National Leadership Grants for Museums

Sample Application MG-251607-OMS-22

Rochester Institute of Technology

Amount awarded by IMLS:	$711,598
Amount of cost share:	$0

The Image Permanence Institute at the Rochester Institute of Technology will research approaches that help support the physical stability of plastics and plastic composite materials in museum collections. Objects such as modern and contemporary artworks, design, fashion, and ethnographic items often include plastics, as do the storage materials used for photographs. The project team will use multiple types of analyses, including a case study, to assess the effect of microscopic changes in humidity on the physical structure of two types of plastics commonly found in museum collections. The project will establish safe preservation and handling conditions for these plastics, specifically temperature and relative humidity. They will share findings through journal articles, conference presentations, and a web publication.

Attached are the following components excerpted from the original application.

- Narrative
- Schedule of Completion
- 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 and project category (if applicable) to which you are applying.

Mapping Environmental Conditions That Prevent Plastic Deterioration
While Contributing to Sustainable Preservation Environmental Management

Image Permanence Institute, Rochester Institute of Technology

NARRATIVE

The Image Permanence Institute (IPI) at Rochester Institute of Technology is applying for a National Leadership Grant for Museums to support a three-year research project that will study the relationship between equilibrium moisture content (EMC) and the physical stability of plastics and plastic composite artifacts found in museums. Plastic objects, including modern and contemporary artworks, design, fashion, and ethnographic items, as well as photographic supports, form a significant portion of our modern cultural heritage and exist in all collections containing twentieth and twenty-first century materials. The field has developed methodologies for the identification and characterization of plastics, and there are numerous resources available on these topics. However, despite an observed awareness of the chemical and physical instability of most plastics an in-depth understanding of the chemical and physical degradation of plastics and possible mitigation strategies is limited. Therefore, resources to inform preservation planning for plastics in collections are scarce.

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 environmental conditions on the physical stability of plastic artifacts. This will be a comparative study focusing on two major classes of plastics commonly found within museum and heritage collections, namely cellulose acetate and polyurethane, and will assess their physical response to changes in equilibrium moisture content (EMC). EMC represents the amount of moisture in hygroscopic materials when they are at equilibrium with their ambient environmental conditions. Changes in temperature and relative humidity cause hygroscopic materials, such as plastics, to absorb and desorb moisture accordingly. These changes can impact the physical stability of materials. This project will address gaps in our knowledge of plastic deterioration and how best to mitigate physical damage related to environmental conditions. Ultimately, the results will inform guidelines for sustainable preservation environmental management of plastics and plastic composite artifacts, by identifying a range of temperature and relative humidity conditions that provide safe EMC conditions for plastics, and ensure museums and other collecting institutions can preserve and provide access to these modern materials long-term.

Project Justification

The twentieth and twenty-first centuries would be unrecognizable if plastics did not exist: these ubiquitous modern materials emblemize our everyday, consumer-driven culture, and can be found in all areas of life, including art. As such, plastic artistic objects, including not only modern and contemporary artworks, but also design, fashion, ethnographic items, as well as photographic supports, form a significant portion of our modern cultural heritage. Such artifacts require preservation, however, a comprehensive understanding of the extent of instability and the broader issues surrounding their preservation in cultural heritage has matured only in the past two decades. Contextually, a research branch focused on the care of plastic objects in artistic and historical collections has progressively grown. While the Image Permanence Institute (IPI) was at the forefront of research into the degradation of semi-synthetic cellulose-based film [1-4], only sporadic studies into other plastics were carried out during the 1990s [5-7], with a systematic approach to this challenge only taking hold in the 2000s [8-10]. An important milestone in this context was the POPART (Preservation Of Plastic ARTefacts in museum collections) project, a 42-month international research project partially funded by the European Commission [11, 12], which aimed at defining widely accepted strategies of preservation and maintenance of plastic artworks in museum collections. The Principal Investigator of this current proposal was a member of the POPART consortium and amongst the priorities singled out within that research project was a need to understand exposure and response of plastics to environmental stressors [13]. While the field has developed methodologies to identify and characterize the different types of degradation in plastic artifacts, an in-depth understanding of the routes to degradation and potential mitigation is currently limited.

Although research into the chemical stability of plastic materials has become commonplace [14-17], research into the physical response of plastic artifacts to their collection environments and safe working conditions is lacking and highlighted as a priority by leading figures in plastics conservation [11, 18]. The primary agents of instability for plastic artifacts within the indoor environment are temperature and moisture content. Cold storage of plastic materials in collections is recommended as a means of reducing the rate of degradation for the most problematic plastics [19, 20] and relative humidity is recommended to be kept below 50% [3, 21] due to hydrolysis playing a major part in chemical degradation. It has long been understood that environmental fluctuations cause physical change to objects owing to their thermal coefficients of expansion and changes in moisture content as they equilibrate to their surroundings. The resulting expansion and contraction does not necessarily cause damage; the impact to the object is often reversible. However, under certain circumstances irreversible physical change occurs, often displayed as buckling, crazing and delamination [Appendix 3, Figures 1-3]. The extent to which these changes induce irreversible damage is dependent on a number of factors beyond the environment, such as the underlying chemical composition of the material and the size, shape and complexity of the object.

Over the past 150 years there have been a myriad of plastics developed for market, resulting from extensive experimentation with different polymers and additive components. It is therefore surprising that the conservation field has largely overlooked the role that both the structural form of an object and chemical components play in moisture permeation into plastics and the subsequent physical impact on plastic composite artifacts. This is especially true given that in some cases additives can comprise more than a third of the final plastic material. The authors are aware of only one study interrogating the impact of environmental changes to three-dimensional plastic artifacts [19, 20]. In this study the primary focus was the linear coefficient of expansion due to temperature change. Of the papers that have studied the effects of additive components the majority have focused on the chemical instability of the polymer [22, 23] rather than the environmental moisture response and concomitant physical alterations. There has been some research into the relationship between chemical composition, moisture sorption and mechanical change undertaken in the food packaging industry [24-26], however the working lifetime of such materials differs greatly from those of cultural heritage collections.

Determining the mechanical properties of plastics at given temperature, RH and EMC provides a pathway to predicting material behaviour in different collection environments. That knowledge can then inform guidelines for dynamic environmental management to achieve energy-savings, as well as the coordination of temperature and relative humidity conditions between storage, display and use spaces that reduce, if not eliminate, plastic artifacts experiencing physical responses to changing environmental conditions. As Ken Sutherland, Andrew W. Mellon Director of Scientific Research, Art Institute of Chicago states [Appendix 2, Letters of Support], “such data will be essential to optimize protocols and develop recommendations for storage, handling and use, balancing preservation concerns with practical considerations of collections access and issues of environmental sustainability."

It is readily accepted within the field that the five most problematic classes of plastics (Polymer Classes) within museums and modern collections are cellulose nitrates, cellulose acetates, polyvinyl chlorides, polyurethanes and rubbers. In this project two classes of polymer, namely cellulose acetate and polyurethane, will be studied with historically appropriate additive components [Table 1]. The rationale behind this selection is that they will allow for a range of material and object characteristics to be interrogated. Namely, assessing the influence of the polymer class and the polymer subclass, the impact of the physical form of the material and the influence of different additive components. These materials will act as proxies for plastics with similar compositional and physical characteristics and will enable future assessment of how such factors influence EMC and mechanical response.

Polymer Class	Polymer Sub-class	Acronym	Physical Form	Characteristics
Cellulose Acetate	Diacetate	CDA	2D Film	Unplasticized
				Plasticized
Cellulose Acetate	Triacetate	CTA	2D Film	Unplasticized
				Plasticized
Polyurethane	Polyester	PUR-PEs	3D Foam	No Surfactant
				Surfactant
Polyurethane	Polyether	PUR-PEt	3D Foam	No Surfactant
				Surfactant
Gum Arabic	Polysaccharide	GA	2D Paint Layer	Plasticized

Table 1: Polymer class and physical characteristics to be interrogated for their influence on equilibrium moisture content and mechanical response

Underpinning Research

This research leverages IPI's experience and capabilities in preservation management. It builds on recent research, funded by the National Endowment for the Humanities (NEH), which demonstrated that the moisture content of a range of archival materials is dependent on both temperature and RH and varies significantly for different materials at the same conditions. That research found that for the materials studied, there were temperature and RH combinations within which changes in moisture content were greatly reduced. The implication being that transferring objects from cold storage to warmer temperatures for use or display may result in differing moisture contents, but this can be mitigated if RH is appropriately controlled during changes in temperature. This has particular relevance for plastic objects that are routinely moved from use or display conditions into cold and freezing storage conditions.

In a further study funded by NEH, IPI investigated the use of a novel imaging technique, Digital Image Correlation (DIC), to study the mechanical response of paper-based materials to changes in relative humidity (RH). The project highlighted the applicability of DIC for assessing the real-time response of objects in changing environments and found a clear relationship between percentage change in RH and the resulting strain of the paper-based materials; as the RH changed by 10% there was a concomitant doubling of strain. It is unlikely the same behaviour will hold for all materials but identifying a similar response for each plastic material would support future modeling of mechanical properties.

In preliminary moisture sorption/desorption studies into plastic film, it has been demonstrated that at relative humidities above 40% the amount of moisture absorbed by different compositions of cellulose acetate film increases rapidly and differentially. In one example, a cellulose diacetate film containing the fire retardant triphenyl phosphate (TPP) exhibited an increase in mass of 2.8% when exposed to 50% RH following initial conditioning at 30% [Appendix 3, Figure 4]. By comparison, a pure cellulose diacetate film showed a 4.2% mass increase under the same conditions. At 70% RH the same films increased in mass by 11.8% and 20.8% respectively. These vastly different sorption behaviours will result in differing degrees of expansion and contraction. However, change does not always constitute damage and defining acceptable working limits of deformation necessitates an understanding of the elastic (reversible) response of the materials and their ductile and brittle behaviour.

Moisture response and associated physical properties will be interrogated within the proposed project with a view to identifying safe working ranges for EMC of plastics, resulting in sustainable environmental management guidelines for museum collections that aim to limit physical damage to modern materials while allowing safe variations in temperature and relative humidity conditions. This will support museums in implementing dynamic environmental management and energy-saving strategies that drive down costs without compromising on collections care.

Project Work Plan

This project will consist of a three-year study on the relationship between equilibrium moisture content (EMC) and the mechanical response of plastics and plastic composite artifacts. The project will examine plastics on multiple scales, and the following terminology will be used to ensure clarity when discussing project activities and goals. Plastic materials will be used to refer to specific plastics, each consisting of a combination of organic polymers and various additives, such as plasticizers and fire retardants, which endow the plastic with highly varied properties and behaviours. Examples of plastic materials present in museum collections include Bakelite (phenol formaldehyde) [Appendix 3, Figure 5], Plexiglass (acrylic), Celluloid (cellulose nitrate), and Nylon (polyamide). Plastic composite artifacts will be used to describe artifacts composed of multiple plastics, such as polyurethane foam furniture, 35mm cellulose nitrate film, acrylic paintings on canvas and cellulose acetate fashion accessories [Appendix 3, Figure 6], as found in museums and other collecting institutions.

The research questions to be addressed are:

- What impact are temperature changes having on the equilibrium moisture content of plastic materials as they move in and out of storage?
- Can temperature and relative humidity combinations be identified that maintain a stable equilibrium moisture content while objects move through different collection environments?
- How do additive components and physical characteristics influence the equilibrium moisture content of plastics?
- When do changes in equilibrium moisture content result in irreversible change (damage) and can a method be developed to assess the point of irreversible physical change?
- Is there a clear relationship between plastic material and plastic composite artifact and the amount of change in equilibrium moisture content that can be physically tolerated?

Methodology, Data Collection and Data Analysis

The research questions will be addressed through a series of laboratory-based experiments designed to interrogate the relationship between temperature, relative humidity, equilibrium moisture content (EMC) and the mechanical properties of cellulose acetates and polyurethanes. These plastic materials serve as good proxies for additional plastics with similar compositional and physical characteristics allowing project results to be applied to a broader range of plastic materials than those tested. Initial work will focus on determining the EMC at different temperature and relative humidity conditions. The results will establish what temperature and relative humidity combinations can be used to maintain constant EMC. The experiments will follow a methodology previously established at IPI for determining EMC of archival materials [see Underpinning Research and Phase Two details below]. The EMC will be mapped against equilibrium relative humidity for each temperature, generating correlation charts that will enable temperature and RH conditions to be directly related to EMC [Appendix 3, Figure 7].

Later stages of work are designed to provide data on the mechanical properties of the plastics when subjected to changes in temperature and relative humidity and to assess whether the associated changes in EMC constitute irreversible physical damage. We will establish the mechanical response of the plastic samples equilibrated at set temperature and relative humidity using dynamic mechanical analysis (DMA). DMA measures changes in dimensions or mechanical properties of a material while exposed to different environmental profiles. Depending on the geometry of the sample and final application there are different approaches to analysis, but samples are usually tested in tensile or bending modes. The sample is held between two clamps, one of which is stationary and the other mobile, and a cyclical (sinusoidal) load or displacement is applied. The analysis chamber is concurrently heated or humidified and the changes in stress, strain and modulus of the material are measured as a function of time, temperature or RH. Two types of experiments will be undertaken. The first will establish the coefficient of hygroscopic expansion, which is the constant that relates the dimensional change of a material to a change in the surrounding RH, essentially due to absorption of moisture. The second set of DMA experiments will determine the brittle or ductile behaviour of the samples at given temperature and relative humidity. This data will be combined with that from the equilibrium moisture content experiments using multivariate mixture analysis to identify which factors, such as additives, influence EMC and mechanical response. A series of correlation tables and response maps will be generated to predict the physical behaviour of plastic artifacts and inform preservation environmental management guidelines.

The final stage of the experimental work will be aimed at validation of the methodology and will draw together data from the laboratory analysis of prepared samples with real-time imaging of historic animation cels, representative of plastic composite artifacts, exposed to changing environments. Digital Image Correlation (DIC) will be used to quantify the degree of dimensional change in plastic composite artifacts as they are exposed to set temperature and RH changes, following imaging protocols previously established at IPI [see Underpinning Research]. DIC operates by recording a number of digital images of the surface of the object, with each image compared back to an initial reference image. When calibrated to a standard of known dimensions, the dimensional changes recorded between successive images provides a non-invasive measure of how each material deforms within a given environment and how each component behaves in combination. Physical samples of the animation cels will also be subjected to DMA as outlined in research Phase Three and Four [see Research Phases below] for direct comparison with the DIC data.

Research Phases

In this proposed project, a series of experiments will be undertaken to determine how additive components and structural form of plastics affect the relationship between temperature, moisture and physical response. This is with a view to establishing guidelines that optimize the preservation quality of museum collection and storage environments such that dimensional changes are maintained within safe working limits to prevent irreversible physical damage to plastic artifacts, while identifying opportunities for dynamic environmental management and energy savings.

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, which will ensure that anomalies are highlighted and where necessary allow for later experimental methodologies to be adapted. Potential risks that may impact effective progression are outlined in the Risk Log in Appendix 4.

Phase One: Preparation (6 months)

Purpose/Activities

The first six months of the project will be devoted to establishing the methodology and preparing the test samples. Phase One will involve a number of concurrent activities, including: i) recruitment of a postdoctoral researcher; ii) a literature review to finalize the synthesis methodology for the plastic materials samples; iii) sample preparation and characterization; iv) procurement and installation of the dynamic mechanical analyzer (DMA); and v) calibration of the climate-controlled chambers (IPI is equipped with a walk-in chamber and five incubation chambers necessary for Phase Two).

Time/Resources

A series of cellulose acetate and polyurethane plastic samples with different polymer and additive compositions will be prepared in IPI's chemistry laboratory using previously established methodologies and an accompanying literature review. Method standardization and production will be undertaken over the course of five months, following appropriate health and safety procedures. Subsequent characterization of the test samples using microscopy and thermal analysis using the DMA will provide a baseline understanding of the material properties and homogeneity.

Understanding the impact and interrelationships of different additive components of plastics is one of the primary aspects of this research. To optimize for component effects, <u>the principles of Design of Experiments (DoE) for mixtures will be used to ensure the impact of varying relative proportions of components can be assessed simultaneously, while also allowing each factor to be evaluated independently.</u> Rather than varying one factor at a time, designing mixtures ensures that final sample compositions cover enough of the variability to <u>provide sufficient information for mapping interrelationships while keeping experiments to a minimum</u> [27]. Based on data gathered from previous research, we estimate that six different plastic compositions will be required for each polymer subclass i.e. cellulose triacetate, cellulose diacetate, polyurethane polyether and polyurethane polyester.

Dr. Emma J. Richardson and Dr. Meredith Noyes will collectively lead the literature review and design of experiments for Phase One. Noyes will lead the synthesis of the plastic materials and Richardson will lead the postdoctoral researcher recruitment process, procurement and calibration activities.

Phase Two: Establishing the relationship between plastic composition, temperature, relative humidity and equilibrium moisture content (9 months)

Purpose/Activities

The primary goal of Phase Two is to establish the relationship between temperature, relative humidity and moisture content at equilibrium for each polymer subclass of plastic. Phase Two will develop sorption isotherms for each material across a range of temperatures that are recommended for display and storage of plastics, mapping the equilibrium moisture content of these plastics at set temperature and relative humidity conditions.

The samples prepared in Phase One will be exposed to a series of one-time temperature changes at constant moisture content, measured using a moisture analyzer. This will be achieved by conditioning each sample at five relative humidities at 20 °C [Table 2] until equilibrium is reached and then sealing the prepared samples within aluminized polyethylene and nylon barrier film (Marvelseal) bags alongside temperature and relative humidity data loggers. Each sample will be exposed to a series of temperature changes from 20 °C to -20 °C and held for two weeks while measuring the associated equilibrium relative humidity.

<table>
<tr><th>Material</th><th>Moisture Conditioning: RH at 20 °C</th><th>Enclosure</th><th>Temperature Setpoints/°C</th><th>No. Samples</th></tr>
<tr><td>Cellulose Triacetate</td><td rowspan="5">20%
30%
50%
70%
80%</td><td rowspan="5">Double bagged inside two heat sealable aluminium foil bags</td><td rowspan="5">20
15
10
5
-20</td><td>6</td></tr>
<tr><td>Cellulose Diacetate</td><td>6</td></tr>
<tr><td>Polyurethane Polyester</td><td>6</td></tr>
<tr><td>Polyurethane Polyether</td><td>6</td></tr>
<tr><td>Gum Arabic (Case Study, Phase 5)</td><td>3</td></tr>
</table>

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

Time/Resources

The rate of equilibrium at each relative humidity will be determined following initial synthesis of materials, with a total of one month for initial conditioning at each RH allocated. Determining the timescales to reach equilibrium will help inform later experimental Phases of work. Initial RH conditioning will be undertaken in IPI's walk-in climate-controlled chamber and subsequent temperature conditioning will be undertaken using IPI's incubation chambers and freezers and held for two weeks at each setpoint. All samples will be conditioned concurrently, with each material type exposed to a total of 25 environmental conditions. The total duration of Phase Two will be nine months, including data analysis and regression modeling.

Dr. Emma J. Richardson and the Postdoctoral Researcher will collectively lead the experimental portion of Phase Two and the Postdoctoral Researcher will undertake the data analysis and modeling.

Phase Three: Determining the coefficient of hygroscopic expansion (8 months)

Purpose/Activities

The main goal for Phase Three is to establish what degree each material will expand or contract when the relative humidity is changed at a constant temperature setpoint (isothermal). The information derived from these experiments will shed light on how different synthetic polymers, additive components and three-dimensional structures influence the moisture sorption properties of plastics.

Understanding the impact these factors have on dimensional stability will enable collection care and handling policies to be tailored to the need of the object or the collection type.

The coefficient of hygroscopic expansion (CHE) is the constant that relates the dimensional change of a material to a change in the surrounding RH and will be determined using a dynamic mechanical analyzer (DMA) coupled with a humidity controller [see Budget Justification and Appendix 5 for Instrument Specifications]. Each sample will be held by the instrument in tension or compression and, following initial conditioning at each temperature setpoint in Table 3, the initial sample length will be measured by the instrument. Incremental humidity steps will be controlled within the chamber as the temperature is held constant and the displacement of each sample measured at equilibrium relative humidity. <u>Comparing the degree of dimensional change between materials (CHE) and the rate of that change is aimed at assessing how spatial and temporal differences in expansion relate to the risk of physical harm when two materials are combined</u>. Where material properties are mismatched irreversible change is more likely [28]. This relationship will be further interrogated as part of the Case Study in Phase Five.

Material	Mechanical Test Geometry	Isothermal Temperature Setpoints/°C	RH Increments/5%	No. Samples
Cellulose Triacetate	Tension	20 15 10 5	20% to 80%	24
Cellulose Diacetate	Tension			24
Polyurethane Polyester	Compression			24
Polyurethane Polyether	Compression			24
Gum Arabic (Case Study, Phase 5)	Tension			12

Table 3: Summary of the Phase Three experimental parameters and samples

Time/Resources

A dynamic mechanical analyzer (DMA) with humidity control chamber will be purchased and installed during Phase One of the project. The expected duration of Phase Three is 8 months. The coefficient of hygroscopic expansion will be determined for each sample at four set temperatures. Each test takes 8 hours in total, with the sample chamber holding one sample per experiment, necessitating testing of samples in succession over the course of 8 months. Data will be analyzed throughout the test period.

Dr. Emma J. Richardson and the Postdoctoral Researcher will collectively lead the CHE experiments for Phase Three, with the Postdoctoral Researcher taking responsibility for data analysis and hygroscopic mapping.

Phase Four: Establishing safe preservation and handling conditions for plastics (9 months)

Purpose/Activities

Phase Four will establish the methodology for assessing the safe working limits for a subset of plastics, determining the ductile or brittle response of each material at specified temperature and relative humidity setpoints. This information will be combined with the equilibrium moisture content established during Phase Two, providing complimentary information on the preservation and handling conditions within which a plastic material displays reduced risk of permanent mechanical damage. Owing to the large amount of data generated, the sample set will be reduced to focus on the materials associated with animation film composites, namely cellulose acetate and gum Arabic, to support later validation through an object-based Case Study in Phase Five.

Individual samples will be conditioned in the dynamic mechanical analyzer at each temperature and relative humidity combination and the flexural properties will be determined using 3-point bending over a period of 120 minutes. The temperature and RH will be held constant throughout the test (isotherm and isohume, respectively) and the changes in flexural modulus (ΔE) presented as a function of time. The difference between the modulus (E) at 5 minutes into the experiment and at termination (120 min) will be used as a measure of strain hardening. Strain hardening is possible in plastics that are tough and tend to undergo ductile, rather than brittle, deformation under force. These materials are capable of rearrangement on a molecular level and dissipation of the applied stress. Brittle materials do not exhibit strain hardening during deformation. Therefore, the samples that harden over the course of the experiment are classed as ductile and those that do not strain harden classed as brittle [29, 30] [Appendix 3, Figure 8].

The data generated from Phase Two and Phase Four will be collectively analyzed using multivariate analysis (MVA) to develop a prediction versus measured regression model and establish the relationships between composition, equilibrium moisture content and brittle behaviour. This work will define safe working limits for informed decision making and the model will enable future predictions to be made relating to similar plastic material types.

Material	Mechanical Test Geometry	Isothermal Temperature Setpoints/°C	Isohume RH Setpoints/%	No. Samples
Cellulose Triacetate	3-point bending	20 15	20% 30%	126
Cellulose Diacetate	3-point bending	10 5	50% 70%	126
Gum Arabic (Case Study, Phase 5)	3-point bending	-20	80%	63

Table 4: Summary of the Phase Four experimental parameters and samples

Time/Resources
A dynamic mechanical analyzer with humidity control chamber will employ a 3-point bend sample geometry. The strain hardening capacity will be determined for each subset of samples at each temperature and RH combination, totaling 21 setpoints per sample (the sub-freezing temperature setpoint allowing only one RH setpoint). Following initial conditioning, each experiment will take 120 minutes per sample in succession. The expected duration of Phase Four is 9 months. Data will be analyzed throughout the test period, although MVA cannot be finalized until all data is collated.

Dr. Emma J. Richardson and the Postdoctoral Researcher will collectively lead the strain hardening analysis for Phase Four, with Richardson leading subsequent multivariate data analysis and the Postdoctoral Researcher taking responsibility for data synthesis and automation. Automated data analysis will be applied to overcome the large manual workload that would otherwise be required.

Phase Five: Case Study (3 months)

Purpose/Activities
The goal of Phase Five is to demonstrate the relationship between non-composite sample plastic materials studied in the laboratory setting and composite objects found in modern materials collections, with a view to validating the methodology. Phase Five will make use of digital imaging

technologies to visually map dimensional changes across original animation film cel composites and correlate this information with accompanying laboratory tests as outlined in Phases Two, Three and Four.

Painted cellulose acetate film material from the 1976 animation *The Mathematician*, and donated by the British Film Institute for invasive testing, will be analyzed as a plastic composite artifact [see Appendix 2, Letters of Support]. This composite material will be subjected to changing temperature and RH setpoints within the walk-in climate-controlled chamber and imaged in real-time using digital image correlation. Samples will also be taken and analyzed using dynamic mechanical analysis as outlined in Phases Three and Four for direct comparison with the DIC data.

Time/Resources
Phase Five will utilize IPI's climate controlled walk-in chamber and digital image correlation system. The DIC cameras will be positioned above each object and their deformation monitored in real-time as the temperature and RH are altered. Temperature and RH will be set at combinations between 10°C to 20°C and 20% to 80% RH, the maximum limits achievable by the environmental chamber. Each sample will be allowed to equilibrate at each setpoint, the time to achieve this having been determined during Phase Two. The expected duration of Phase Five is three months.

Al Carver-Kubik will lead the digital image correlation analysis of the case study material, with Dr. Emma J. Richardson and the Postdoctoral Researcher supporting data analysis and interpretation.

Phase Six: Analysis and Dissemination (4 months)

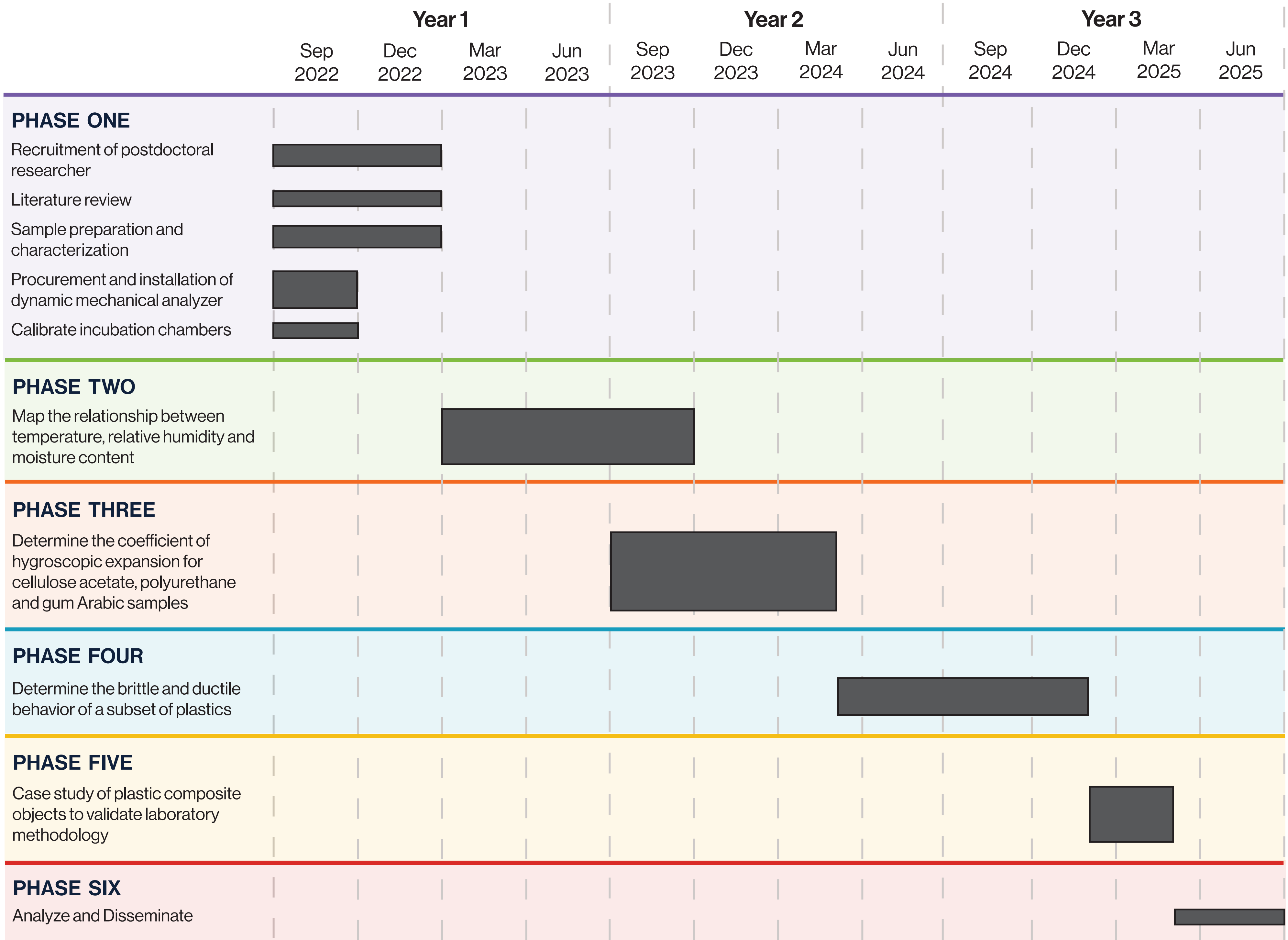
Purpose/Activities
Data analysis will be undertaken throughout each phase of work, which will inform experimental method development. The goal of Phase Six will be to draw together and synthesize the results for the collections care and conservation communities. The data will be collated into a final report, made available online from IPI's preservation research webpages (https://www.imagepermanenceinstitute.org). Research findings will additionally be published as two journal articles, one aimed at the collections care community outlining the implications of the work and guidelines for preservation environments for plastics, and the second published as a technical paper focused on disseminating the experimental methodology.

Time/Resources
The duration of Phase Six will be 4 months and the entire project team will participate in the collation and interpretation activities and the publication of results.

Project Deliverables and Pathways to Impact

The results of this essential research will be made accessible to a global audience providing collection stewards of modern materials collections with critical preservation guidelines for environmental conditions that prevent plastic deterioration while simultaneously allowing for the implementation of energy-saving strategies. Dissemination will take several forms including conference papers, peer-reviewed publications in targeted journals, and reference data maps and data tables made available via IPI's webpages. The findings will also feed back into IPI's guidelines for storage conditions of materials and inform future updates to the preservation metric for mechanical damage used in eClimateNotebook™, IPI's web-based environmental analysis software, reaching a wide audience.

Schedule of Completion



DATA MANAGEMENT PLAN

Following initial synthesis of test materials, characterization using thermal analysis and microscopy will be undertaken, generating .csv files of the thermal transitions and .tiff and .jpeg image files. Both sets of data will be used to understand the properties of the starting materials, which will aid interpretation of the later testing. IPI will collect temperature, relative humidity (RH) and equilibrium moisture content (EMC) data during the laboratory-based research activities, which will enable the relationship between these three parameters to be determined for each sample. This data will be collected during the first year of research and the RH and MC at each temperature setpoint will be used to highlight environmental combinations where changes in EMC can be minimized. This data will be combined with that gathered in later stages to establish guidance on environmental control for objects. Years two and three will generate mechanical data (stress, strain, modulus) in .csv format with accompanying temperature and RH .csv files. This information will be coupled with the material characteristics and moisture content data and interrogated using multivariate statistical techniques to establish prediction models. These models will enable unknown samples to be regressed against these calibration and validation models, enabling future predictions of a material's response to environmental change.

INTELLECTUAL PROPERTY RIGHTS AND PERMISSIONS

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DIGITAL CONTENT

IPI will collect temperature and relative humidity data during the laboratory activities. This will be accompanied by data on mechanical properties of materials, including stress/strain analysis and digital image correlation files. Due to the number of TIFF images generated by digital image correlation, we estimate we will collect approximately 300 GB of data.

Software used to create the digital content will be TA Instruments Trios software v.5.3; Correlated Solutions software VIC-3D v.7; Camo Unscrambler X 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 1 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.