspected by eye for discoloration or other evidence of corrosion. This test has historically provided guidance to the museum community for building new exhibit cases, crates, and galleries.


The Met (1999) | British Museum (2017) | The Met (2017)

Figure 2. Example Oddy test configurations from The Met[10,11,12] and The British Museum[9]

Several other surrogates have been developed to understand the degradation that occurs on various types of artists' materials, such as paper, glass, and plastic. However, these materials are rarely commercially available or standardized. This is an advantage of the Oddy test, where the metal coupons used are commercially available, and there have been efforts to standardize protocols. Due to the lack of viable alternatives, the results of Oddy testing have broadly been applied to tackling problems of degradation across *all media types*, not just bronze, silver, and lead objects. While it is known that different media likely have a range of sensitivities to pollutants, there is only limited understanding of exactly which chemicals in what amounts will damage one media type over another.

Degradation tests face reproducibility problems and other limitations as well. One issue with accelerated corrosion tests is that as materials degrade and transform, the types and amounts of compounds that they emit can vary. The Oddy test does a better job than typically shorter, GC/MS-based tests in evaluating the volatiles that emit from a material as it degrades, since it is carried out over timescales of several weeks.[13] But it is also limited in their scope, as the tests are most often conducted on one material at a time and thus do not take into account synergistic effects of multiple materials inhabiting the same space.

While many types of degradation caused by such interactions are permanently damaging to art objects, some may be reactions occurring primarily on the surfaces of objects, or even on superficial coatings such as waxes. In some cases, reaction products may be removed without apparent damage; nevertheless, it is possible that the art has been altered through these chemical reactions, and in some cases, physical and chemical damage has, in fact, been observed. For example, crystals formed on artifacts through the reaction of piperidinol (a base) and acids seen in many modern display cases appear to leave no lasting physical damage on ceramics, textiles, or other materials (Figure 3). Having to devote time and resources towards removing these products, however, limits conservators from working on other objects which may be actively deteriorating.

Figure 3. Acids and bases from low VOC case construction materials reacted to form crystals on a ceramic object housed in a modern display case[2]

*III. B. ii. Needs of short-term display, long-term display, and storage*

Approaches like the Oddy test generally separate materials into three categories, depending on their suitability for use with art: permanent, temporary, or unsuitable. Materials in the first category can reasonably be deployed in permanent exhibitions. In the second category, materials are only to be used for shorter-term exhibits — generally on the order of three to six months. Materials in the third category should be avoided if at all possible. Thus, the conservation requirements will vary based on the length of its exposure to those materials.

Objects that are routinely rotated in and out of exhibition and storage are often said to be “resting” or “recovering” when not on display, but this characterization is inaccurate. Removing a piece from display does slow the damage, as storage is generally done in dark spaces and with a greater degree of atmospheric control, but the damage done to an object while it is on display is not reversed in any way. Thus, rotation from display to storage can prolong an object’s life only by virtue of extending the period of time over which damage is done. Care must also be taken when considering storage and display environments to ensure that an object will not take up chemicals in one environment that can then react with different compounds existing in the other environment.

Additionally, much of our understanding of indoor air chemistry comes from studying photo-catalyzed reactions. Items in storage are kept in the dark, raising the possibility of dark chemical processes that differ from those affecting objects on display, even keeping all other factors the same.

And for many objects that are the centerpieces of their museum's collections, display is their "permanent storage" — these are artifacts that are so widely known and loved that they will rarely if ever be removed from public view. These objects pose yet another unique challenge to conservators. In many cases, exhibits can be modified to help prolong an object's useful life. For example, nitrogen gas is piped into the cases which hold the sword collection at the Tokyo National Museum. The low-oxygen atmosphere helps prevent oxidation that would otherwise occur.

*III. B. iii. Understanding past treatments*

In the case of objects that have been in collections for a very long time, or for those that have changed hands many times, past treatments can play a significant role in the chemical transformations and reactions that occur. Each object carries with it a unique history of treatment, exhibition, and storage that informs the chemistry that occurs today. In the case of archaeological or other historical artifacts, burial and past use also contribute to the complex chemical transformations that may occur.

For example, the Museum of Fine Arts, Boston, has a large collection of Chinese glass dating to the 18th and 19th centuries. It was originally stored in wood cabinets but moved to resin-coated plywood cabinets in the 1980s. Museum staff later found that nearly half of the objects in the collection had begun to degrade in some way, including about 10% that had severe degradation. It is an open question as to what extent the inherent instability of these objects was exacerbated by the change in storage environments.

These problems are heightened even further when previous treatments or storage conditions are not well-documented or are unknown. Ideally, a full understanding of previous treatments and environmental agents is available before the objects change environments or before damage mitigating treatments can be applied.

## III. C. Advances needed

Broadly speaking, there is a need to understand what chemicals cause what types of reactions on which materials (section II. B. i). There are a number of facets to this: increased standardization of degradation testing, advanced analytical techniques applied to degradation products, and further research on synergistic effects of compounds.

Degradation testing, such as the Oddy test mentioned above, continues to be the standard by which materials are tested for suitability, despite its flaws. Attempts at standardization of these tests have been relatively successful within museums, but these methodologies have not necessarily been adopted between museums. A recent survey revealed 20 distinct protocols in use between 31 institutions carrying out Oddy tests (Figure 4).[14] The Metropolitan Museum of Art has worked to strengthen and standardize their protocol to a great degree of success, but the fact remains that these tests vary significantly from institution to institution.[10]

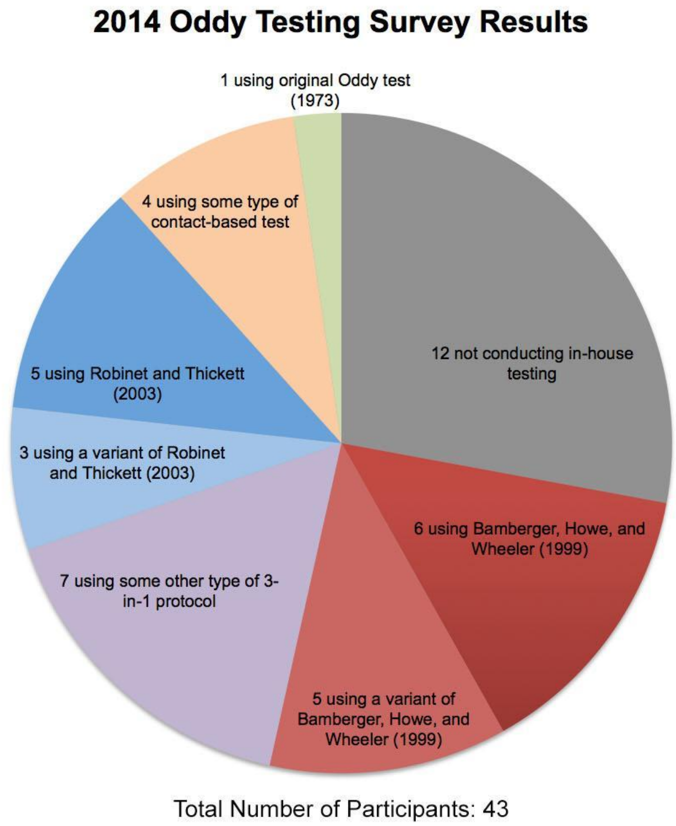


Figure 4. 2014 Oddy test methodology survey of 43 cultural heritage institutions.[14] Tests include the original methods and variants from Oddy,[15] Bamberger,[11] and Robinet,[16] as well as other 7 other unpublished accelerated corrosion tests.

Another limitation of these material degradation tests is that many of them rely on the subjective visual inspection of the metal coupons to determine whether damage might occur. However, using advanced analytical techniques such as X-ray diffraction, infrared spectroscopy, mass spectrometry, and electrochemistry, to name a few, to test degradation products can help fill this knowledge gap. Direct thermal desorption GC-MS, for example, can reveal the compounds making up corrosion products, films, and other degradation products forming on the coupons used in these tests, lending insight into the chemical transformations occurring. The use of analytical techniques also has the advantage of revealing damage that may be occurring but is not immediately visible to the naked eye in a standard test.

Some institutions have also begun to deploy the use of study collections in understanding and forecasting chemical transformations. Study collections can give more realistic results of potential transformation and may lead to meaningful forecasts of chemical transformations on various materials and media. Analysis of deterioration shown by collections can give important insight into the deterioration mechanisms and relative risks. For example, identification of a blue sodium copper carbonate acetate corrosion on Egyptian bronzes indicated acetic acid as a key cause of deterioration. Looking at the acetic acid concentration and relative humidity in different cupboards, and how objects in those cupboards were damaged, gave valuable insights into the risk posed to similar objects.[17]

Almost all of the current understanding of corrosion and degradation of art objects comes from single-material tests, but no museum case or exhibition is made solely of one material. It is clear that testing single materials in isolation, while a good starting point for understanding what chemicals may contribute to degradation, is not sufficient to understand the potential of an exhibition case or storage container to generate damaging compounds. Understanding synergistic reactions, then, is a critical area where advances are needed. Additionally, while synergistic reactions may occur that exacerbate or accelerate the damage done to an object, the opposite may be true as well — there may be compounds that can act “antagonistically” and reduce the amount or severity to an object. The majority of compounds, however, won’t interact with each other at all. A large-scale MuseumChem study could propel the field forward by allowing a more complete examination of the synergistic and antagonistic reactions that may occur in a real museum setting. This work, beyond its inherent merit, will also help researchers better understand the value of the Oddy test.

## III. Grand challenge III: Assessment and mitigation

### IV. A. Overview

In light of the issues outlined above, there is a growing need for the development of tools for monitoring compounds, assessing their potential to cause damage, and mitigating negative outcomes. The academic community has many tools, each having a role to play in defining and solving the problems of the preventive conservation community. These tools range from expensive, highly precise instruments to inexpensive, qualitative ones.

Precision laboratory instruments like real-time GC/MS can be used to gain a deep understanding of the chemicals present in typical spaces and situations such as exhibition galleries, storage areas, and display cases (Figure 5). The insights that such instruments provide can be used to select the appropriate tools to monitor a given space for the most likely chemical culprits. These advanced techniques will also help conservation scientists identify gaps in museum toolsets; academic scientists can then help develop monitoring tools to fit those needs.

On the other hand, these complex analytical techniques are impractical for day-to-day use: beyond their expense, they would overwhelm conservators with the amount of unprocessed information they generate if used in a day-to-day capacity. Tools for monitoring must be easy-to-use and provide easily digestible information. Ideally, monitoring tools will be developed that require little to no technical expertise to operate and understand and can potentially be separated from the job of the conservator. There is also the issue of cost: most museums are much lower-resourced than even small academic laboratories.

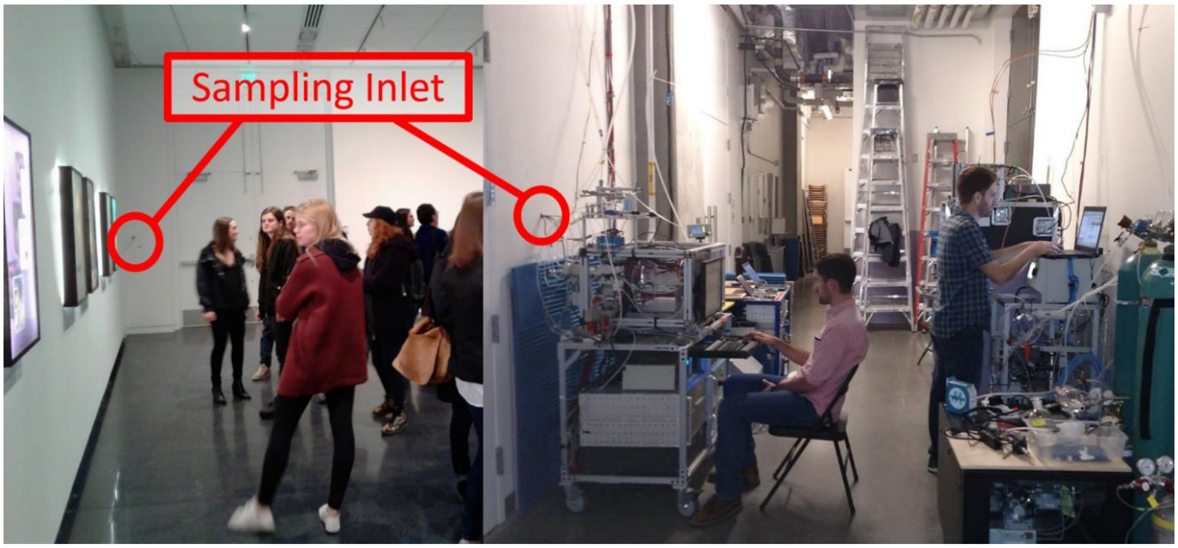


Figure 5. Complex implementation of advanced analytical GC/MS tools in a gallery setting[18]

The museum and art conservation communities have a hierarchy of methods to approach degradation prevention: avoid, block, dilute, passively absorb, and actively remove or absorb. Harmful pollutants should be avoided if at all possible, but as outlined above, this is often not the case. The next easiest prevention method is blocking — either with a physical barrier or coating on an object, or via more tightly-sealed cases. Dilution is the next step, an attempt to lower the concentration of a harmful chemical below the LOAED. Finally, passive methods of mitigation, such as the use of chemical sorbents, and active methods of mitigation such as forced air filtration can help prevent or limit damage when all other approaches have failed or are not applicable.

## IV. B. Research themes

### *IV. B. i. Monitoring in museum environments*

The key components of pollutant assessment research are understanding where, when, and for how long to measure contaminant levels. Monitoring can be done both actively and passively. Each method has its positives and negatives: passive monitoring tends to be single-point, semi-quantitative (i.e., less precise), and cheaper, while active monitoring can give real-time, precise, accurate data but at much higher cost.

Monitoring methods for use in museum cases has to be relatively fast, easily understood, and visually unobtrusive. Diffusion tubes, as described above, are one way that conservators collect information about the pollutants in a case. Other methods are even more rudimentary — metal coupons or other indicators can be placed in a case; if they begin to corrode or degrade, it signals to the conservator that adjustments are needed to the environment within the case.

When a more targeted approach is needed, more complex monitoring techniques can be employed. Solid-phase micro-extraction (SPME) has been used in many museums to understand the chemical transformations occurring in specific cases to cause degradation. When coupled with gas chromatography-mass spectrometry (GC-MS), SPME can reveal the chemical source of degradation. The Museum of the American Indian has even shown that SPME samples can be shipped and produce the same results several days later, opening the possibility of utilizing pay-per-use SPME/GC-MS analysis services for relatively resource-poor museums.

### *IV. B. ii. Mitigation of pollutants*

On the broadest scale, museums have to contend with the air that is brought into their environments through HVAC systems every day. Depending on the museum, the sophistication of these systems can vary dramatically: some filter large amounts of particulate matter and even certain gaseous pollution, while others intake outdoor air and only control temperature and humidity to the best of their abilities.

There are two primary ways of mitigating pollutants and their effects on art objects: active and passive mitigation. Active mitigation techniques include the above mentioned filtration systems operating on the building or display-case levels (Figure 6).

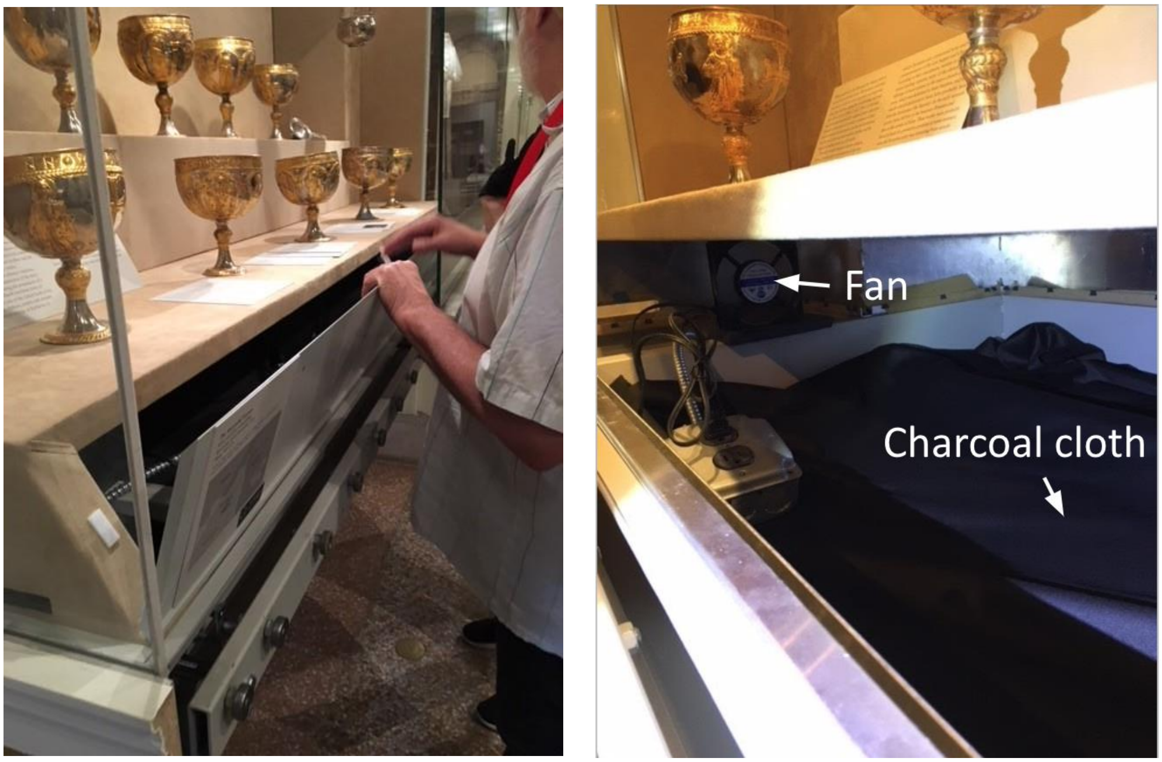


Figure 6. Active filtration of display case using circulated air over activated-charcoal cloth**Error! Bookmark not defined.**

Passive deployment of sorbents and other scavenger products is more common and cost-effective than active deployment or filtration, but the results are harder to predict. The use of sorbents also brings up its own set of questions: how long can a sorbent be used before it needs to be changed? Are there easy ways (e.g., visual cues) to tell when a sorbent is losing its effectiveness? To what extent do sorbents off-gas and re-emit the compounds that they initially absorbed? In mitigation especially, there is a need to develop a trustworthy body of knowledge. Can museum conservators take claims from commercial manufacturers at face value, or should they only rely on scientists and other conservators for understanding the appropriate uses of mitigation techniques?

Lastly, barriers can be applied to exclude chemicals and block them from an art object's surfaces. However, this can lead to complications when previous conservators have applied unknown treatments to a piece.

## IV. C. Advances needed

Myriad academic groups are already tackling the development of low-cost, easy-to-use sensors for many applications. One promising approach is printed sensor strips, which are deployed in many ways to detect and semi-quantitatively assess the presence of a multitude of volatile and semi-volatile organic compounds. Such strips can be printed with a variety of compounds and then placed in display cases; these react chemically with different analytes to alert a user to the presence of a specified compound.[19] While this concept is promising, such sensors are both patented and not commercially available. Developing the idea into a low-cost, commercially available product could be of great use to the conservation community.

The further development of real-time low-cost samplers and sensors is another area in which the museum community could benefit from the resources of the academic community. Although low-cost sensors exist for certain compounds of interest and broadly for VOCs, options for detecting specific classes of volatile organic compounds at low cost remain scarce. While it is not feasible to develop sensors to detect every organic compound individually, sensors capable of detecting certain pollutants or classes of pollutants that are known to be harmful to cultural heritage objects would be a great boon to the field.

At the same time, compact technologies for performing gas chromatography are being rapidly developed and are a viable alternative to traditional GC-MS setups that cost hundreds of thousands of dollars. But realistically, the price point of these field-deployable GCs will still pose a significant barrier to entry to most, if not all, museums. Additionally, while the vast amounts of data generated by such instruments would be instructive in understanding indoor air quality in museums at large, the knowledge and tools needed to quickly translate that data into practical decisions on a project by project basis do not exist. Museums with the financial means and technical expertise to use such instrumentation could implement them to both develop the knowledge and tools needed to translate their data as well as transfer functions that allow the practical use and interpretation of less-expensive sensor data.

Tied into the concept of easy-to-use sensor development is the need to be able to present data in a way that makes sense and facilitates decision-making. One option is the development of an air quality index, which takes into account the concentrations of various pollutants and provides a single number by which the suitability of an enclosure can be judged. Alternatively, if complex instrumentation is used (such as instrumentation that provides continuous or near-continuous data), there are several ways in which the output data can be simplified and made easier to digest. Scripts can be used that will automatically generate graphs and other visual representations of large amounts of data; these data can also simply be reported using summary statistics. Decision support models can also provide a higher level of understanding, going beyond whether an atmosphere is suitable to which mitigation methods are likely to be most successful.[20]

It would behoove the community to work together to generate sets of standard guidelines for designing exhibition and storage spaces. A good starting point would be an interactions matrix that can offer guidance on what construction materials are or are not suitable for use with certain types of media. Further guidance could provide best practices for filtration and sorbent use and for placement of objects in a case depending on how specific pollutants tend to stratify within cases. Assessment and mitigation is another area where a MuseumChem study could significantly advance the conservation science field by allowing for detailed comparisons and evaluations of multiple types of compact sensors against advanced analytical technologies.

## IV. Broader impacts and outreach

Although museums and other cultural heritage institutions are themselves prolific in terms of outreach to communities, the integration of their conservation research and efforts into outreach is significantly lagging. As a result, many members of the public are unaware of conservation science research. Stronger outreach efforts could generate more public interest in both conservation science and science as a whole, and also lead to improvements in collections care.

A large-scale project like a MuseumChem experiment would be able to significantly raise the profile of preventive conservation research. By coupling atmospheric chemistry research and collections care, we could stimulate public excitement in both fields in a more immediate way. Drawing collaborators from across the country and around the globe would be sure to garner significant attention from the press and the public at large. This type of experiment would not have to be done behind the scenes, either. Rather, creating real-time displays of air quality information could engage visitors in both the conservation and the indoor air chemistry sides of research by creating awareness and a sense of urgency around protecting these priceless works of art.

With the increased focus of many engineering and design programs on addressing societally relevant problems, museum indoor air chemistry offers great opportunities for academic research centers to collaborate with art institutions within their communities. Local opportunities for partnership would allow solutions to be designed to the specific needs of a given museum or institution. This type of collaboration would also expose more undergraduate students to the field of conservation science and could potentially attract them to the field upon graduation. At a larger scale, a program like the US National Science Foundation’s Research Experiences for Undergraduates provides a research-intensive experience for a cohort of students that could be placed on a variety of research projects over the course of a summer. Collaborating on projects with cultural heritage institutions is also advantageous to researchers within the academic community, as it is an opportunity for universities to showcase the work that their scientists are doing to give back to their communities.

Museums could also enhance the public understanding of their conservation work through displays that demonstrate the damage that has been done to their collections over time. For example, the special exhibitions gallery at the Harvard Art Museums held an exhibit of a series of Mark Rothko murals in late 2014–2015. These murals, which had faded over time, were displayed with projected overlays that were used to temporarily return the works to their original states. By showing the public what has been lost already, we can engage them in the desire to better preserve works for the future.

## V. Conclusions

Humans spend approximately 90% of their time in indoor spaces. Despite this, air quality research has traditionally focused on studying the chemistry of outdoor air. Only recently has the interest in indoor air quality increased both within and outside the atmospheric chemistry community.

This research area is also one of concern to the conservation science community. One-quarter of European museums and cultural heritage sites surveyed as part of the MEMORI project found that air pollution was a primary cause of short-term damage to objects in their collections. The two modes of damage that were more prevalent — insufficient controls of temperature and relative humidity — are much more highly understood and much more closely maintained than air quality is. Thus, there is a growing need to understand the complexities of the indoor air quality system as it pertains to museums, exhibitions, and even individual display cases.

The issues and areas for advancement in the preventive conservation field fall largely within three categories: pollutants, chemical transformations, and assessment and mitigation. Each one builds upon and influences the other, but each distinct challenge may be tackled separately.

The pollutants category focuses primarily on identifying and characterizing the components of museum air that are potentially harmful to objects in a collection. There is a need to understand not only what chemicals are present, but at what levels they can be harmful and over what timescales. These compounds can come from myriad sources, including construction materials, museum guests, and the artifacts and art objects themselves. Outstanding questions in the field remain about how to understand and define acceptable thresholds for pollutants (and acceptable levels of damage), improving detection levels, efficient methods of decreasing background pollution levels, and integrating modeling, laboratory experiments, and a large-scale “field” campaign.

Chemical transformations research highlights the need for understanding and characterizing the degradation of certain types of objects. It must take into account how the needs of an object vary based on whether it is intended for long- or short-term display, or for storage. Even two objects that appear on the surface to be very similar can have vastly different levels of risk based on previous treatments or compounds that they were exposed to in previous storage or display cases. More standardized and quantitative ways of assessing the potential to damage — for example, the use of object-appropriate art surrogates in degradation testing rather than solely metal coupons — will help conservators select and utilize the least harmful materials when caring for each type of object. As this body of knowledge grows, the need for understanding the synergistic effects of different compounds will also grow.

Lastly, assessment and mitigation emphasizes the development and deployment of tools that can help conservators and other museum staff make critical decisions about how to best preserve their collections. This includes qualitative, quantitative and semi-quantitative methods of assessment. Advances in this realm are constantly battling trade-offs: the more advanced a method of assessment, the more costly it is, and the more complex its outputs will be. Low-cost sensors are the primary need of many museums for assessing their air quality, even if this comes at the cost of some degree of precision or depth of knowledge. However, more complex studies may offer insight that can be applied broadly across many museums and collections and thus must also be a priority for the field.

The workshop that this document is based on brought together leading experts in the fields of atmospheric and indoor chemistry and conservation science and conservation and sparked many fruitful discussions about the potential for collaboration between the two. It is evident that there is still a great need to foster and strengthen collaboration between the museum and academic research communities for the advancement of conservation science.

## VI. Overall Recommendations

The field of museum indoor air chemistry is emerging as a key area for the development of more sophisticated preventive conservation methods. This research, and the policies that it can inform, will lead to better preservation of cultural heritage collections and maintain them for future generations.

At the same time that museum professionals are becoming increasingly aware of and concerned about the effects of indoor air pollutants on art and artifact collections, the academic research community is making significant advances in the real-time detection of pollutants and understanding of both indoor air and surface chemistries. Leveraging the expertise of these two communities by fostering collaborations across institutions would greatly advance our capacity to preserve cultural heritage objects. By partnering with museums in these vital scientific efforts, universities will be able to add an invaluable new component to both research training and scientific education. Conservation science represents a new direction for many researchers and a way in which science can have greater impacts in the arts and culture.

Some museum indoor air chemistry research has already been spearheaded by individual cultural heritage institutions, or by consortia of museums, through their own fundraising. But without dedicated research funding from federal and/or private foundations, substantial growth in the field — both in terms of the quantity and quality of research and the amount of cross-field collaboration that can be done — will not be possible. The field is in critical need of funding for graduate and postdoctoral fellowships as well as the instrumentation these scientists will need in museum research laboratories. This type of funding will help support the next generation of conservation scientists and help preserve our cultural heritage for years to come.

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David Thickett, conservation scientist, English Heritage

This document reflects conversations and presentations at the workshop as captured by Giuliana Viglione, freelance science writer, and this committee has reviewed, edited, and approved this report.

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