National Leadership Grants - Museums

Sample Application MG-255535-OMS-24
Project Category: Collections Stewardship

Rochester Institute of Technology

Amount awarded by IMLS:	$552,679
Amount of cost share:	$0

The Rochester Institute of Technology will conduct research on the relationship between room-level relative humidity, object-level water activity, and the associated risk of fungal germination on paper and parchment. Biodeterioration of organic collections is common and widespread; however, an in-depth understanding of the conditions that favor fungal growth are limited, despite the increasing importance and need due to climate change. This project will collaborate with university and museum partners to undertake laboratory analysis and simulated experiments, and to apply novel instrumental and field analysis. The results of this research will inform the management of objects with collection environments, by balancing the preservation of organic objects with environmental sustainability in the face of collection emergencies.

Attached are the following components excerpted from the original application.

- Narrative
- Schedule of Completion
- Performance Measurement Plan
- Data Management Plan

When preparing an application for the next deadline, be sure to follow the instructions in the most recent Notice of Funding Opportunity for the grant program to which you are applying.

NARRATIVE

The Image Permanence Institute (IPI) at Rochester Institute of Technology (RIT) is applying for a National Leadership Grant for Museums to support a three-year research project to study the relationship between room-level relative humidity, object-level water activity, and the associated risk of fungal germination on organic collections. This research will inform the management of collection environments, by balancing the preservation of organic objects with environmental sustainability, and increasing resilience in the face of collection emergencies. Organic collections, which include textiles, furniture, objects, photographs, and archival documents, constitute at least two-thirds of tangible cultural heritage in collecting institutions across the United States [1]. The field has developed an extensive understanding of the impact of the environment on the chemical and physical deterioration of such collections. However, despite common and widespread biodeterioration of organic collections, an in-depth understanding of the conditions that favor fungal growth, most commonly referred to as mold, are limited. Therefore, resources that inform environmental management for mold prevention are scarce, albeit of increasing importance in light of changing global climates and the concomitant need for heritage institutions to sustainably manage their collection environments.

This project directly addresses Goal 3 of the National Leadership Grants for Museums program, advancing collections stewardship and access, by undertaking research into the impact of static and dynamic environmental conditions on the rate of fungal germination on organic materials. This will be a comparative study focusing on two major classes of materials susceptible to germination, namely paper and parchment, and will assess their germination response to changes in relative humidity, equilibrium moisture content (EMC), and water activity[1] (Aw). This is with a view to providing guidance on how to optimize the preservation quality of museum, library and archive collections, such that fungal growth is avoided, while supporting sustainable environmental management in order to meet institutional sustainability goals. This research will also assess the impact of emergency mitigation strategies, such as increasing airflow, to help guide emergency response when faced with mold outbreaks.

IPI has a history of research relating to dynamic environmental management of organic collections and the development of methodologies for sustainable HVAC[2] operation in collection environments. This experience will be leveraged to establish optimum environmental controls such that the equilibrium moisture content and water activity of organic materials remain within safe limits for the prevention of mold germination. During this project, IPI will work in collaboration with Georgia Southern University (GSU) and the Colonial Williamsburg Foundation (CWF). GSU will undertake a discrete portion of research to determine how the rate of germination on organic substrates is impacted by different environmental conditions, while CWF will deploy dosimeter samples across representative historic sites to help understand how the water activity of organic materials on open display is influenced by changing environmental conditions *in situ*.

PROJECT JUSTIFICATION

Mold spores are ubiquitous, and yet, of the major contributors to the deterioration of museum collections, their proliferation and degradation mechanisms are poorly understood. Concerns over mold germination are one of the primary reasons for tight restrictions on the upper limits of relative

[1] Water activity is defined as $Aw = p/p_0$, where p is the vapor pressure of a material and p_0 is the vapor pressure of pure water at the same temperature and external pressure. At equilibrium, water activity of a material is directly proportional to relative humidity and moisture content.
[2] Heating, Ventilation and Air Conditioning (HVAC)

humidity in collecting institutions, resulting in expensive dehumidification operation in the face of uncertainty. These limitations in knowledge have resulted in the field's reliance on unsustainable, tight environmental controls, with collections care professionals being hesitant to broaden the range of relative humidity (RH) set points for fear of increasing the risk of fungal activity. This essentially limits potential energy-savings gained from sustainable environmental management strategies, and also increases the threshold that borrowing institutions need to meet in order to secure loans, which has a disproportionate impact on small and medium sized collecting institutions.

However, this focus on relative humidity belies the fact that it is not the relative moisture content of air that determines mold germination, but rather the amount of moisture at the surface of an object available to support growth, known as the water activity (Aw). When an object is at equilibrium with its immediate environment, the water activity is proportional to the equilibrium relative humidity (ERH), and the equilibrium moisture content of the material at a given temperature **[Appendix 4: Figure 1]** [2]. While mold germination occurs across a relatively tight band of water activity [3][4], due to the slow rate at which organic objects equilibrate to their prevailing RH, mold is often seen to occur across a broad range of relative humidity levels, making ambient RH alone a poor indicator for mold risk. Florian [5] states that the 'choice of lower than 70% RH to control fungal activity is arbitrary' and that further work is necessary to understand the interrelationship between collection objects, mold germination, water activity and their immediate environment.

For collections themselves, molds excrete enzymes and acids that can cause staining, weakening, and disintegration of organic materials, including wood, paper, textiles, animal hides and adhesives [6]–[10]. Germination can also occur on inorganic objects, such as stone [11][12] and glass [13][14], resulting in staining and etching of surfaces. Remedial treatments are limited, and once the physical integrity of the material is compromised through enzyme degradation, they are subsequently more vulnerable to (re)germination. For example, sizing components in paper provide a source of nutrients for molds that are readily digested by enzymes, which in turn makes paper more hygroscopic, providing a source of water for (re)germination [15][16]. Additionally, a lack of clarity on the risk of mold spores to human health has resulted in restricted access to collection materials [17], particularly following salvage operations, with those in vulnerable populations more frequently impacted by such restrictions [18]. Owing to these health concerns, staff are often reluctant to perform mold remediation and external contracts for this work can be expensive. In 1995, the Detroit Historical Museum reported a $900,000 emergency response price tag [19] , the equivalent of $1.8 million today for a single outbreak at one institution.

The Heritage Health Index [1] found that 57% of museums had experienced damage or loss within the two years prior to the survey caused by water or moisture. This was the most cited cause of damage and, under the rubric of the survey, included mold. While collecting institutions rarely publicize mold outbreaks, and therefore it is difficult to establish the scale of the issue, there have been some reports in the media on institutional closures ranging from local historical societies [20][21], art museums [22][23], university libraries [24], and rare book collections [25], highlighting the range of collections vulnerable to mold growth. These challenges are reflected in the **Letters of Support [Appendix 3]**, which demonstrate the experiences of those working with institutions and communities to preserve collections. As Fran Ritchie, objects conservator from the National Park Service (NPS) states, "Mold is a familiar foe to me, as I specialize in organic materials that are vulnerable to fungal growth, such as leather and skin. I receive monthly emails asking for advice regarding mitigation and feel this research project would benefit me as a conservator, and the NPS as a whole."

Unfortunately, mold outbreaks are likely to increase in frequency and severity due to climate change, with increased precipitation and flooding events predicted. As evidenced by the recent Preventive Conservation session at the 2023 ICOM-CC Triennial, which brought together speakers focusing on disaster recovery following floods [26][27], including mold remediation [28], flooding events are increasing in regularity across the globe, with collections placed at increasing risk. In the U.S., the regions likely to see the greatest impact of such events are located in the southeast [29][30], home to many of the Historically Black Colleges and Universities (HBCU), and other institutions with historically fewer resources, serving communities that are often under-represented.

Despite widespread damage, research into the prevention, proliferation, and mitigation of fungal growth within the context of collections has been limited [28][31][32]. The extensively cited publication by Florian [5] was published nearly 20 years ago, and one of the newest guidelines for environmental management in museums, galleries, archives, and libraries mentions mold when describing types of damage to collections [33], but relies on references dating from 1933 to 2001, in some cases originating from food industry applications. Other guidance documents recommend maintaining levels anywhere from below 40% to 75%RH in order to avoid mold germination [34][35][36]. Where airflow is cited, the use of fans is recommended, but the speed and duration required are not specified and no details are provided for assessing ongoing risk [37][17].

In light of the above, the proposed research aims to understand the risk of mold germination associated with managing collections environments sustainably, and establish safe emergency response when outbreaks do inevitably occur in collecting institutions.

UNDERPINNING RESEARCH

This research leverages IPI's experience and capabilities in preventive conservation research and sustainable environmental management. In the early 2000's, researchers at IPI developed an interactive mold growth metric designed to help collections management teams assess the likelihood of a mold outbreak based on temperature and relative humidity data collected in storage environments. This tool was derived from research undertaken in the food industry [38][39], which established there is an optimum temperature for which the least amount of water is required for mold to grow; as the temperature gets higher or lower, the minimum relative humidity required for growth increases. IPI's mold growth metric has been shown to be the most accurate of the available tools for predicting mold germination within museum collections [40]. However, there remain many unanswered questions relating to the role of temperature, relative humidity and other environmental factors, such as air flow, on the rate of germination on organic collection materials, especially in light of climate change and the drive for heritage institutions to meet local and national sustainability goals.

This proposed study builds on recent research funded by the National Endowment for the Humanities (NEH) and IMLS, which demonstrated that the equilibrium moisture content of a range of natural and synthetic polymers found in museum collections is dependent on both temperature and equilibrium relative humidity and varies significantly for different organic materials at the same conditions. That research found that there are temperature and ERH ranges where changes in moisture content were minimized and essentially constant. This is particularly relevant for understanding the relationship between material, environment, water activity and mold germination and the potential options for mitigation. The implication being that particular environmental combinations can be used to control moisture content, and therefore water activity of organic materials, which will limit germination.

PROJECT WORK PLAN

This project will consist of a three-year study on the relationship between water activity and rate of mold germination on organic materials found within museum, archive and library collections. The project will examine the factors influencing germination on paper and parchment, through simulated environments in the laboratory, and onsite analysis across different collection environments at the Colonial Williamsburg Foundation, VA. The laboratory experiments will establish the relationship between material, environment, equilibrium moisture content, water activity and rate of mold germination under controlled conditions. Onsite field analysis of commercially supplied, well-characterized paper and parchment samples, serving as project dosimeters and deployed at CWF, will provide a preservation-specific context to verify how these materials respond to controlled and uncontrolled historic collection environments. Combined, this information will inform current methodologies for sustainable environmental management and guide good practice for mitigating mold outbreaks.

The research questions to be addressed are:

- What impact do temperature and relative humidity have on the equilibrium moisture content and water activity of paper and parchment?
- How rapidly does mold germinate on paper and parchment when at equilibrium with specific environmental combinations and at a constant water activity?
- Can temperature and relative humidity combinations be identified that maintain water activities at sufficiently low levels to prevent mold germination in paper and parchment?
- To what degree can temperature and relative humidity fluctuate before water activity reaches a critical level for mold germination?
- What impact do seasonal fluctuations and sustainable environmental setpoints have on water activity?
- To what extent does airflow influence the water activity of paper and parchment and therefore the rate of mold germination?

METHODOLOGY, DATA COLLECTION AND DATA ANALYSIS

The research questions will be addressed through a series of complimentary laboratory-based experiments and fieldwork, which are designed to interrogate the rate of mold germination in paper and parchment when subject to static and dynamic environmental conditions.

Following **Phase One**, which will be dedicated to procurement and calibration activities, initial research **[Phase Two]** will focus on characterizing the microstructure and physical properties of the substrate test materials, namely paper (cellulose) and parchment (protein), with a view to understanding how the material characteristics influence their moisture response and potential influence on mold germination. These materials will be used as test substrates during the laboratory experiments and deployed as dosimeters during the fieldwork. Two groupings of these substrates will be used for project analysis, unaged and artificially aged samples. Their physiochemical characteristics will be assessed using attenuated-total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) and dynamic mechanical analysis (DMA), the former providing information on the molecular structure of the organic substrates, and the latter highlighting differences in the microstructure and environmentally influenced properties of each substrate (such as the softening temperature). Surface properties will be characterized using microscopy and gloss measurements, microscopy providing a qualitative assessment of surface characteristics, and gloss measurements providing a quantitative measure of surface specular reflectance, and therefore affording an indirect measure of surface

roughness [41]. Surface features influence the entrapment of dust and dirt, which can contribute to higher rates of mold germination.

Following initial characterization, **Phase Three** will establish the relationship between temperature, relative humidity, equilibrium moisture content and water activity. This work will follow a methodology previously established at IPI **[see Underpinning Research]** employing a moisture content analyser (owned by IPI), a water activity meter, and IPI's climate-controlled walk-in chamber. **Phase Four** will run concurrently, during which sample substrates will be subject to different isothermal and isohume conditions[3] and the rate of germination determined for two genera of mold, namely A*spergillus and* P*enicillium* [42]. Owing to health and safety reasons, Phase Four will be undertaken by the College of Public Health, Georgia Southern University. The results will determine the relationship between water activity and growth rate.

Phase Five will establish the relationship between water activity of the substrates and single-sided nuclear magnetic resonance relaxometry (SS-NMR), to allow for time-resolved and depth-resolved measurements during dynamic environmental control. SS-NMR is a non-invasive, portable technique that detects and quantifies the presence of protons (in this case hydrogen in water molecules). The technique enables 50 µm cross-sections to be analyzed up to a depth of 5 mm into a material in real-time. The information acquired relates directly to the presence of hydrogen, offering the potential to understand the surface stratigraphy of organic materials, and to monitor the rate of moisture equilibrium, water activity, and material relaxation properties in the presence of water **[see Appendix 4: Figures 2-4]**. The amplitude of the SS-NMR signal is a measure of the hydrogen density and is used to quantify moisture content in real-time, making it ideal for monitoring water activity in changing environments. This technique has been successfully applied in the food industry to monitor water activity in food stock and food additives [43][44]. The relationship between water activity and the SS-NMR relaxation signal established by **Phase Five [Appendix 4: Figure 5]** will be modeled alongside the material characteristics, equilibrium moisture content, and rate of mold germination using multivariate statistical techniques to enable prediction of germination rates relative to static and dynamic environmental conditions. This analysis will further support *in situ* measurements during **Phases Six and Seven**.

Phases Six and Seven are designed to investigate the impact of environmental fluctuations and air flow on water activity in real-time. **Phase Six** will run for 12 months, focusing on the onsite analysis of paper and parchment samples serving as dosimeters deployed at Colonial Williamsburg Foundation. Dosimeters will be located in representative collections environments across the site and changes in water activity (Aw) and local temperature, RH, airflow and surface contamination will be monitored periodically[4] to understand how Aw changes with seasonal fluctuations. This will provide information on the potential for mold growth on organic objects when on open display in controlled and uncontrolled environments. Additionally, the environmental data will be used to inform the test parameters in **Phase Seven**. During **Phase Seven**, paper and parchment samples will be subjected to simulated environmental fluctuations, including those employed during sustainable HVAC operation, in a climate-controlled walk-in chamber and water activity monitored in real-time using the SS-NMR. This will systematically interrogate the various parameters influencing mold germination and provide insights into their optimization to avoid germination during sustainable environmental management of collections. Please see **Appendix 4: Figure 6** for a schematic illustrating how the analysis undertaken in each Phase of work intersects.

[3] Isothermal and isohume describe constant temperature and relative humidity conditions, respectively

[4] Using a water activity meter, environmental data loggers, an anemometer, and ATP luminometer

RESEARCH PHASES

The project will run according to the **Schedule of Completion**, with some tasks running simultaneously. The conclusion of each Phase completes a milestone, enabling effective management and progression as mapped in the **Performance Measurement Plan**. Data analysis will be undertaken throughout each phase of work to allow for adaption of experimental methodologies. Potential risks that may impact effective progression of the project are outlined in the **Risk Log [Appendix 5]** along with mitigation actions. All data will be managed as laid out in the **Data Management Plan**.

PHASE ONE: Preparation (3 months)

Purpose/Activities: The first 3 months of the project will be devoted to confirming the methodology and procurement. Phase One will involve a number of concurrent activities, including: i) procurement of the SS-NMR, water activity meters, and environmental loggers, ii) procurement of paper and parchment sample substrates, iii) initiation of the sub-award with Georgia Southern University, and iv) calibration of the climate-controlled walk-in chamber, incubation chambers, and the DMA.

Time/Resources: Dr Emma J Richardson will lead procurement and calibration activities in Phase One.

PHASE TWO: Artificial Aging, Characterization and Deployment of Dosimeters (4 months)

Purpose/Activities: The goals of Phase Two are to prepare artificially aged paper and parchment substrates and to undertake subsequent characterization of a representative set of test substrates (unaged and aged) prior to analysis in later Phases of work. These materials have been selected to represent substrates routinely colonized by fungi in historic collections [8]. Lignin-free, sized paper[5] and goatskin parchment[6] will be purchased, constituting materials vulnerable to germination [42].
A series of paper and parchment substrates will be artificially aged using IPI's incubation laboratory following previously established methodologies from the field [45][46], and the ASTM method for the accelerated aging of paper [47]. Prior to incubation, the surface of the materials will be sterilized with 70% ethyl alcohol to prevent unintentional germination of biofilms [5]. This method of sterilization has been shown to have no detrimental effect on the physical properties of paper and parchment [42].
Test substrates will subsequently be characterized using ATR-FTIR, DMA, microscopy and gloss measurements, providing a baseline understanding of the unaged and aged material properties, and enabling differences in equilibrium moisture content, water activity and rates of mold germination to be attributed to their physiochemical attributes, supporting future guidelines for mitigating germination on vulnerable materials.

Time/Resources: Following initial sample preparation and sterilization, artificial aging will be undertaken using the IPI incubation chambers and will run over the course of 2 months. Concurrently, a representative subset of unaged (and subsequently aged) samples will be characterized. Dynamic mechanical analysis with low temperature capabilities and a humidity controller will be used to determine the softening temperature and moisture response of the substrates, respectively. Each test takes 2 hours in total, with the sample chamber holding one sample per experiment, necessitating testing in succession over the course of 4 months. Data will be analyzed throughout the test period.

[5] Paper will be a lignin-free, gelatin-sized wove cotton rag paper, provided by Shepherds bookbinders, dating circa 1950 and selected to closely represent historic paper technology.
[6] Parchment will be a contemporary goat hide, prepared to order from Pergamena, and selected to ensure the most consistent surface properties across the sample set.

All incubation equipment for the artificial aging regime and analytical instrumentation for the characterization work are available at IPI and RIT.
Dr Emma J Richardson and the Sustainable Preservation Specialist will collectively lead the substrate aging regime and material characterization for Phase Two.

PHASE THREE: Establishing the Relationship Between Temperature, Relative Humidity, Equilibrium Moisture Content and Water Activity (7 months)

Purpose/Activities: The goal of Phase Three is to establish the relationship between temperature, relative humidity (RH), equilibrium moisture content (EMC) and water activity (Aw) for the substrates. Phase Three will establish sorption isotherms **[Appendix 4: Figure 1]** for each material at different temperatures commonly encountered in controlled and uncontrolled collection environments, mapping the EMC and Aw of these organic substrates at set temperature and relative humidity combinations. Developing sorption isotherms that span an extended range of temperature and RH conditions expands the application of the calibration data, facilitating future research into different fungal species[7] specific to given geographic locations.
The samples prepared in Phase Two will be exposed to a series of isothermal and isohume conditions, and the EMC and Aw will be measured using a moisture content analyzer and a water activity meter. Conditions will be maintained using IPI's climate-controlled walk-in chamber and the samples allowed to equilibrate for two weeks prior to measuring the EMC and Aw. As outlined above, substrates will be sterilized with ethyl alcohol prior to conditioning within the climate-controlled walk-in chamber.

Substrate	Isothermal Temperature Setpoints/°C	Isohume RH Setpoints/%	No. Samples (Incl. Replicates)
Unaged Paper	15 20 25	40% 50% 60% 70% 80%	45
Aged Paper			45
Unaged Parchment			45
Aged Parchment			45

Table 1: Summary of the Phase Three experimental parameters and samples

Time/Resources: The rate of equilibrium at each relative humidity will be determined during Phase Two, with two weeks allocated for initial conditioning at each temperature and RH setpoint. Paper and parchment substrates will be exposed to 15 environmental conditions and conditioned concurrently. The total duration of Phase Three will be 7 months. Climate-controlled walk-in chamber and the moisture content analyzer are available at IPI. The water activity meter will be purchased during Phase One.
Dr. Emma J. Richardson and the Sustainable Preservation Specialist will collectively lead the experimental portion of Phase Three, with Dr Marvin Cummings taking responsibility for data analysis and hygroscopic mapping.

PHASE FOUR: Understanding the Rate of Germination at Isothermal and Isohume Conditions (Sub-recipient, 12 months, concurrent with Phase Three)

Purpose/Activities: The goal of Phase Four is to establish the rate of mold germination on two organic substrates, paper and parchment, when subjected to different temperature and relative humidity setpoints. The paper and parchment substrates prepared in Phase Two will be intentionally contaminated with two species of mold, exposed to a series of isothermal and isohume conditions,

[7] While the reaction rates of fungi germination increase with water activity, until an upper limit is reached, the xerophilic species of fungi are capable of germination at low Aw. For example, the xerophilic *A. peniciloides* is shown to germinate as low as Aw 0.585, equating to an ERH of 58.5% [50].

and the time required for the mold to grow will be determined. Relative humidity levels will be maintained at set temperatures using saturated salt solutions and the water activity of each substrate monitored throughout the germination period. Substrate surfaces will be imaged prior to testing and following germination. The high degree of variability during mold germination necessitates a minimum of six replicates per experiment. As such, due to time constraints, the substrates tested during Phase Four will be restricted to unaged paper and parchment[8]. Later Phases of work will interrogate the relationship between material characteristics, environment and water activity.

Substrate	Mold Species	Isothermal Temperature Setpoints/°C	Isohume RH Setpoints/%	No. Samples (Incl. Replicates)
Unaged Paper	Aspergillus *niger*	15 20 25	40% 50% 60% 70% 80%	90
Unaged Paper	Penicillium *brevicomactum*			90
Unaged Parchment	Aspergillus *niger*			90
Unaged Parchment	Penicillium *brevicomactum*			90

Table 2: Summary of the Phase Four experimental parameters and samples

Time/Resources: Phase Four will be undertaken by the project sub-recipient, Georgia Southern University, over 12 months concurrent with Phase Three. The data generated from Phase Three and Phase Four will be collectively analysed by IPI and GSU.
Dr Atin Adhikari, Associate Professor of Environmental Health Sciences at the College of Public Health, Georgia Southern University, will oversee Phase Four activities. Please see **Sub-recipient Scope of Work** and **Budget Justification** for details.

PHASE FIVE: Establishing the Relationship Between Water Activity and the SS-NMR Relaxation Time (6 months)

Purpose/Activities: Phase Five will establish the relationship between water activity and the relaxation signal generated by the single-sided nuclear magnetic resonance relaxometer. Following isothermal and isohume conditioning, substrates will be analyzed using a SS-NMR relaxometer and a Carr-Purcell-Meiboom-Gill (CPMG) echo radiofrequency pulse sequence [17][18] to obtain echo signals through the depth of each substrate, creating spatial profiles of effective spin-spin relaxation time (T_{2eff}). This will produce time- and depth-resolved information on water activity during dynamic environmental control, aiding optimization of sustainable environmental management.
The data generated during Phases Two, Three, Four and Five will be collectively analyzed using multivariate analysis (MVA) to develop a prediction versus measured calibration model to establish the relationship between material characteristics, equilibrium moisture content, water activity, $T_{2eff,}$ and germination rate. The use of MVA will allow subsequent Aw and SS-NMR sample measurements to be regressed against the calibration, enabling prediction of germination rates relative to changing environmental conditions.

Substrate	SS-NMR Experiment	Isothermal Temperature Setpoints/°C	Isohume RH Setpoints/%	No. Samples (Incl. Replicates)
Unaged Paper	CPMG (T_{2eff})	15 20 25	40% 50% 60% 70% 80%	45
Aged Paper	CPMG (T_{2eff})			45
Unaged Parchment	CPMG (T_{2eff})			45
Aged Parchment	CPMG (T_{2eff})			45

Table 3: Summary of the Phase Five calibration parameters and samples, finalized following review of preceding data

[8] While it is acknowledged that the majority of materials housed in historic collections have undergone some form of aging, no single method of artificial aging will capture all mechanisms of degradation. As such, understanding the fundamental germination behaviour of new substrate materials exposed to different collection environments will provide a robust foundation for correlating mold growth with water activity.

Time/Resources: Phase Five will utilize IPI's climate-controlled walk-in chamber and the SS-NMR purchased through this grant. Paper and parchment substrates will be conditioned concurrently in the walk-in chamber. Experimental parameters will be finalized following review of data from Phase Two, Three and Four. Following equilibrium, each sample will be analyzed sequentially to establish SS-NMR relaxation times. A total duration of six months is estimated for the completion of Phase Five.
Dr. Emma J. Richardson and the Sustainable Preservation Specialist will collectively lead the experimental portion of Phase Five, with Dr Marvin Cummings taking responsibility for data analysis and multivariate statistical analysis.

PHASE SIX: Analysis of Dosimeters Deployed in the Field (12 months, concurrent with Phases Three, Four and Five)

Purpose/Activities: Phase Six will interrogate the impact of controlled and uncontrolled display environments on the water activity of paper and parchment dosimeter substrates deployed on open display at the Colonial Williamsburg Foundation. Dosimeters[9] will be placed at three different indoor locations across this historic site **[Table 4]** and their microenvironments continuously monitored using temperature and RH loggers. Changes in water activity, airflow, and surface contamination of the dosimeters will be measured *in situ* periodically, providing information on the potential for mold growth on organic objects on open display. The factors considered when identifying sampling locations at CWF included the building envelope, environmental control, the potential for sustainable operation of the mechanical system (if present), the level of occupancy, and potential risk of mold germination **[Appendix 4: Figures 7 and 8]**. The information gathered onsite at CWF will directly inform the test parameters employed during Phase Seven.

Substrate	Location	Indoor Environment	No. Samples (Incl. Replicates)
Unaged & Aged Paper	Powell House	Uncontrolled historic house environment, closed to the public	30
Unaged & Aged Parchment	Powell House	Uncontrolled historic house environment, closed to the public	30
Unaged & Aged Paper	Thomas Everard House	Mechanically controlled historic house environment, open to the public	30
Unaged & Aged Parchment	Thomas Everard House	Mechanically controlled historic house environment, open to the public	30
Unaged & Aged Paper	DeWitt Wallace Decorative Arts Museum	Mechanically controlled new built environment, open to the public	30
Unaged & Aged Parchment	DeWitt Wallace Decorative Arts Museum	Mechanically controlled new built environment, open to the public	30

Table 4: Summary of the sampling locations and number of samples to be deployed at CWF during Phase Six

Time/Resources: This Phase of research will be undertaken onsite at the CWF, spanning a 12-month period concurrent with Phases Three, Four and Five. A total of 180 dosimeters will be deployed and analyzed on a bi-weekly basis using a water activity meter, anemometer for air flow measurements and an Adenosine Triphosphate (ATP) luminometer surface contamination meter. See **Budget Justification** for further details.
Kelly McCauley Krish, Preventive Conservation Manager at Colonial Williamsburg Foundation, will consult on this project **[see Budget Justification and Appendix 6: Quotations]** and lead the field analysis activities at the CWF historic site. Dr Emma J Richardson and Dr Marvin Cummings will incorporate the data acquired onsite at CWF with data from Phases Three, Four and Five.

[9] Commercially supplied, well-characterized paper and parchment samples, serving as project dosimeters

PHASE SEVEN: Monitoring Real-time Water Activity in Simulated and Real Environments (12 months)

Purpose/Activities: The goal of Phase Seven is to monitor real-time water activity of paper and parchment samples while subject to simulated temperature and relative humidity fluctuations and real environments. Phase Seven will use SS-NMR to monitor real-time changes in T_{2eff} as the environment in the climate-controlled walk-in chamber is fluctuated. Coupled with the multivariate calibration established in Phase Five, these experiments will assess the potential for mold germination on each substrate when exposed to different environmental scenarios. The precise parameters for the simulated experiments will be informed by the results of the onsite monitoring during the field analysis in Phase Six, but will include simulation of intentional short-term temperature and RH setbacks aimed at sustainable environmental management, an evaluation of seasonal fluctuations, conservation heating practices, and increased airflow. These parameters will be designed to inform decision making when implementing sustainable HVAC operations and emergency response.
During this Phase, two weeks of SS-NMR field analysis will be conducted onsite at CWF, to supplement the water activity measurements undertaken during Phase Six, and support validation of the simulated environmental experiments.

Time/Resources: Phase Seven will utilize IPI's climate-controlled walk-in chamber and the SS-NMR purchased through this grant. The SS-NMR analyzes one sample per experiment, therefore paper and parchment substrates will be analysed sequentially under each simulated environment. The SS-NMR and precision lift can be automated to allow continuous analysis over extended periods of time. The expected duration of Phase Seven is 12 months.
Dr Emma J Richardson and the Sustainable Preservation Specialist will collectively lead the experimental portion of Phase Five, Dr Emma J Richardson will travel to CWF to undertake the onsite analysis, and Dr Marvin Cummings will undertake the data analysis and modeling.

PHASE EIGHT: Analysis, Dissemination, and Pathways to Impact (4 months)

Purpose/Activities: Data analysis will be undertaken throughout each phase of work, with Phase Eight drawing together and summarizing the results for the collections care community. Key findings will be synthesized into a free to download good practice guide for preventing mold outbreaks during sustainable environmental control and emergency response, made available online from IPI's preservation research webpages (https://www.imagepermanenceinstitute.org). The results will be further disseminated through a free, online workshop, outlining the good practice guidelines. The target audience for this workshop will be those working with collections vulnerable to mold, namely small to medium-sized museums and historic houses with limited control of the environment, National and Regional Preservation Organizations, and heritage emergency responders. Additionally, facilities teams from larger institutions will be invited to participate, particularly where mechanical system operations can be modified to incorporate sustainable environmental management strategies. The methodology, analysis, and calibration of the dosimeters will be published in two journal articles, one aimed at the collections care community, and the second published as a technical paper focused on disseminating the experimental methodology. This will enable analogous paper and parchment samples to be deployed by other collecting institutions as early warning indicators for mold germination and will support research into other types of organic collection materials. Please refer to the **Budget Justification** for more details.

Time/Resources: The duration of Phase Eight will be four months and the entire project team will participate in the collation and interpretation activities, and the publication of results.

Investigating the Prevention of Mold Germination in Museum Collections During Sustainable Operations and Emergency Response

Image Permanence Institute, Rochester Institute of Technology

Schedule of Completion

	Year One				Year Two				Year Three			
Activity	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Phase 1: Preparation												
Image Permanence Institute												
Phase 2: Artificial Aging, Characterization and Deployment of Dosimeters												
Image Permanence Institute												
Phase 3: Establishing the Relationship Between T, RH, EMC and Aw												
Image Permanence Institute												
Phase 4: Rate of Germination (See SoW from Sub-recipient)												
Georgia Southern University												
Phase 5: Establishing the Relationship Between Aw and SS-NMR T2eff												
Image Permanence Institute												
Phase 6: Analysis of Dosimeters Deployed in the Field												
Colonial Williamsburg Foundation/Image Permanence Institute												
Phase 7: Monitoring Real-time Aw in Simulated & Real Environments												
Image Permanence Institute/Colonial Williamsburg Foundation												
Phase 8: Analysis and Dissemination												
Image Permanence Institute/Georgia Southern University/Colonial Williamsburg Foundation												

PERFORMANCE MEASUREMENT PLAN				
Performance Measure	**Data We Will Collect**	**Source of Our Data**	**Method We Will Use**	**Schedule**
Effectiveness: The extent to which activities contribute to achieving the intended results	• This project will follow a waterfall project management approach. • Monthly project meetings will be held between the IPI team and CWF to review results and identify changes to the methodology based on the aims of each the laboratory and field experiments. • The end of each research Phase completes a milestone, with defined deliverables that will be mapped against the original project plan. • At the end of each research Phase the data will be collated, analysed and presented to the project team for review prior to the initiation of the next Phase of work. • The interdependencies of each Phase of laboratory experiments necessitates successful completion of the individual Phases in sequence to support experimental design. For example, at the end of Phase Two it is required that artificial ageing of substrate materials and their characterization is complete prior to initiating the EMC and Aw experiments in Phase Three. Additionally, the results from Phase Three will directly inform the analysis of the single-sided nuclear magnetic resonance experiments in Phases Five and Seven.			
Efficiency: How well resources (funds/expertise/time) are used and costs are minimized while generating maximum value for the target group	• Monthly project meetings will be held to assess progress towards data collection and analysis against projected delivery. • Each month the PI will map financial expenditure against the original project profile and adjust spending expectations as required. • The subrecipient PI be responsible for expenditure during Phase Four and provide financial reports to RIT for annual IMLS reporting.			
Quality: How well the activities meet the requirements and expectations of the target group	• As outlined in the Data Management Plan, requirement statements and success criteria will be captured at the beginning of the project for each Phase of work, outlining **what** will be implemented rather than how it will be implemented. • At the end of each research Phase these statements will be used to benchmark success and validation of the process. Validation will assess whether each Phase has met the overall aim and whether it has delivered on the specifications. • Where changes to the experimental design are required, these will be formally agreed to by the Project Team, documented and reported as exceptions in annual reports. • When exceptions change the intended impact of the research, these will be immediately reported to IMLS.			
Timeliness: The extent to which each task/activity is completed within the proposed timeframe	• Each month the PI will map time expenditure against the original project profile and adjust delivery and workload as required. • Annual interim reports on project progress will be submitted by the PI to IMLS for review.			

DATA MANAGEMENT PLAN

Following initial artificial aging of test materials, characterization will be undertaken using thermal analysis, infrared spectroscopy, surface measurements and microscopy. This will generate .csv files relating to the thermal properties, spectral absorbance and reflectance properties, and .tiff and .jpeg image files. Each set of data will be used to understand the properties of the starting materials, which will aid interpretation of the later experimental results. IPI will collect temperature, relative humidity (RH), equilibrium moisture content (EMC), and water activity (Aw) data during the laboratory-based research activities, which will enable the relationship between these four parameters to be determined for each sample. This data will be collected during the first 14 months of research and the RH, EMC and Aw at each temperature setpoint will be used to highlight environmental combinations where safe EMC and Aw levels can be maintained. This data will be combined with that gathered in later phases to establish guidance on environmental controls for mold prevention in organic collections.
Years two and three will generate data on mold germination rates, and Aw and relaxation times for materials subject to fluctuating environments, with each dataset saved as .csv format with accompanying temperature and RH .csv files. This information will be coupled with the material characteristics and equilibrium moisture content data and interrogated using multivariate statistical techniques, namely principal component analysis and partial least squares establish prediction models. These models will enable unknown samples to be regressed against these calibration models, enabling future predictions of mold germination rate relative to environmental conditions.

INTELLECTUAL PROPERTY RIGHTS AND PERMISSIONS

Raw data is not copyrightable. The derivatives from the data will be made available through Creative Commons under a CC BY NC - attribution and non-commercial use. Publications of this work will include the statement: “except where otherwise indicated, this XXX is licensed under CC-BY-NC”

DIGITAL CONTENT

IPI will collect temperature and relative humidity data during the laboratory activities. This will be accompanied by data on physical properties of materials, including spectra, thermographs, micrographs, moisture content and water activity files. Due to the number of TIFF images generated by microscopy, we estimate we will collect approximately 300 GB of data.

Software used to create the digital content will be Shimadzu LabSolutions IR v.1.10; TA Instruments Trios software v.5.3; X-rite ExactXP DataCatcher 1.3; HW4-P QuickSoftware; Magritek Prospa software; Camo UnscramblerX software v.10.5.1; MathWorks MatLab software v.R2020b. Digital File formats will include CSV, TIFF, JPEG, DOC and PDF and will be accessible by anyone with programs capable of opening these file types.
Comma Separated Values (CSV) files. The CSV format is an open standard maintained by the Internet Engineering Task Force (IETF) for use by anyone. Because it is an open standard, the data will be available for reading for many years after collection without relying on proprietary software.
Tagged Image File Format (TIFF) for storing and interchanging raster images. The format is widely supported by image-manipulation applications (Adobe Photoshop and many others), by desktop publishing and page layout applications (QuarkXPress, Adobe InDesign, and others), and by scanning, faxing, word processing, optical character recognition, and other applications. The TIFF 6.0 standard recommends the use of tif (or TIF) as extension.
JPEG is a File Interchange Format (JFIF) is a minimal file format that enables JPEG bitstreams to be exchanged between a wide variety of platforms and applications. It is very widely adopted. It does not include any of the advanced features (like tagged headers) found in the TIFF specification.

DOCX is a Microsoft Word document that typically contains text, based on XML. Because it is based on XML it is widely-used and publicly documented.
Portable Document Format (PDF) files developed by Adobe, offering searchable text, lossless compression and high resolution images.
Reference:
Format Description Categories - Sustainability of Digital Formats | Library of Congress (loc.gov)

DATA QUALITY CONTROL PLAN

Requirement statements and success criteria will be captured for each Phase of work, outlining what will be implemented rather than how it will be implemented.
These specifications will be agreed by each team member and will provide a benchmark for evaluation of success and validation of the process. Validation will assess whether each phase has met the overall aim and whether it has delivered on the specifications.
During Phase Two a unified nomenclature of samples and naming conventions for files will be documented.
The Library of Congress recommendations for metadata capture will be followed for each data type. Where the metadata is not integrated into the file format, as a minimum the metadata will be provided separately in external text XML-based file (DOCX).
Document control pages will be included containing details of version, status (draft, released etc), review date, reviewer names, actions.
README FILES will accompany all folders indicating what the folders contain and enabling other users to navigate the directory.
Graphs will be linked to the software version and associated data files through inclusion of footnotes and/or headers on each output.

ACCESS AND USE

All data will be stored on IPI's file storage cluster, maintained by the RIT College of Art and Design's technology department. An automated process creates daily backups of all data, which is routinely verified. The college has provisioned a large amount of space for file storage and there are no concerns about storage limits or data retention associated with this project. Each document will contain a control page outlining the administrative and/or technical information relating to the data following the Dublin Core Schema: DCMI: DCMI Metadata Terms (dublincore.org). A domain-agnostic list of core metadata properties chosen for the accurate and consistent identification of data for citation and retrieval purposes. Long-term storage and data migration is managed centrally by RIT College of Art and Design.

The research conclusions will be summarized and published on IPI's website and in peer-reviewed publications. Original research data will remain accessible on IPI's server cluster. We will not collect any personal or proprietary information during the project. The RIT College of Art and Design reviews their backup plan annually to ensure business continuity. Additionally, backups are continually monitored for issues. This DMP will be reviewed annually throughout the lifetime of the project once the experimental work and data analysis is underway to ensure continued relevance and to capture appropriate changes.