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Application of comparative design study in the development of preservation encasements for historical documents

The preservation of historical documents is a task that requires a multidisciplinary team. Mechanical engineering can make valuable contributions. Historical documents made of paper have unique characteristics that must be considered for their preservation and exhibition. Specially designed encasements have emerged as a solution to meet these requirements. In the present research, a comparative design study was carried out. The study comprises identifying the main functions of the encasements. Subsequently, it is analyzed how the capsules that appear in the literature have solved these functions. With the information obtained, three new encasements were designed for historical documents in Mexico. From the results and design experiences, some insights and design principles were obtained; these can be universally applied.

1. Introduction

Mexico has many institutions responsible for guarding, preserving, maintaining, protecting, and exhibiting the most important historical documents. For example, the National Institute of Anthropology and History [1] (INAH, by its acronym in Spanish) and the General Archive of the Nation [2] (AGN, by its acronym in Spanish). There are museums, libraries, cultural centers and collaborations with universities. These exhibition spaces have in common the challenge of preserving said heritage, while satisfying the need to bring them closer to the public, disseminate their collections, promote research, and show their historical relevance. These institutions need technology development, and the mechanical engineering field

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can help them to achieve their goals. Similar institutions exist around the world with similar goals.

Some studies related to the protection of historical documents refer to the use of acetate films [3]. These chemically stable films are wrapped around documents to protect them. Current methods are related to the preservation of documents through digitalization [4] and [5], but digitalization techniques do not preserve the original document. Conservators know that a bad combination of oxygen and light is responsible for the fading of inks on historic documents [6] and [7]. Removing the oxygen from the atmosphere surrounding the document eliminates photo-oxidation. Therefore, controlling the environmental conditions of the exhibition or the storage rooms is another way to preserve historical documents [8].

One specific invention to preserve and exhibit historical documents it hermetic encasement. These devices have proven to be capable of reducing or mitigating significantly the risk associated with part of the agents that generate deterioration, even during the harsh conditions created by thousands of people visiting daily during the periods of public exhibition. They a combination of the known preservation techniques and the new technology. Some of the most representative examples are the Charters of Freedom [8], the Carta Magna whose procedure to protect it was documented in [9], the mummies of Egypt [10], the original documents of the constitution of India [11] and the encasement for The Waldseemuller world map [12].

The design of encasements for the preservation of historical documents have not followed a unique methodology because they have emerged in different parts of the world with different approaches and different needs. The factors that affect the integrity of documentary materials on paper are varied and present complex interrelationships, generally difficult to predict and mitigate due to the enormous diversity of materials and the history of each piece. This diversity offers the possibility of applying the comparative design methodology to synthesize the main functions common to the encasements. In a basic concept, a comparative design study involves the description of similarities and differences. To do this, a category of products is selected and a study of the different types of products is carried out, comparing strengths and weaknesses, appreciating their evolution over time (timeline), changes in the way of use, materials, and manufacturing technologies [13].

The purpose of this study is to analyze the encasements for the preservation of historic documents using the function-based analysis methodology to establish the functions involved in the encasements, then, applying comparative design methodology to compare the key characteristics with those of other encasements. Finally, the ideal characteristics of encasements for the preservation of documents are found. The cost and peculiarities of the insertion process for the encasements do not allow their use to become extensive, but the benefits that it entails justify their acquisition for irreplaceable pieces, such as the documents presented in the case studies of this research.

In section 2 of this paper, the function-based analysis methodology to analyze encasements for historical documents is addressed; in section 3, a comparative procedure is carried out to observe the different characteristics of encasements in the literature and synthesize what was learnt of them. In section 4, three case studies about encasements developed in Mexico for historical documents are described. They are summarized in a comparative table to appreciate the differences in the solutions. Consequently, section 5 presents the results on the behavior of the variables relative humidity and temperature for the three study cases. Finally, section 6 presents the pertinent conclusions and suggest future work.

2. Function-based analysis

To clarify the full behavior of the encasements, a function-based analysis was carried out. To do this, the methodology of Phal et al. [14] with some modifications [15] was used. The encasements have two main functions, "show the document" and "preserve the document". The inputs of material (hollow line), energy (continuous line), and information (dashed line) are shown in Fig. 1.

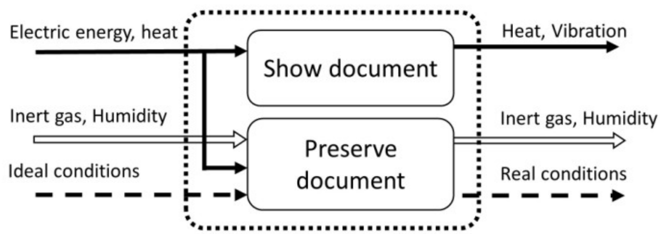


Fig. 1. Two main functions of the encasements

The main functions "show the document" and "preserve the document" are codependent and coexist in the design. The "preserve the document" function cannot exist by itself, as this would imply eliminating some light spectra that can damage the document. A completely sealed encasement with no light input or output would not be a suitable selection because the document must be shown. There cannot be a "show the document" function by itself, this would imply not designing a mechanical container to generate a microenvironment and light protections, leaving the document exposed to environmental factors. Nine subfunctions were derived from these two previously defined main functions. The subfunctions solve the complete design of the encasements for the preservation of historical documents.

The subfunctions identified have the characteristic of being universal for all encasements whose goals are to show and preserve historical documents. This way, there is a reference framework to compare the peculiar characteristics of the various encasements developed for the preservation of historical documents in the world. These are nine subfunctions whose relationships with the flows of energy, information, and matter of a preservation encasement are shown in Fig. 2.

Fig. 2 indicates that the type of energy that enters the system is electrical. This energy is used by some subfunctions in lighting, powering the sensors, or powering the control system. As a result of the operation of electronic circuits, heat and vibration are generated. Energy transformation is not a priority in the encasement. The information that enters the system is the set of parameters that define the ideal conditions that should be established for the document. The use of this information will depend on the "control the environment" function. If there is no closed-loop control, then the ideal parameters will be achieved only with the mechanical characteristics of the encasement. Ideally, there should be no flow of matter in the system due to the airtightness of the capsule. Initially, the encasement is filled with inert gas, sealed, and then there is no entry or exit of matter. But there is a transformation of matter, the gas needs to be at a specific temperature and relative humidity percentage, therefore, the preservation encasements of historical documents can be seen as a machine that transforms matter.

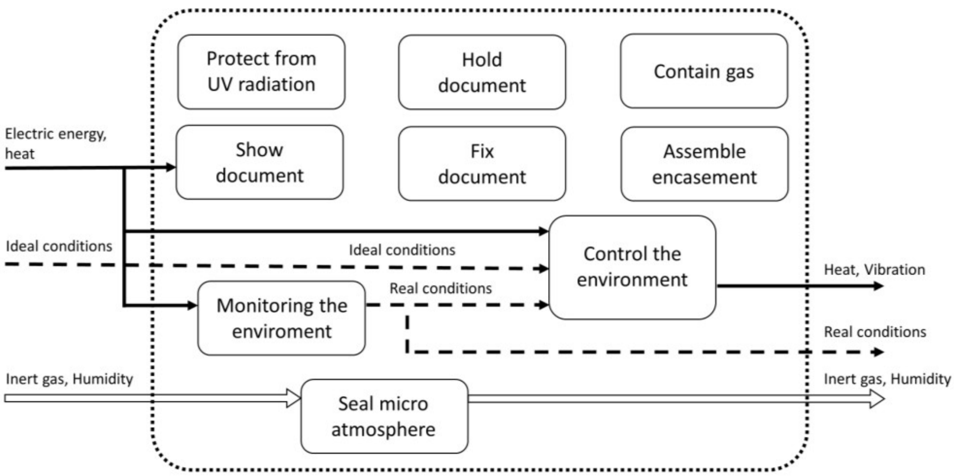


Fig. 2. The encasement's subfunctions

The functions presented in Fig. 2 have the characteristic of being universal. In each encasement for the preservation of historical documents developed in the world, the subfunctions presented have been solved in some way. Below we find a brief description of each function.

- Show the document. This subfunction implies to show the document to people in museums and exhibitions. Usually, this is done inside exhibition rooms with a large influx of people.
- Protect from UV radiation. Displaying the document involves lighting it up, but ultraviolet radiation will lead to weakening, bleaching, and yellowing of the paper and other organic materials. Thus, it is important to block it.

- Hold the document. This function defines the place where the document rests. Geometry and materials are key elements so that the function is fulfilled without damaging the document.
- Fix the document. This function defines the way the document is fixed to prevent it from moving. The pressure on the document and the contact points are key elements for the function to be carried out correctly.
- Contain gas. It involves keeping the document in a micro atmosphere isolated from the outside. The function is solved with the elements that isolate the interior atmosphere from the exterior one.
- Assemble the encasement. It implies how the mechanical elements that make up the capsule are joined. This union can be permanent or reversible.
- Seal micro-atmosphere. This is an additional subfunction that helps the contain gas subfunction. It is located between the union boundaries of the elements necessary to contain the gas.
- Monitoring the environment. With this function, the variables involved are observed. The objective of the observation is to verify that the conditions of the document are within the allowed ranges. It is also a requirement for automatic control.
- Control the environment. This function seeks to maintain the ideal conditions inside the capsule. The main variables to control are temperature and relative humidity.

3. Comparative study

This section describes how some existing encasements in the world were analyzed to identify how they solve the subfunctions established in the previous section. For comparison, the encasements of the Charters of Freedom, the Carta Magna, the mummies of Egypt, the original documents of the constitution on India, and the Waldseemuller world map are used. There are some examples of comparison as a path to design and innovate [16].

These encasements solve the previously described subfunctions in different ways. There is not much information published regarding the technical details of the encasements that have the objective of protecting the materials and historical objects they conserve. However, general information about the construction and functions of the encasements can be obtained in the references presented in the introduction section.

Table 1 shows the solutions that were made for each of the subfunctions, these are presented in the categories of configuration, materials, and processes. This table helps to get an overview of the solutions that other designers have carried out on their encasements. There is no single correct solution as each historical document to be preserved has its specific context and needs.

With this information, it is possible to visualize some patterns followed by the designers of preservation encasements. Note that encapsulation systems develop-

Table 1.
Comparison of different functions and characteristics of the encasements in the literature

Auxiliary functions	Configuration	Materials	Manufacturing Process
1. Show document	Front visualization. Front and sides visualization. Front, sides, and back visualization.	Glass. Polycarbonate. Plexiglas.	Floating Glass. Laminated casting.
2. Protect from UV radiation	Protection on the glass surface.	A film with protective layers.	Laminated films. Adhesive films.
3. Hold document	Grid plate. Threads. Mesh.	Aluminum. Titanium. Polycarbonate. Neutral Ph paper.	Laminated. Machined.
4. Fix Document	Small pressure. Removable support. Permanent glue.	Neutral Ph paper. Polycarbonate. Polyester.	Machined. Laminated.
5. Contain gas	Square box.	Polycarbonate. Stainless Steel. Plastic.	Machining. Bending.
6. Assemble encasement	With document inside. Without document inside.	Screws. Bolts.	Manual assembly. Welding procedures.
7. Seal micro-atmosphere	Permanent seal. Non-permanent seal.	Incromel Metallic C-Ring. Polymer Viton O-Rings. Indian – Cable.	Welding. Extruded. Molded. Laminated. Bended.
8. Monitoring the environment	Sensors inside the encasement.	Temperature. Relative humidity. Pressure.	
9. Control the environment	Closed-loop control. Open-loop control.	Electronic sensor embedded in stainless steel casings.	

ment represents a challenge in each country. Therefore, its preservation institutions have researched and developed their customized options reflecting that each solution integrates the best means to meet its own needs.

The solutions reflect a wide range of creative alternatives, from low cost, standardized parts, and simple materials to manufacture elements of highly intricate designs and materials to develop systems with high precision and tolerances for their manufacture.

There is consensus that the elimination of oxygen and the use of inert gas in the atmosphere inside the encasement is a solution that generates benefits for the preservation of the document. In some encasements, the monitoring and control instruments are located inside the encasements, while other systems avoid introducing electronic elements into the encasement. The different alternatives that exist reflect the level of resources that each institution can generate. The solutions have different forms of sophistication.

4. Design and construction of encasements in Mexico

In this section, three encasements developed for the preservation and exhibition of historical documents in the Mexican context are described. These encasements were developed after the function-based analysis and the comparative study. The origins and characteristics of the documents to be preserved are detailed and the procedure that was carried out for the design and construction of the encasements is described. Finally, the context in which they were exhibited is mentioned.

The first case is an encasement for the "Declaration of Independence of Mexico". With this document, Mexico declared its independence and sovereignty. It was signed on November 28, 1821. It is a document made of cotton paper and ferrogalic ink, it has dimensions of 52.9 by 71.8 cm. It is exhibited in the National Palace, Mexico City.

The main structure of the encasement is made of machined 7075 aluminum with an adonized superficial treatment. It consists of two rectangular plates which are assembled using pivots and are fastened by stainless steel screws throughout the periphery. It was designed to withstand a maximum internal pressure of 41.36 kPa. The relative humidity and temperature sensors are in the back of the lower plate, as well as the inlet and outlet for the inert gas (99.9999% Argon). A Vienna glass is placed on the upper plate, which has a high-purity polished coating to reduce reflections. The document can be seen through this glass. Between both machined aluminum plates, two concentric Vitton O-rings are placed to perform the function of sealing the encasement. It is achieved with the help of the pressure of the screws. The encasement has dimensions of 1.22 m wide, 1.4 m long and 0.14 m thick. Design principles were used, some of which are summarized in [17]. Fig. 3 shows a general view of the encasement and a close-up of the document "Declaration of independence", the signatures can be appreciated. In Fig. 4, some details such as the location of the sensors and the internal part of the encasement are shown.

The "Bicentennial encasements" project was carried out at the request of the General Archive of the Nation (AGN) and the Presidency of the Republic in the framework of the celebrations of the Bicentennial of Mexico's independence in 2010.

The second case is an encasement to preserve the Aubin Tonalámatl codex, an ancient document made by an old civilization in Mexico called Mexica. It is theorized to have been elaborated in the 15th century by Tlaxcalans, and according to its literal translation (paper of the days), it is an almanac of 260 days used as a natal chart and ritual calendar. Its dimensions are 4.95 m by 0.27 m, it is painted on amate paper made of tree bark and folds like a folding screen.

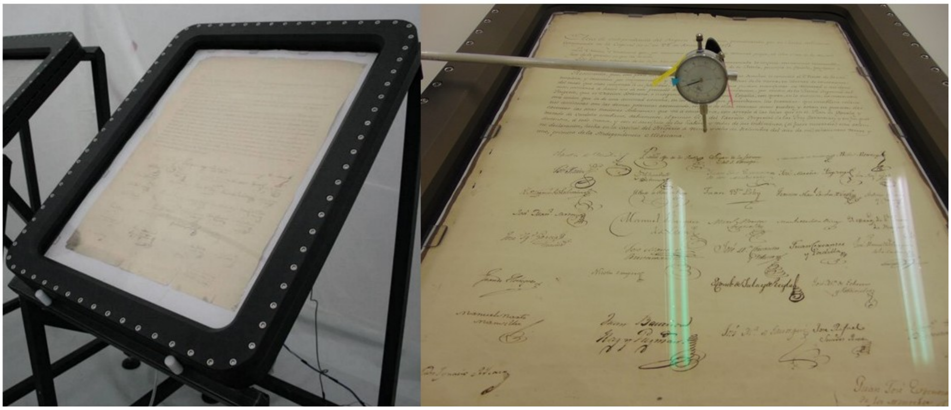


Fig. 3. Encasement for "Declaration of Independence"

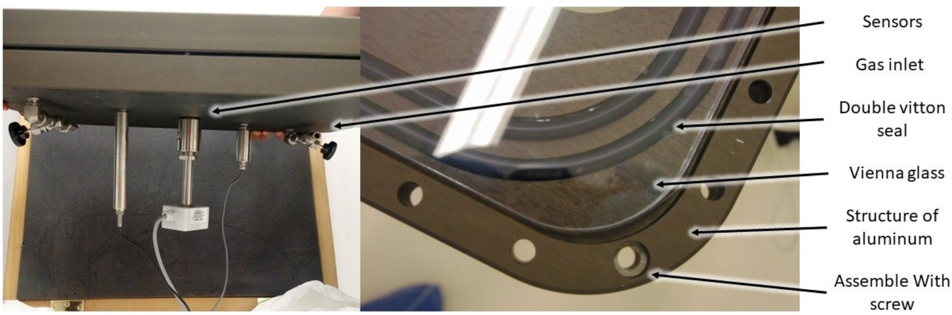


Fig. 4. Details of the encasement for the "Declaration of Independence"

The encasement is different from the first case study. It is made of long sheets of folded polycarbonate, withstands internal pressure up to 1.37 kPa. Its dimensions are 6 m long by 0.5 m wide. The encasement is joined using an SMX polymer-based sealant and adhesive. On the sides, it is joined by screws. The temperature and relative humidity sensors are placed in the lower part of the encasement. The codex is inserted through the front of the encasement and is closed using a door. The document rests on a neutral pH paper and this paper rest on a polycarbonate base that has the shape of the wavy folds of the codex. This geometry is to match the shape of the codex and prevent it from moving and damaging. Fig. 5 shows codex images inside the encasement, as well as some of the parts that make up the encasement.

The project "Encasements of Mexican codices" was carried out at the request of the National Institute of Anthropology and History (INAH) in the framework of the celebrations of the 75th anniversary of the INAH and 50 years of the National Museum of Anthropology. The exhibition was called "The Codices of Mexico, memories, and knowledge" and was presented in the temporary exhibition hall of the National Museum of Anthropology from September 2014 to January 2015.

Fig. 5. Details of the encasement for the “Aubin Tonalámatl codex”

44 codices were exhibited, including the Tonalámatl de Aubin. It was carried out through the link made by the Center for Mechanical Design and Technological Innovation (CDMIT) belonging to the School of Engineering of the National Autonomous University of Mexico.

The third case is an encasement designed to preserve the “Mayan Codex of Mexico”, which stands as the oldest legible pre-Hispanic manuscript in the American continent. This document is a divinatory calendar of Venus made by the Mayan culture in the period 1021 AD and 1154 AD. It is divided into 10 pieces. Its dimensions are of 1.25 m by 0.19 m and it is made of three layers of amate paper.

The encasement for the Mayan Codex of Mexico was constructed of three layers of polycarbonate, it is designed to withstand a maximum internal pressure of 1.37 kPa. It is assembled with screws on the periphery of the encasement. To isolate it from the external environment, it has two Viton rings that surround the entire codex. The temperature and relative humidity sensors, as well as the inert gas inlet and outlet, are located on the sides of the encasement. The codex rests on neutral pH paper and this paper rest on a polycarbonate grid. To prevent the codex from moving horizontally, it is constrained by a layer of polycarbonate cut into the peripheral shape of the codex. The dimensions of the encasement are 1.8 m long, 0.6 m wide and 0.05 m thick. It has an approximate weight of 18 Kg. Fig. 6 illustrates the encasement, as well as details about its construction.

The “Mayan Codex” project was carried out at the request of the National Institute of Anthropology and History (INAH) within the framework of the exhibition “The Mayan Codex of Mexico. Link, source and witness” which was held at the National Museum of Anthropology from September 28 to October 28, 2018. It was made through the link established by the Center for Mechanical Design and Technological Innovation (CDMIT) of the School of Engineering UNAM.

For each one of the three study cases, the subfunctions proposed in section two were solved. This is shown in the comparative Table 2. This table shows the

Table 2.
Comparison of solutions and subfunctions of the three encasements developed concerning the proposed subfunctions

Auxiliary functions	Encasement for “Declaration of Independence”	Encasement for “Aubin Tonalámatl codex”	Encasement for “Mayan Codex of Mexico”
1. Show document	Visualization of the document’s main face. Use of “Extra-clear low-iron glass”. Use of video cameras and large TV screens to support the visualization.	Visualization of the document’s main face. Use of Polycarbonate. Use of video cameras and large TV screens to support the visualization.	Visualization of the document’s main face. Polycarbonate was used. Use of video cameras and large TV screens to support the visualization.
2. Protect from UV radiation	Vienna glass with a high purity finish.	3M metalized & nanoparticles film was used for UV protection.	External filters for UV protection.
3. Hold document	The document rests on a neutral pH paper film, which is placed on a specially machined aluminum grid.	The document rests on a neutral pH paper film, which is placed on a polycarbonate layer with a corrugated shape and holes.	The document rests on a neutral pH paper film, which is placed on a polycarbonate flat base with holes.
4. Fix Document	Use of polycarbonate fasteners with variable pressure and kinematic restrictions.	The document is held because it fits the wavy surface.	Use of polycarbonate frame around the document, it was machined to the shape of the document.
5. Assemble encasement	Use of Pivots, bolts, and nuts. Constant pressure is applied by vacuum during assembly.	Use of screws and a Sealant and adhesive based on polymer SMX.	Bolts and nuts were used. Constant pressure is applied by vacuum during assembly.
6. Contain gas	CNC machined aluminum plates. Maximum pressure of 41.36 kPa.	Bended polycarbonate plates. Maximum pressure of 1.37 kPa.	Flat polycarbonate plates assembled in layers. Maximum pressure of 1.37 kPa.
7. Seal micro-atmosphere	Double Viton seal (O-ring) in a square and tight cavity.	Adhesive sealant and set screws.	Double Viton seal (O-ring) in a rectangular and spacious cavity.
8. Monitoring the environment	Pressure, temperature, and humidity sensors.	Temperature, humidity sensors, and a low range pressure anemometer.	Temperature and humidity sensors.
9. Control the environment	Mechatronic digital picture acquisition system in real-time.	Mechatronic system to measure perturbation in acceleration, displacements and inclination.	Detection of infrared radiation and acceleration and suspended particles.

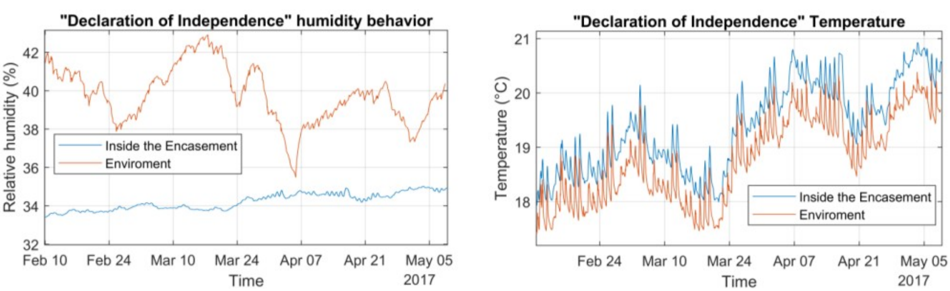
Fig. 6. Details of the encasement for the "Mayan Codex of Mexico"

different solutions used and how they were adapted to the specific case. It is noted that the proposed subfunctions are general for any encasement for the preservation of historical documents.

5. Results

The standard NMX-R-100-SCFI-2018 establishes the acceptable ranges of temperature and relative humidity for the preservation of paper documents. These ranges are between 30% and 50% for relative humidity with a tolerance of ± 3%. For temperature, the allowed range is from 2°C to 18°C with a tolerance of ±1°C. The standard specifies that it is difficult to establish and maintain these ranges for some contexts, but efforts should be made to get there or get as close as possible.

Fig. 7 shows the behavior of the relative humidity and temperature of the encasement for the "Declaration of independence". The left graph of Fig. 7 shows the behavior of the relative humidity inside and outside the encasement. It is seen that the relative humidity oscillations inside the encasement are smaller than

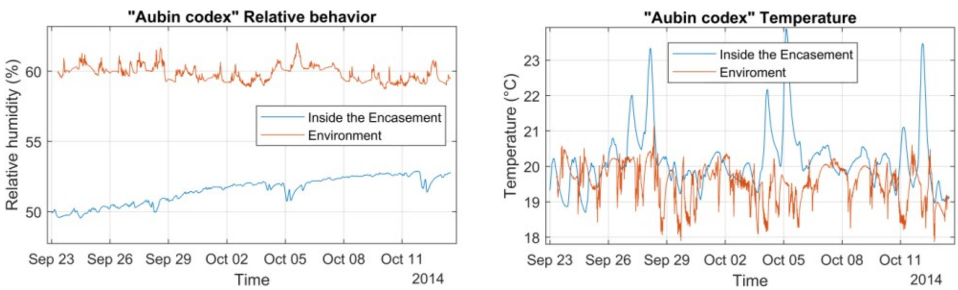


(a) relative humidity (b) temperature

Fig. 7. Graphs of relative humidity and temperature for "Declaration of independence"

outside the encasement and the values are inside the range allowed by the standard. The encasement acts as a damper in the case of relative humidity, it reduces the oscillatory amplitude of this variable. The right graph of Fig. 7 shows the behavior of the temperature inside and outside the encasement. It is shown that the temperatures move similarly. There is a gap between both temperatures; there is a higher temperature inside the encasement, the difference is about 0.5°C.

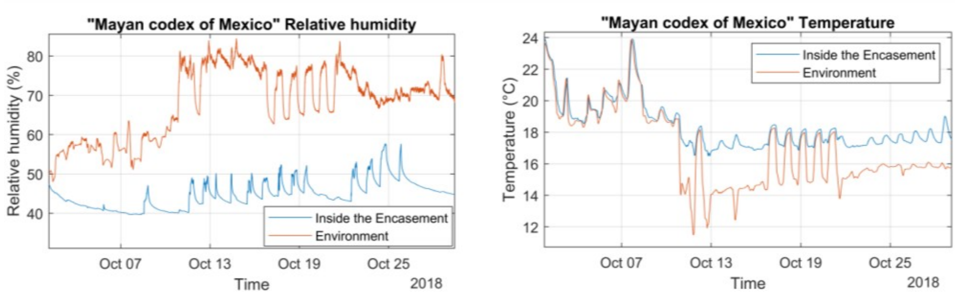
The graphs of Fig. 8 show the relative humidity and temperature behavior inside and outside of the encasement for the "Aubin Tonalámatl codex". Similar behavior is observed concerning the "Declaration of independence" encasement. The relative humidity inside the encasement has variations of smaller amplitude and is close to the allowed upper limit but still within range. The temperature inside the capsule has eventually higher values in comparison with the environmental temperature, the values of environmental temperature remain low.



(a) relative humidity (b) temperature

Fig. 8. Graphs of relative humidity and temperature for "Aubin Tonalámatl codex"

The graphs of Fig. 9 show the behavior of relative humidity and temperature inside and outside the encasement for "Mayan Codex of Mexico". Similar behaviors concerning the previous encasements are observed. In the case of relative humidity, the encasement performs the function of damping the oscillatory amplitudes and keeping said variations within a set range. Regarding the temperature, it is shown



(a) relative humidity (b) temperature

Fig. 9. Graphs of relative humidity and temperature for "Mayan Codex of Mexico"

that after a stabilization period where the temperatures are similar, it follows a period in which the temperature inside the encasement is more stable and whose oscillatory amplitudes are lower compared to the environmental temperature.

6. Concussions

In this research, a function-based analysis was performed to identify the main functions and subfunctions that an encasement for preserving historical documents solves. With these functions identified, some encasements found in the literature were analyzed. Their characteristics and solutions were in a table; it was observed that all these encasements solve the proposed subfunctions in some way. Finally, using the subfunctions, three new encasements were designed for historical documents in Mexico, and their performance was evaluated through the behavior of the variables of temperature and relative humidity.

From the data obtained, it is appreciated that the three new encasements developed have the characteristic of maintaining the relative humidity inside the range allowed by the standard. They also reduce the oscillatory amplitudes of relative humidity; this is a benefit because significant and constant changes in relative humidity force documents to continually try to stabilize. This implies mechanical stress and therefore aging in the document. It was also observed that, in general, the temperature inside the capsule is slightly higher than the ambient temperature, this is probably due to a greenhouse effect.

Through the analysis of the capsules existing in the literature and the experiences obtained in the design of the new three encasements; a set of guidelines or design principles have been synthesized. These can be applied to the design and construction of encasements for the preservation of historical documents. They are described below.

1. The humidity of the historical documents must be stabilized before placing the document inside the encasement. If a document goes into the encasement with humidity values outside the allowed ranges, then, the stabilization period is too prolonged because the microenvironment inside the encasements does not allow rapid changes.
2. If moisture flow is being supplied to stabilize the relative humidity inside the encasement, it should be supplied slowly. The reaction time of the documents is long, and the stabilization could take several hours and even days.
3. If an absorbent material gets in touch with the historical document, the document is destabilized. The absorption takes it out of the allowed humidity range. The time to achieve stability is long. This must be considered when using blotting materials.
4. It should be considered that the electrical cables and hoses that connect the micro atmosphere with the outside atmosphere are points where heat and humidity are transferred. Special care must be taken to isolate them.

5. The encasements should not contain any type of electronic component or integrated circuit inside. This alters the conditions of the micro atmosphere since these elements dissipate energy in the form of heat.
6. Residual stresses resulting from manufacturing processes such as machining can generate plate deformation and assembly failure. These deformations could contribute to a seal failure.
7. During the assembly process of encasements joined by screws, it is necessary to join the plates and generate a vacuum with a pump to exert pressure evenly in the unions and avoid overstress.

Future work is proposed concerning research in new ways of measuring the real humidity of the historical document. In current developments, the humidity of the micro atmosphere is measured, but there is indeed a difference in the actual humidity of the document. Indirect measurements are preferred to avoid damage to the document. With the real value of the humidity of the document being monitored in real-time, the efforts to stabilize it in a specific range will have better results in its attempt to preserve the document.

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