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Preventive Conservation applied to the Mineralogical Collection of the National Museum of Natural History and Science of the University of Lisbon

Dissertação para obtenção do Grau de Mestre em Conservação e Restauro

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“Tenho em mim todos os sonhos do mundo”,
Fernando Pessoa

Resumo

As coleções de minerais fazem parte do nosso património cultural. Neste trabalho de investigação foi aplicada uma metodologia de conservação preventiva à Coleção de Mineralogia do Museu Nacional de História Natural e da Ciência da Universidade de Lisboa (MUHNAC-ULisboa) (Portugal). A metodologia envolveu a caracterização do edifício, da coleção em reserva e exposição, a análise da classificação sistemática, a atribuição de características especiais a minerais, o levantamento do estado de conservação e a determinação das condições ambientais em ambas as salas.

As classes de minerais mais abundantes representadas na coleção em estudo são os silicatos, os sulfuretos e sulfossais. A atribuição de características especiais compreende os minerais sensíveis à luz, sensíveis à humidade relativa, potencialmente tóxicos, amianto e radioativos, sendo que os minerais sensíveis à luz apresentam a maior percentagem (13,6%) e os minerais de amianto a menor percentagem (1,1%).

A aplicação do modelo *Cultural Property Risk Analysis* (CPRAM) permitiu a avaliação de risco para a coleção, bem como a proposta de estratégias para mitigar os riscos específicos identificados. Os principais riscos genéricos identificados na reserva são as Forças físicas, Fogo e Humidade relativa incorreta. Enquanto que na exposição verificou-se que os possíveis maiores riscos estão relacionados com Forças físicas, Fogo, Poluentes, Luz e Humidade relativa incorreta. Os principais minerais em risco são os minerais com estruturas de cristais projetados, minerais sensíveis à luz e pirites/marcassites.

O estudo trata ainda os minerais potencialmente perigosos existentes na coleção de minerais, tais como os minerais potencialmente tóxicos, amianto e radioativos. Estes minerais foram identificados, fotografados, etiquetados e encapsulados. Foi realizada também uma avaliação de risco dos minerais de amianto e radioativos. E, por fim, foram propostos procedimentos de segurança e saúde para o manuseamento destes minerais.

Palavras-chave: Coleção de minerais; Coleções de história natural; Conservação preventiva; Análise de risco; CPRAM; Minerais potencialmente perigosos

Abstract

Mineral collections are part of our cultural heritage. In this work, a preventive conservation methodology was applied to the Mineralogical Collection of the National Museum of Natural History and Science of the University of Lisbon (MUHNAC-ULisboa), (Portugal). The methodology involved the characterization of MUHNAC's building, mineral collection in storage and exhibition, classification system analysis, attribution of special mineral characteristics, condition survey and determination of environmental conditions in both rooms.

Silicates, sulphides and sulfosalts were found to be the most abundant mineral classes represented in the collection. The special mineral characteristics attribution comprises light-sensitive minerals, RH-sensitive minerals, potentially toxic, asbestos, and radioactive. The light-sensitive minerals present the highest percentage (13,6%), while asbestos present the lowest percentage (1,1%).

The application of the *Cultural Property Risk Analysis* (CPRAM) model made it possible to conduct a risk assessment for this collection, as well as to propose mitigation strategies to the specific risks identified. The main generic risks found in storage were Physical forces, Fire, and Incorrect relative humidity. While on display the highest risks are related to Physical forces, Fire, Pollutants, Light, and Incorrect relative humidity. The main mineralogical specimens at risk of being loss are those with projecting crystal structures, light-sensitive minerals and pyrite/marcasite minerals.

The study also discusses hazardous specimens in the mineral collection, such as potentially toxic, asbestos, and radioactive. These minerals were identified, photograph, labelled and encapsulated. Risk assessments of asbestos and radioactive minerals were conducted. Health and safety procedures for handling these minerals have been established.

Keywords: Mineral collection; Natural history collections; Preventive conservation; Risk assessment; CPRAM; Hazardous mineral specimens

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Abbreviations and acronyms

ºC, Celsius

Avg, Average

CL, Control Levels

cm, Centimetres

E, Extent

F/, Fire

FS, Fraction Susceptible

h, hour

HVAC, Heating, Ventilation and Air Conditioning system

inv., Inventory

IPMA, Portuguese Institute for Sea and Atmosphere

IRH/, Incorrect Relative Humidity

km, kilometre

L/, Light

LA, Light-accelerated surface reactions with air, moisture, and/or pollutants

LC, Light-induced colour changes

LD, Light-induced decompositions

LV, Loss in Value

m, Meters

Max., Maximum

MDF, Medium Density Fibreboard

Min, Minimum

MR, Magnitude of risk

MUHNAC, National Museum of Natural History and Science

P, Probability

P/, Pollutants

PE, Polyethylene

PEAR, Collection and Storage Emergency Plan

PF/, Physical Forces

PPE, Personal protective equipment

PS, Polystyrene

RH, Relative humidity

STDEV, Standard deviation

T, Temperature

var., Variety

General Introduction

MUHNAC holds a great variety of natural history collections and science heritage. Science history collections are important for the history of scientific and technological knowledge. Natural history collections are a testimony of missing and contemporaneous natural diversity and are a fundamental database to understand, manage and discover the natural world diversity, knowledge of Earth evolution and development of possible future scenarios [1].

Mineral collections provide information regarding the evolution/history of planet Earth and concerning mineral resource's location. Mineral specimens are also associated with historic, scientific (use of scientific research tools), didactic (education programs), aesthetical (perfected shapes, carved mineral, gems) and economic values (ores). Mineral collections may also be the only way to research material from deposits, mines and sites which are difficult, now closed or impossible to access [2]–[4]. Minerals are "elements in a nation's heritage as important as any work of art, historic building or wildlife site" [4].

A preventive conservation approach was applied to the Mineralogical Collection of MUHNAC. Preventive conservation is based on all indirect measures and actions aimed at avoiding and minimizing future deterioration or loss of cultural heritage [5]. For this study, the ten agents of deterioration proposed by the Canadian Conservation Institute (CCI) were considered: Physical forces; Fire; Water; Thieves and vandals; Pests; Pollutants; Light, ultraviolet and infrared; Incorrect temperature; Incorrect relative humidity; Dissociation [6]. Previous studies showed that mineral specimens are most commonly affected by physical forces (e.g. abrasion), pollutants (e.g. dirt), light, incorrect relative humidity (e.g. pyrite decay, efflorescence) [7], [8].

In this work, "special mineral characteristics" was the designation attributed to specimens that are inherently unstable/susceptible such as light-sensitive and RH-sensitive minerals; and those that present a risk to human health, considering potentially toxic, asbestos and radioactive minerals. Some specimens can have more than one special characteristic.

The present work had two objectives: the risk analysis for the Mineralogical Collection of MUHNAC and the application of health and safety procedures for hazardous minerals. To achieve these goals, this study was divided into three chapters (Table 1).

Table 1 – Chapter contents

Chapter 1	Chapter 2	Chapter 3

• Bibliographic research on mineral concepts and natural history collections;
• Characterization of MUHNAC's building and surrounding area;
• Characterization of the mineral collection in storage and exhibition;
• Classification system analysis;
• Attribution of special mineral characteristics;
• Condition survey;
• Characterization and environmental monitoring in both rooms.
	• Bibliographic research on all the risks affecting mineralogical collections;
	• Application of the Cultural Property Risk Analysis Model (CPRAM):
	  ◦ Identification of all specific risks;
	  ◦ Risk magnitude estimation;
	  ◦ Proposal of risk mitigation strategies.
		• Bibliographic research on potentially hazardous specimens to human health and safety (toxic, asbestos and radioactive);
		• Identification in the collection;
		• Development of procedures for safe handling hazardous minerals;
		• Asbestos and radioactive minerals assessment;
		• Encapsulation;
		• Labelling;
		• Mapping of specimens inside storage and exhibition.

, stands for information analysed and placed in the Microsoft® Excel worksheet file.
, stands for photographic documentation conducted.

All data from the study was documented using Microsoft® Excel worksheets. The information included mineral information; classification system analysis; minerals on exhibition; risk magnitude estimation; special mineral characteristic survey; light-sensitive minerals; pyrite/marcasite; native elements; RH-sensitive minerals; toxic minerals; asbestos (species; texture; surface condition; quantity of loose fibers, type of storage; photograph); radioactive minerals (dose rate from closed drawer, storage material and mineral itself; measurement date; type of storage; photograph; low, weakly and significantly radioactivity level scale); cabinet assessment (quantity of minerals; difficulty opening; empty drawers; padding; container material; minerals overcrowding; oversizing minerals for drawer and card tray; projecting crystal structures; minerals in decay); pH card tray monitoring.

1.1. Introduction

The MUNHAC's mineral collection started to be catalogued in 1769 and can be considered one of the best in the country [1]. The collection has around 10 756 mineral specimens and is a testament to the Portuguese mineralogy and the history of mining in Portugal. The collection also holds a selection of high-quality specimens from the main mines all over the world. Therefore, it has a national and international interest. Some specimens also have artistic value (e.g. carved minerals, gems), others have great museographic interest and there is a historical importance associated with this collection as part of it illustrates the history of concepts in mineralogy (e.g. mineral names, systematic arrangement). Moreover, some specimens are from missing deposits and closed mines where collection is no longer possible.

The access to the collection on storage is open to researchers and visitants by appointment. Groups of visitors inside this room are limited (up to 5) and are always accompanied by the curator. The mineral collection is mostly used for museographic activity (exhibitions) and less frequently for scientific research [1], [9]–[12].

The aim of this chapter is to describe MUHNAC's building and historic context; characterize the storage and exhibition room, including monitoring of environmental parameters; characterize the mineral collection and conduct a condition survey. The information gathered in this chapter will be used to feed the risk analysis model in Chapter 2.

1.1.1. Characterization of the building

MUHNAC is located in *Rua da Escola Politécnica 56/58, 1250-102 Santo António,* Lisbon, Portugal (38°43'03.8"N 9°09'03.0"W (38.717713, -9.150832)). This building is classified as a Monument of Public Interest [13]. The building walls have limestone mortar and after the 1978 fire, some walls were added reinforced concrete.

The Museum's plan is rectangular with a cloister in the centre, and it has four floors which include exhibitions, public activities, laboratories, offices, storage rooms and others. Figure 1.1 presents the Museum building marked in yellow. The Astronomical Observatory, Old Riding Hall and Botanical Garden annexed can also be seen.

Figure 1.1 – Google maps image of MUHNAC location.

The main building of the museum has a total area of 12 997 m^2, of which 5 918 m^2 is used for exhibitions and public activities and 1 627 m^2 is used for storage. The remaining area is used for laboratories, offices, and others.

1.1.2. Building historic context

The historic context of the MUHNAC building is briefly explained in Figure 1.2. The Museum and its collections went through three different buildings in Lisbon. The Museum had its origin in 1768 at the *Royal Natural History Museum and Botanical Garden* in *Ajuda* [1], [12]. This museum was initially intended for the education of princes and royal family, and in 1798 it became accessible to the public [1]. The increase of the collections and the need to exhibit them were incompatible with the dimensions of this location. In 1836 all the collections, archives and belongings were transferred to the *Royal Academy of Sciences* in *Misericórdia* [1], [12]. The collections were expanded, studied and organized [1]. However, as time went by, the lack of rooms suitable for storage and exhibition affected the museum's growth progress [1]. By 1856, the *Royal Academy of Sciences* did not have proper conditions to open the Museum to the public and the collections began to show signs of lack of curation and degradation [1], [12].

The Council of the *Polytechnic School* requested the transfer of the Museum to its facilities since it had the means and personnel required to study the collections [1], [12]. In 1858, the collections were transferred to the *Polytechnic School* in *Santo António* [1], [12], [14]. The Museum was first designated as "National Museum of Lisbon" in 1861 [14] and comprised two sections: zoology and mineralogy [12].

In 1911, the education reform converted the Polytechnic School to "Faculty of Sciences", which was integrated in the University of Lisbon (UL) [1], [12]. Thus, the Museum was declared attached to the Faculty of Sciences [1], [14]. In 1926, the Museum was designated as "National Museum of Natural

History" (MNHN) [1], [14], comprising three sections: botanic, zoology and geology [1]. A violent fire in 1978 destroyed a great area of the Polytechnic School building and severely affected the zoology, anthropology and geology collections [1]. The Museum remained in the same building, while the Faculty of Sciences was transferred to new facilities [12], [14].

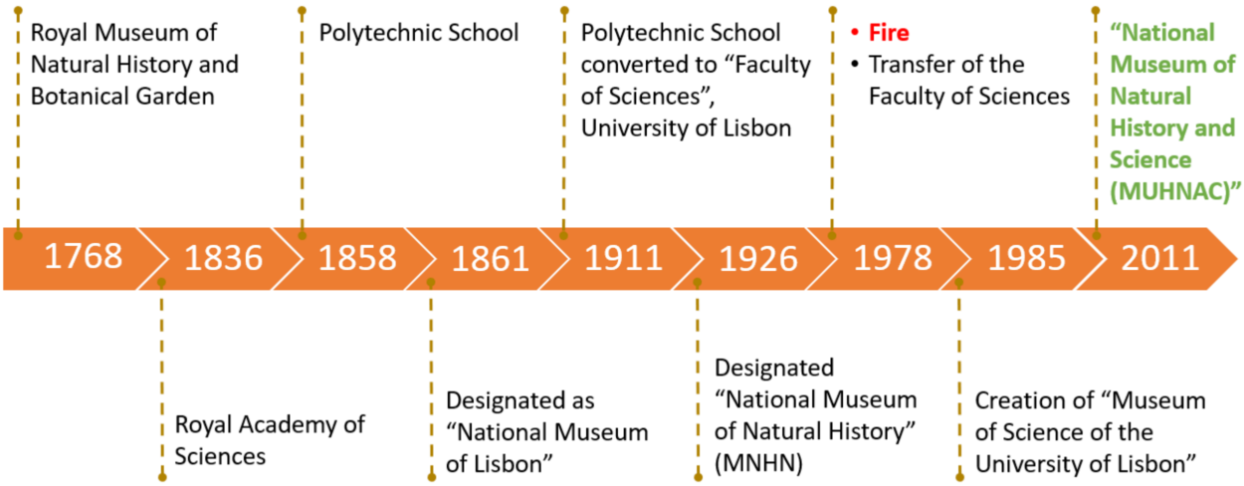


Figure 1.2 – Historic context of MUHNAC's building.

The "Museum of Science of the University of Lisbon" was created in 1985, sharing the same building as the MNHN [14]. In 2003, new bylaws detached the Museum from the Faculty of Sciences [1], [12], [14]. The Museum started to be directly tutored by the rectory of the University of Lisbon [1], [14]. In 2011, the University of Lisbon General Board created a "Museums of the University of Lisbon" unit, with the designation of "National Museum of Natural History and Science" (MUHNAC) [14].

1.1.3. Climate

According to climate norms from 1971 to 2000 of Lisbon Geophysics station (Appendix I - I.1.), January was the coldest month with the temperature average of 11,3ºC, while August was the hottest month with an average of 22,9ºC [15]. December was the month with greater precipitation with an average of 121,8mm and July was the month with the least precipitation with an average of 6,1mm.

1.1.4. Seismic activity

According to the Seismic Susceptibility Map of National Authority for Civil Protection, the Lisbon region is classified as highly susceptible to earthquakes (Appendix I - I.2.) [16], [17]. In Portugal, there is a considerable number of recorded earthquakes such as the earthquakes of 1755, 1909 (Benavente), and 1969 (Banco de Gorringe) [16], [18], [19]. The 1755 Lisbon earthquake had its epicentre near Banco de Gorringe (Atlantic Ocean) and had an estimated magnitude of 8,7 in Richter scale [16]. This earthquake is considered to be the most destructive earthquake in the Portuguese history and destroyed a great part of Lisbon [20]. As reported by the 2011 IPMA seismic activity summary report [21], 2 005 earthquakes with a magnitude between 0,3 and 4,9 were recorded in Portugal.

As stated by the Curator, MUHNAC's building does not have an anti-seismic structure. The 1755 earthquake caused damage to the building, while the 1969 earthquake caused no damage to the building or the collections.

1.1.5. Collection historic context and characterization

In the fire of 1978, approximately only 5 400 mineral specimens (1/3) were saved from a 15 000 specimens collection (Figure 1.3, Figure 1.4). The recovery and reorganization of specimens were made possible by using an old inventory from 1937, and through some labels that were still readable from the fire (Figure 1.5, Figure 1.6). These saved minerals are historically important because they illustrate scientific paradigms from various eras and reflect the institution's history [1].

Figure 1.3 – Former geology room before the fire of 1978. Photograph by Professor Fernando Barriga.

Figure 1.4 – Former geology room after the fire of 1978. Photographs by Professor Fernando Barriga.

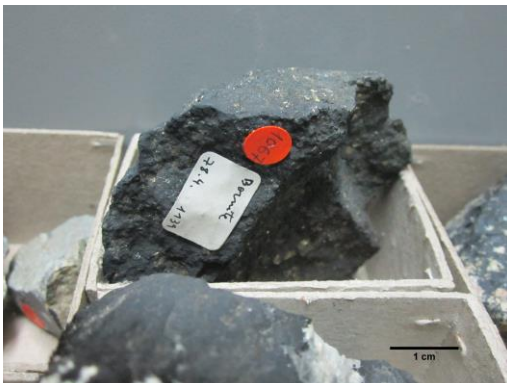


Figure 1.5 – Labels used after the fire.

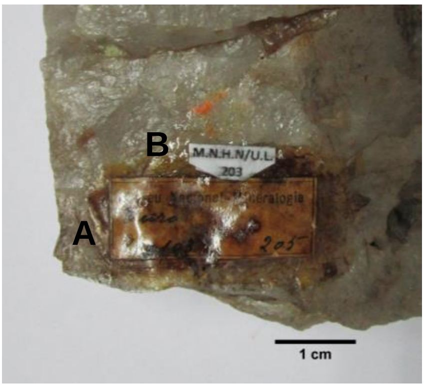
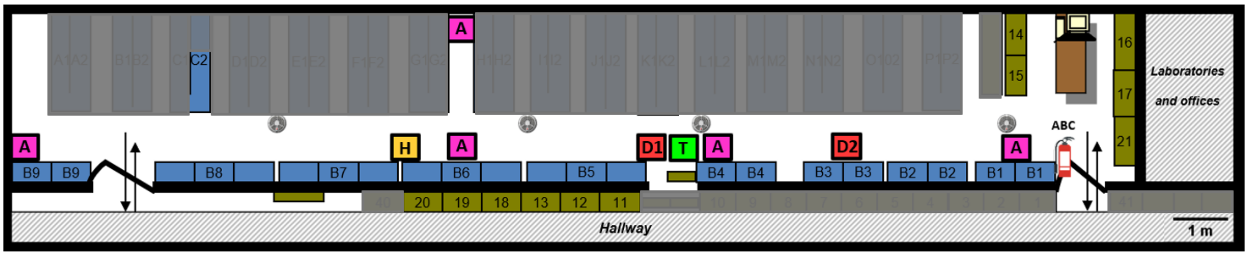


Figure 1.6 – Old label damaged by the fire (A). Most recent label (B).

The current mineral collection can be divided in three groups: collections saved from the fire (approximately 5 400), collections offered to the museum from different institutions after the fire (approximately 600), and collections acquired after the fire (approximately 4 700) [9]–[11]. The collections offered to MUHNAC have particular importance since they are considered to be a memory of a solidarity movement for the museum.

1.1.6. Characterization of the storage room

The mineral collection is stored in floor -1 inside the “Geology Storage Room 1” and “Geology Storage Room 2”. The “Geology Storage Room 1” is the main storage and has approximately 79 m^2 (207 m^3). The construction of the walls is made of reinforced concrete, while the ceiling has a cement plate, and the floor has a double cement plate. This room has a total of 3 wooden doors (2 operating) and several small windows in the upper part of the wall that faces an interior hallway. The storage hallway is 62 cm wide. Figure 1.7 shows the schematic drawing of the main storage room blueprint. There are approximately 10 529 minerals in storage.



A	Mechanical ventilation system	T	Thermohygrograph
H	Dehumidifier		Smoke detector
D	Thermohygrometer data logger		Fire extinguisher

Figure 1.7 – Schematic drawing of the “Geology Storage Room 1” room blueprint (provided by mineral staff and adapted to this study). The mineral collection stored in cabinets corresponds to the coloured areas. Blue squares correspond to metal cabinets with metal drawers, and green squares are metal cabinets with shelfs. Other equipment is also signalled.

Smaller specimens are stored in metal cabinets with metal drawers (9 blocks, 10 312 minerals) (Figure 1.8 and Figure 1.9). The cabinets drawers are 12 cm from the floor. From a total of 852 drawers, 816 are being used (96%). Each drawer contains 1 to 59 minerals, depending on the mineral’s size. Some drawers are difficult to open, so it must be done carefully (221 drawers, 27% of all).

Larger specimens are stored in metal cabinets with shelfs inside and outside the storage (11 cabinets, 176 minerals), and inside “Geology Storage Room 2” (4 cabinets, 41 minerals). These cabinets are 12 cm and 7 cm from the floor, respectively. Only the “Geology Storage Room 1” has environmental monitoring and control. None of the cabinets are floor/wall fixed.

Figure 1.8 – Photograph of the “Geology Storage Room 1” hallway and metal cabinets with drawers.

Figure 1.9 – Example of minerals organization inside drawers.

Most specimens are stored in 40-year-old grey card trays (not acid-free). The trays are joined at the side with staples (no oxidation is visible). Other specimens are stored inside similar brown card trays and white card trays. Different storage materials are presented in Table 1.1. Inventory numbers are visible on the mineral, outside the card trays and/or have a label paper inside the trays.

Table 1.1 – Storage materials within the storage room

Storage materials		**Storage materials**	
	**Type A:** Open card trays with staples without other support		**Type D:** Styrofoam® polystyrene (PS) foam base
	**Type B:** Plastic tubes/boxes		**Type E:** Stratocell® polyethylene (PE) foam base
	**Type C:** Glass containers (sealed or not)		**Type F:** *Minigrip®* plastic bags

The “Geology Storage Room 1” has a total of four smoke detectors connected to a fire alarm that is transmitted to the museum security. There is a Dry Chemical fire extinguisher (effective on Class A, B and C fires) placed inside the storage and another placed in the hallway outside the storage; and two

Carbon Dioxide fire extinguishers (effective on Class B and C fires) placed in the hallway outside the storage. All equipment locations inside the storage are illustrated in Figure 1.7.

1.1.7. Characterization of the exhibition room

Currently, the mineral specimens can be viewed in four different exhibition rooms: “Minerals: identify, classify”, “Jewels of Earth: Panasqueira Ore”, “Mar Mineral: Science and Natural Resources on the Deep Sea Floor” (all in floor level 0) and “SPECERE” (floor level 1). A total of 227 minerals (approximately 2,1% of the mineral collection) are on display for public viewing. The *“Minerals: Identify, classify”* exhibition room was selected for this study, since it can be considered the main one, presenting a greater variety of minerals. This exhibition has a total of 170 minerals on display and has been open to the public since 6th December 2001. The schematic drawing of the exhibition blueprint is presented in Figure 1.10.

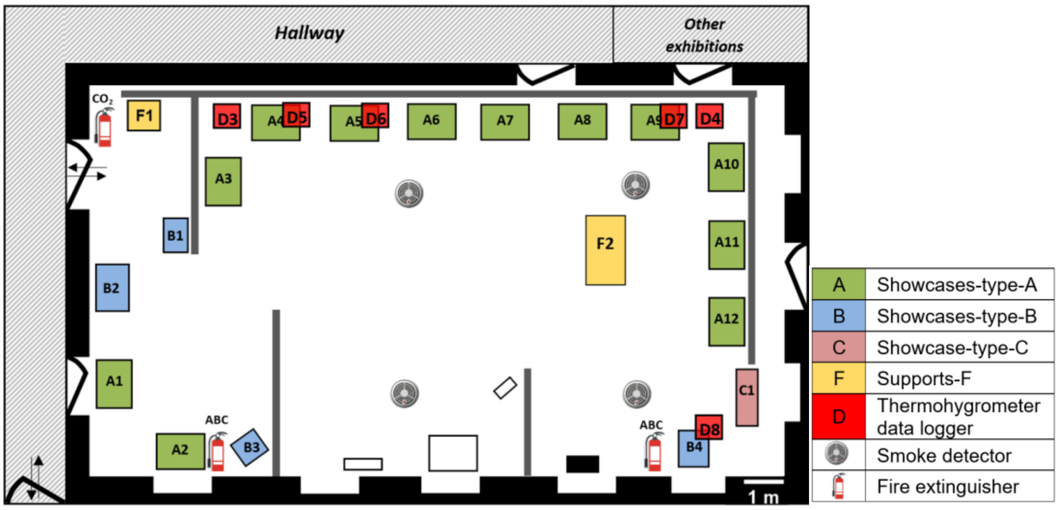
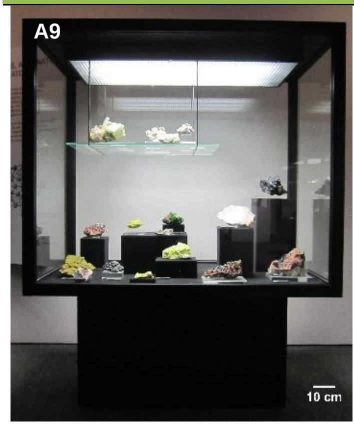


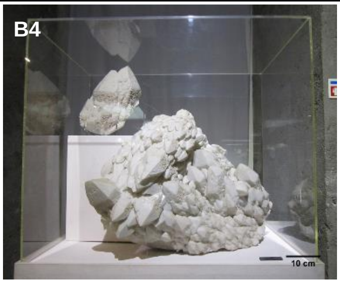
Figure 1.10 – Schematic drawing of the exhibition room blueprint provided by the museum and updated for this work. Distribution of distinct showcases/supports and other equipment are signalled.

This exhibition room has a total area of 225 m^2 (1 013m^3). The walls of this room are made of reinforced concrete, but the construction is unfinished since it does not have insulation. The floor is made of cement with an industrial grey carpet on top. The area has a total of five wooden doors (one facing outside) and seven windows with closed wooden shutters (all facing the Botanical Garden).

The first part of the exhibition shows examples of how minerals are designated (F1, B1, B2, A1, A2, B3). The second part is organized according to the following classification: native elements (A3); sulphides and sulfosalts (A4); oxides, hydroxides and halides (A5); carbonates, nitrated and borates (A6); sulphates and chromates (A7); tungstates and molybdates (A8); phosphates, arsenates and vanadates (A9); and silicates (A10, A11, A12, C1, B4, F2). The description of different type of showcases/supports are presented in Table 1.2.

Table 1.2 – Type of exhibition showcases/supports

Showcase-type-A		Showcase-type-C	
	**Showcases:** 12 **Minerals:** 162 **Materials:** • Metal and glass structure • MDF wrapped in acrylic velvet– base and supports • Acrylic supports • Glass shelfs • Interior LED tubes		**Showcases:** 1 **Minerals:** 1 **Materials:** • Metal and glass structure • Interior LED focus

Showcase-type-B		Supports-F	
	 **Showcases:** 4 **Minerals:** 5 **Materials:** • MDF stand • Crystal acrylic case • Outside LED focus	 **Supports:** 2 **Minerals:** 2 **Materials:** • **F1:** Metal structure / **F2:** MDF pallet • Outside LED focus	

The exhibition room has a total of four smoke detectors connected to a fire alarm that is transmitted to the museum security. There are two Dry Chemical fire extinguishers and one Carbon Dioxide fire extinguisher place inside the room. All equipment locations are illustrated in Figure 1.10.

1.2. Methodology

1.2.1. Pollutants

MUHNAC is located in an urban area and the main facade faces southwest towards the traffic road (the storage and exhibition rooms are facing southeast and the Botanic Garden). Currently there is no pollutant monitoring being conducted by the museum. The *QualAr* station (air quality monitoring database created by the Portuguese Environment Agency, APA) used in this study was in *Entrecampos* (approximately 3 km from MUHNAC) [22].

Particulate matter will not be considered in Chapter 2 as a specific risk for the storage room since it has a mechanical ventilation system, and the doors are always closed when entering/leaving the room.

The metal drawers also prevent the entrance of dust since the top area of the drawers have 1 cm in advance.

Within the storage room, the acidification of card trays was measured due to possible emission of organic acid vapours (mainly carboxylic acids) from the material [23]. The pH test was carried out with a flat head pH meter (CRISON pH Meter Basic 20) in three different areas for grey and brown card trays and two for white card trays, repeating the measurement three times in the same area.

1.2.2. Mineral collection characterization

An analysis on classification system of MUHNAC's mineral collection was conducted [24]–[26]. The mineral collection was also characterized by the presence of minerals with special characteristics (light-sensitive, RH-sensitive, toxic, asbestos and radioactive). The data was documented using Microsoft® Excel worksheets.

1.2.3. Mineral collection condition survey

The condition survey performed includes minerals with incorrect support, fragile minerals, particulate matter accumulation, and minerals with signs of decay. A particular condition survey of Pyrite and Marcasite was also conducted. All minerals surveyed were documented using Microsoft® Excel worksheets.

1.2.4. Monitoring of environmental conditions

Only the "Geology Storage Room 1" has both temperature (T) and relative humidity (RH) monitoring and control. This storage room has a mechanical ventilation system (*DST Seibu Giken RECUSORB DR-030C*[1]*)* linked to a wall humidistat (*REGIN HMH* 10A, 250 VAC) to keep RH at 55% and T around 18-20ºC. The air is drawn outside, and the outside air is filtered and heated to remove the moisture. There is also a portable dehumidifier (*JuneX DJ12)* to help the mechanical ventilation system to keep RH at 55%. To record RH and T values there is a thermohygrograph (*RATONA)* and the sheet is reusable and changed annually unless a major change in RH and T occurs. Therefore, to acquire more precise values, two thermohygrometers data loggers (ROTRONIC HW4-LITE HL-1D / TL-1D) were placed in the storage room (all equipment positions are illustrated in Figure 1.7.):

- One in the room (D1), near the thermohygrograph;
- One inside a drawer with Pyrite specimens (D2, in Block3 drawer 35).

[1] DST Seibu Giken Recusorb DR has heat recycling but has a fan for both the dry airflow and the wet airflow (https://www.dst-sg.com/dehumidifiers/recusorb-dr-20b-30d/, consulted in October 2020). The mechanical ventilation system has 4 air vents inside the storage room.

Regarding light condition, the minerals in the storage room do not suffer damage due to light since they are stored in closed cabinets and the lights are always off unless someone is in the room. Therefore, light damage will not be considered in Chapter 2 as a specific risk inside the storage room. Nevertheless, if light-sensitive minerals go on display, some precautionary measures need to be taken.

The exhibition room does not have a RH and T control system. Therefore, six thermohygrometers were placed (all equipment positions are illustrated in Figure 1.10):

- Two in the room (D3, D4);
- One inside showcase-type-A of Pyrites (A4) (D5), since the deterioration of these specimens is caused/accelerated by the presence of oxygen and water;
- One inside showcase-type-A of Halite (A5) (D6), due to current deliquescence reaction that is now occurring;
- One inside showcase-type-A of Autunite and Vivianite (A9) (D7). Autunite can undergo efflorescence and Vivianite is considered as having light-accelerated surface reaction with air, moisture and/or pollutants;
- One inside showcase-type-B of Milky quartz (B4) (D8) to provide information regarding insulation quality of showcase-type-A and B.

Damage by ultraviolet and infrared radiation were not considered since the light sources (LED) in the exhibition do not emit these radiations. Illuminance was measured near the minerals in different showcases by using a Visible and UV light meter (764 Environmental Monitor by ELSEC).

1.3. Results and discussion

1.3.1. Pollutants

The last validated data possible for transfer from *QualAr* website are dated between 01/01/2018 and 31/12/2018 (Table 1.3). The average and deviation values were calculated with this data from 2018. The estimated values for the storage/exhibition room were calculated according to dilution rule ("100, 10, 1") proposed by Tétreault [27]. Tétreault [27] and Thomson [28] suggest maximum average concentration limits on particulate matter, ozone (O_3), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) inside museums (Table 1.3).

Note that most of the collection is located inside cabinets and showcases. Therefore, when comparing the recommended values to those estimated inside cabinet/showcases it is easy to see that the O_3 and NO_2 are higher than the maximum limits proposed by Tétreault [27]. However, NO_2 is within the range proposed by Thomson [28]. Particulate Matter <2,5 µm is another pollutant to consider since it is estimated concentrations are slightly above the limit recommended by Tétreault [27]. SO_2 value is within the limit suggested by literature for the interior of a museum. It is important to notice that these are rough estimations since it does not consider the pollutants produced inside the museum.

Table 1.3 – Average pollutants concentration and standard deviation from 2018 annual data of "Entrecampos" station air monitoring station. Pollutant concentrations inside MUHNAC were estimated according to Tétreault dilution rule [27].

Area \ **Pollutant concentration (µg/m³)**	**Particulate matter <10 µm**	**Particulate matter <2,5 µm**	**Ozone (O_3)**	**Nitrogen dioxide (NO_2)**	**Sulphur dioxide (SO_2)**
***Entrecampos* air quality measurement station**	39,5 ± 14,7	14,0 ± 9,3	30,9 ± 25,7	49,8 ± 26,8	0,8 ± 1,2
Estimation for storage room / exhibition room MUHNAC	3,95 ± 1,47	1,4 ± 0,93	3,09 ± 2,57	4,98 ± 2,68	0,08 ± 0,12
Estimation for inside cabinets / showcases MUHNAC	0,395 ± 0,147	**0,14 ± 0,093**	**0,309 ± 0,257**	**0,498 ± 0,268**	0,008 ± 0,012
Recommended values (100 years) [27]	-	0,1	0,1	0,1	0,1
Recommended values [28]	-	-	0 - 2	≤10	≤10

No detailed information was found in the literature regarding reactions between O_3 and NO_2 with mineral collections. Therefore, the specific risks for these pollutants are not considered in this study. SO_2 can accelerate pyrite decay, acidification of labels/storage media, corrosion of copper and reactions with non-noble metallic minerals, carbonates and borates [23], [27], [29]. However, the SO_2 pollutant concentration estimate is within the limit recommended for the interior of a museum. Particulate matter can have an adverse effect on minerals through surface abrasion, discoloration and impact on visitor's perception [27]. Thus, particulate matter will be the only pollutant considered for risk assessment in Chapter 2.

Concerning the measurement of pH of card trays within the storage room, the results show a slightly acid pH, with an average value of 6,01 for grey card tray, 6,15 for brown card tray, and 6,52 for white card tray. Organic acids will not be considered in the risk assessment, since it would require monitoring organic acid vapours emitted by the card trays.

Regarding particulate matter in the exhibition room, according to the Curator, showcases-type-B seem to accumulate fewer quantity of dust than type A and C. Supports-F do not have a case, therefore these are always exposed to dust. However, particulate matter was not monitored in this study. Thus, it is only speculated that showcases-type-B accumulate less dust.

1.3.2. Mineral collection characterization

MUHNAC's mineral collection can be systematically arranged according to the Dana Classification [24]–[26] (Figure 1.11). The analysis of this figure shows that silicates, sulphides and sulfosalts are the most abundant mineral classes. The digital database of the mineral collection includes information regarding old and new inventory numbers, names, classes, associated collections, locations, regions, countries of origin, type of acquisition, collector, and acquisition date.

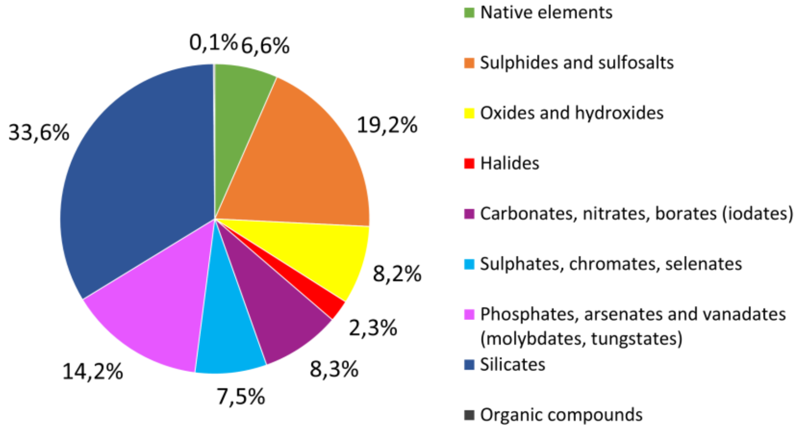


Figure 1.11 – MUHNAC's mineral collection arranged according to the Dana Classification.

Table 1.4 lists the number of minerals with special characteristics within MUHNAC's mineral collection. The information regarding special mineral characteristics was gathered from compilation studies by different authors [30]–[37]. Every mineral name cited in these compilations was searched and counted on the digital database of the mineral collection. Note that the information provided by the authors is not exhaustive [31], [32] (e.g. pink Halite is a light-sensitive mineral and it is not listed by the authors). Also, some minerals have more than one special characteristic, such as Realgar which is light-sensitive and has a toxic element (As).

Table 1.4 – Number of minerals with special characteristics in MUHNAC's mineral collection

Mineral characteristics	Storage	Exhibition	Total	Reference
Light-sensitive	1 434	32	1 466	[30], [34]
RH-sensitive	760	13	773	[32], [38]
Potentially toxic	245	4	249	[31], [37]
Asbestos	115	2	117	[35], [36]
Radioactive	334	5	339	[31], [33]

Light-sensitive minerals were identified accordingly to Nassau [30] and Horak [34]. Not all colours from a mineral species are light-sensitive (e.g., yellow beryl is not light-sensitive but blue beryl is). For this reason, it was necessary to check the colour of each light-sensitive mineral name. In MUHNAC's mineral collection there are 1 466 light-sensitive minerals. The exhibition room holds 32 minerals currently susceptible to light damage due to the showcase's conditions.

RH-sensitive minerals were identified with Waller's list of mineral specimens that can undergo humidity-related phase transitions [32] and Howie's list of native elements that can suffer problems due to T and RH [38]. Pyrite and Marcasite minerals were also counted in this special characteristic. Thus, there are a total of 773 RH-sensitive minerals, of which 202 are named in this study as "non-specific minerals" compilated from Waller's list [32], 304 are native elements and 267 are Pyrite/Marcasite. Wherein 13 are in the exhibition, from which 5 are non-specific minerals, 6 are native elements and 2 are Pyrite/Marcasite.

Potentially toxic minerals were identified accordingly to Howie [31] and Markov [37]. The first compilation includes the present toxic element(s) and which route is likely to be highly toxic (ingestion, inhalation, skin contact). Note that it is unlikely that most activities carried out by the staff will result in a dangerous hazard to health due to the handling of these specimens (e.g., quartz is considered to be toxic via inhalation of prolonged exposure to airborne particles but is not common to grind/polish specimens in museums). Therefore, the survey included all minerals that presented toxicity via skin contact. There are 249 potentially toxic minerals identified, from which 4 are in the exhibition room.

Asbestos mineral's identification was conducted using the list of names provided by Horák et al. [35] and Lambert [36]. There are 117 asbestos minerals present in the mineral collection, wherein 2 are on display.

Radioactive specimens were first identified from the list compiled by Howie [31] and Lambert [33]. Some minerals are not considered radioactive but can sometimes contain small quantities of uranium/thorium elements, making it difficult to identify them [39]. To be certain that all minerals containing radioactive elements were detected, all the specimens of the mineral collection were surveyed with a nuclear radiation monitor (*Radalert 100*™). There are 339 radioactive specimens in the collection, from which 5 are on display.

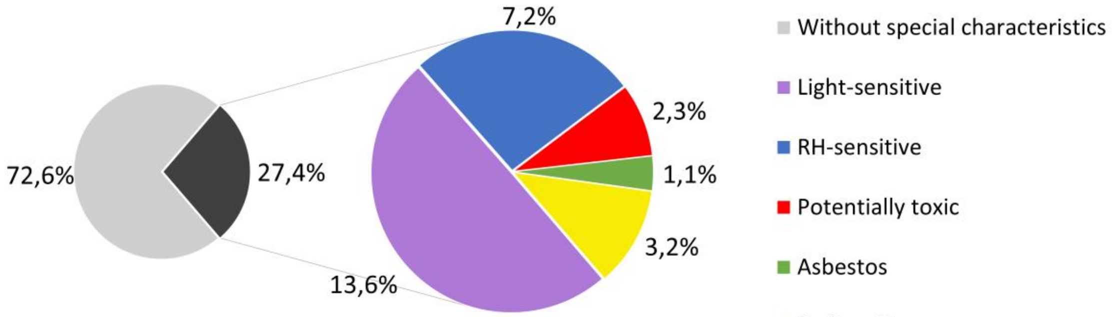


Figure 1.12 – Percentage of minerals with special characteristics within MUHNAC's mineral collection.

Figure 1.12 shows the percentage of minerals without special characteristics, light-sensitive, RH-sensitive, potentially toxic, asbestos, and radioactive minerals. Most of the minerals in the collection do not have a special characteristic, therefore they are mentioned as "without special characteristics". Light-sensitive minerals comprise the highest percentage (13,6%), while asbestos present the lowest (1,1%).

1.3.3. Mineral collection condition survey

1.3.3.1. Storage room

Table 1.5 represents the condition survey conducted on specimens inside the metal drawers. The survey considered the packaging type, fragile minerals, and specimens under deterioration.

Table 1.5 – Packaging, fragile minerals and minerals under deterioration survey condition conducted in the storage room

Packaging	No padded support (Figure 1.9 and Table 1.1 – Type A);	8 364
	Stored with more than one specimen in the same card without tray without partition (overcrowded) (Figure 1.9);	1 636
	Bigger than the card tray (Figure 1.13, Figure 1.14);	700
	Large size to be kept inside the drawers, since they can suffer abrasions when opening the drawer (Figure 1.15). All drawers with minerals in this situation were identified with a white label with black stripes.	37
Fragile minerals	Projecting crystal structures without proper cushioning (Figure 1.16).	666
Under deterioration (unstable minerals)	Visual signs of decay, such as material loss, chemical reactions. These minerals should be evaluated in detail and preventive measures must be applied. The total also includes Pyrite/Marcasite's survey on 1.3.3.3. .	374

Figure 1.13 – Aragonite oversize for the card tray. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.6302. Image taken on 13/07/2020.

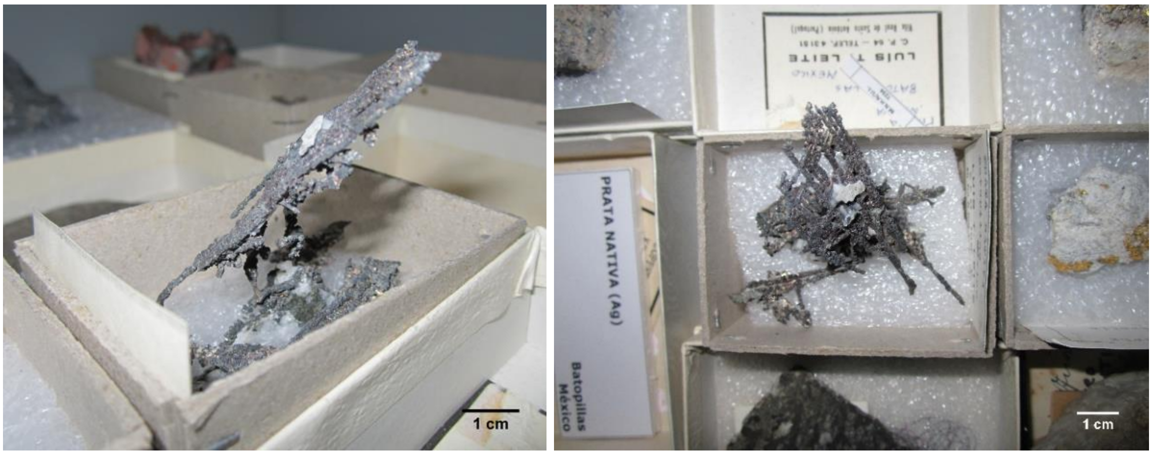


Figure 1.14 – Native silver with Stratocell® base oversized for the card tray. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7236. Image taken on 13/07/2020.

Figure 1.15 – A detail of Gypsum (variety Selenite) surface abrasion on the projecting structures when operating the drawer. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.6327. Image taken on 13/07/2020.

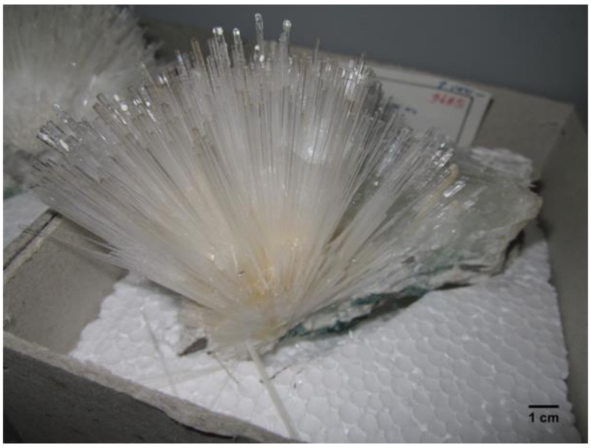


Figure 1.16 – A detail of Mesolite with Styrofoam® base and surface abrasion/material loss on the projecting structures. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.8847. Image taken on 15/07/2020.

1.3.3.2. Exhibition room

Table 1.6 shows the condition survey conducted on exhibition, considering minerals in critical supports, fragile minerals, accumulation of particulate matter, and specimens under deterioration.

Table 1.6 - Packaging, fragile minerals, dust, and minerals under deterioration survey condition conducted in the exhibition room

Minerals likely to move if there is a strong disturbance/ vibration	Placed in high critical supports inside showcases-type-A	116
	Inside showcases-type-B (B2 and B3)[1] susceptible to fall.	2
	Placed in high critical supports inside showcases-type-B.	1
	Inside showcase-type-C susceptible to fall.	1
	On support-F (F1 has an iron structure smaller than the mineral) susceptible to fall.	1
Fragile minerals if they move/fall	Goethite, Native copper, Rhodochrosite, Aragonite, Dolomite, Gypsum (var. selenite), Torbernite, Fluorapatite, Citrine quartz, Hyaline quartz.	10
	Minerals with projecting crystal structures pointing upwards (Figure 1.17, Actinolite).	2
	Minerals with projecting crystal structures in the lower area that can develop changes (Figure 1.18, Figure 1.19, Anhydrite, Scolecite over Apophyllite).	4
Particulate matter	Minerals on supports-F accumulate dust more easily because they do not have a case.	2
	Minerals with projecting crystal structures inside showcases-type-A that if left with dust, are difficult to clean without damaging it (Figure 1.18, Figure 1.19, Actinolite, Chrysolite, Scolecite over Apophyllite).	5
	Minerals with projecting crystal structures inside showcase-type-B that if left with dust, are difficult to clean without damaging it (Figure 1.17)	1
Under deterioration (unstable minerals)	Figure 1.18, Figure 1.19, Figure 1.27, Figure 1.28 (latter is suspected to have changed). These minerals should be evaluated in detail and preventive measures must be applied	4

[1] Minerals inside B1 and B4 were not considered since these are heavy and their showcases height and width dimensions are similar.

Figure 1.17 – Example of fragile mineral Anhydrite with projecting structures inside a showcase-type-B. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7877. Image taken on 12/02/2019.

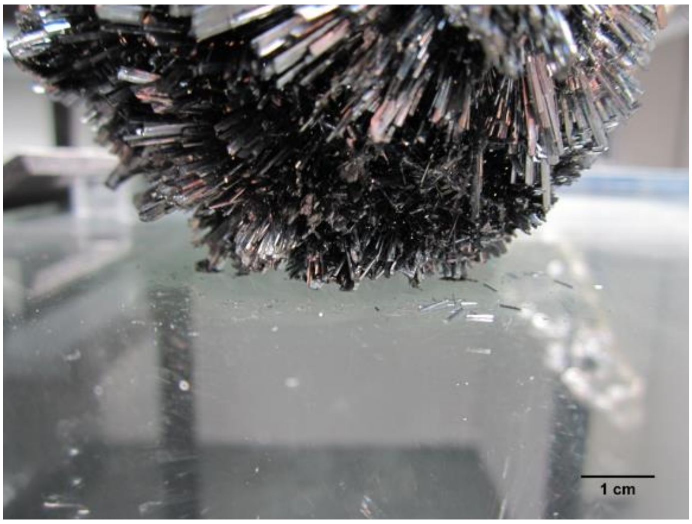


Figure 1.18 - Detail of Stibnite surface abrasion due to incorrect support/gravitational forces on the projecting structures inside a showcase-type-A. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7358. Image taken on 28/08/2020.

Figure 1.19 – Halite with acrylic support and silica gel bag inside a showcase-type-A. Halite shows signs of deliquescence (slightly wet). MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7506. Image taken on 24/10/2019.

1.3.3.3. Pyrite and Marcasite

A condition survey of all Pyrite and Marcasite in storage and exhibition was carried out (Figure 1.22). Figure 1.20 shows Pyrite in good condition, while Figure 1.21 presents a deteriorated Pyrite.

Figure 1.20 – Pyrite in a good condition. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7270. Image taken on 23/10/2019.

Figure 1.21 – Pyrite decay. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7280. Image taken on 15/02/2019. This mineral is no longer part of the mineral collection.

The survey includes visual analysis on shine, presence of powder, cracks, breakage, stained labels, crystal size and form, and if the specimen consists only of pyrite or if it has another materials present. The condition survey system applied was the following:

- **Good:** no visual problems;
- **Fair**: sign of small cracks, possible dulling, small areas with yellow/white powder;
- **Poor:** several areas affected and with greater severity; specimen is not broken; acidification of labels may occur;
- **Very poor:** specimens completely or very deteriorated; normally show all signs: dull, powder, cracks, breakage, and possible acidification of labels.

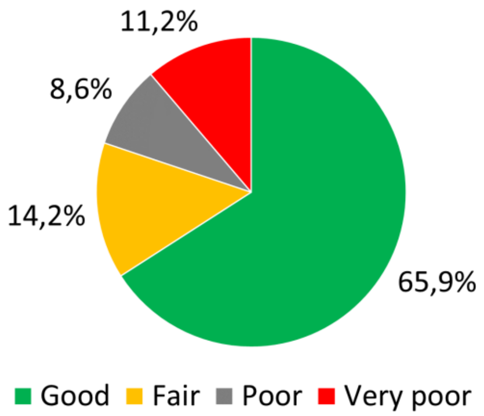


Figure 1.22 – Condition survey results of pyrite, marcasite, and pyrite with marcasite specimens.

Of the 267 minerals, 34,1% (91 specimens) showed some or abundant decay products (Fair + Poor + Very poor). However, some of these visual effects could be related to the 1978 fire, since 76,9% (70/91 specimens) are from collections prior to the fire (these effects were not present immediately after the fire). The two minerals on exhibition appeared to be in a good condition.

1.3.4. Environmental monitoring – Storage room

1.3.4.1. Temperature and relative humidity

Full monitoring and same timeframe of exposure of T and RH is presented in Table II.3 (Appendix II-II.3.1.). The exact appropriate condition will be specific to the mineral. The recommended values of T and RH for mineral collections, according to the literature, are 16-22 ºC and 50 ± 5% RH [2], [40]–[44] (Appendix II – II.1.). Pyrite specimens require a specific RH, the recommended RH is around 30%, depending on if the reaction is treated or not (Appendix II - II.1.) [8], [32], [50], [51], [40], [43]–[49]. Native metals, such as Silver and Copper can also corrode due to high values of RH. The RH level recommended for metal objects should be between 35% and 55% for mixed collections [52]; actively corroding metals should be stored in RH below 35% [52].

Concerning the T and RH monitoring inside the storage room, the values of both thermohygrometers inside the room and drawer are similar and within the recommended limits for mineral collections. Figure 1.23 and Figure 1.24 represents the monitoring of T and RH of the room and Pyrite drawer within the same timeframe of exposure to conduct a better comparison of the locations. The RH inside the room presented an average of 47,6 ± 2,6%, while the Pyrite drawer presented an average of full monitoring 48,0 ± 1,5% (min. 45,7% and max. 52,1%). The values inside the drawer presented lower fluctuations than in the room, as expected. Thus, the results are within the recommended values for mineral collections, however, it is not suitable for minerals that need to be stored in a specific RH, such as Pyrite. These minerals and other RH-sensitive minerals are further discussed in 2.3.5. (Chapter 2).

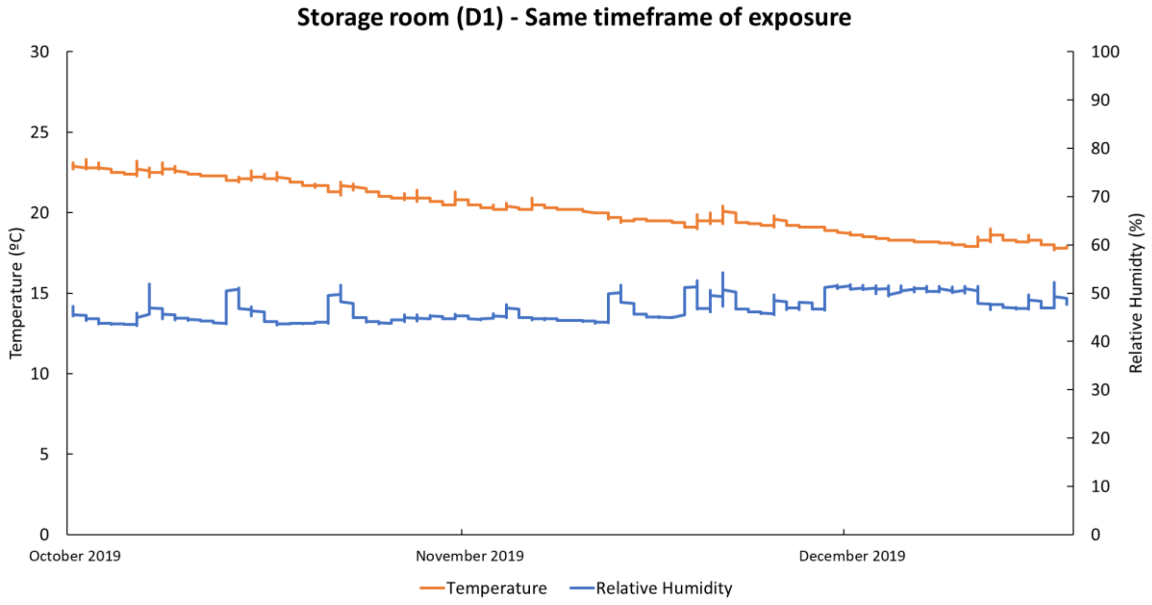


Figure 1.23 – Monitoring values of T and RH from thermohygrometer in the storage room (D1). The average value and deviation of T is 20,2 ± 1,5 ºC and the average value and deviation of RH is 46,7 ± 2,6 %. Monitoring period: 23/10/2019 – 09/01/2020.

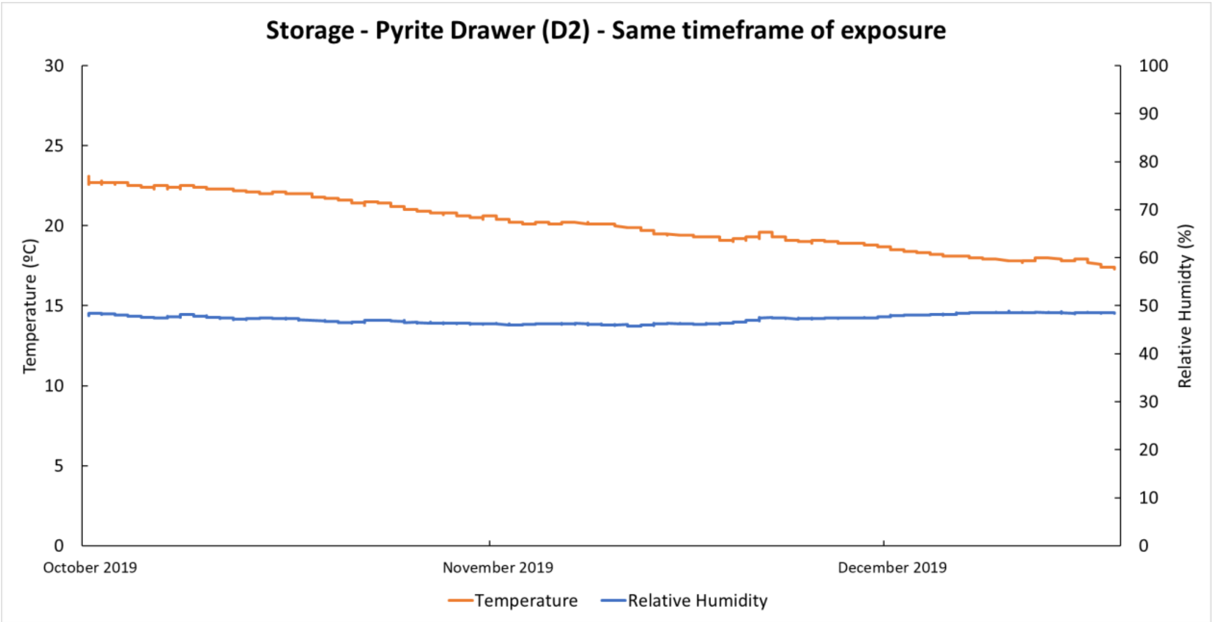


Figure 1.24 – Monitoring values of T and RH from thermohygrometer inside a drawer in the storage room (D2). The average value and deviation of T is 21,8 ± 2,0 ºC and the average value and deviation of RH is 47,9 ± 1,7 %. Monitoring period: 23/10/2019 – 09/01/2020.

1.3.5. Environmental monitoring – Exhibition room

1.3.5.1. Light

The maximum recommended value for illuminance in geological collections according to the literature, is 300-350 lux [41], [43] (Appendix II - II.2.). However, particularly sensitive specimens should be displayed with a maximum of 50 lux (Appendix II - II.2.) [28], [34], [43].

Illuminance monitoring of light-sensitive minerals on display was conducted (Table II.5 in Appendix II - II.4.2.). Showcases-type-A and C have high lux values for general mineral collections: values between 354 – 1 644 lux (A9) and 156 – 413 lux (C1), respectively. The supports-F present the lower value of illuminance since the light source is further away: between 69,8 lux (F1) and 74,4 – 113 lux (F2). The light source in showcases-type-B is placed outside, thus creates a greater distance between the light and the mineral, therefore presenting a 90,4 lux (B1). Moreover, the acrylic may eliminate part of the emitted light. Thus, showcases-type-B present lower values of illuminance than showcases-type-A and C. Nevertheless, all showcases present high values of illuminance for light-sensitive minerals. The highest illuminance value measured was 1 862 lux in a glass shelf of showcase A11 (due to being the closest position a mineral has to the light lamps). Also, all showcases exceed the annual light exposure limit for highly sensitive objects.

Until 2020, 3 minerals suffered colour changes and 1 is suspected to have also changed due to exhibition conditions according to the Curator. In the 1994 “Simpósio de mineralogia” exhibition, one Realgar (Figure 1.25), and one Pink Halite (Figure 1.26) were displayed in showcases-type-A with fluorescent tube light (there is no data on illuminance values). Realgar changed red crystals to yellow (decomposition to yellow Pararealgar, As_2S_4), while the pink colour on Halite partially faded – both changed in about one to two months.

Figure 1.25 – Realgar with partial colour change. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.6912. Image taken on 13/11/2019.

Figure 1.26 – Faded pink Halite. The bottom area (right) did not receive as much light and represents the most similar colour more to the original. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7506. Image taken on 18/11/2020.

Figure 1.27 – Vivianite with partial colour change and fragmentation inside a showcase-type-A (626 lux measured). MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7996. Image taken on 24/10/2019.

Figure 1.28 – Spodumene suspected to have faded inside a showcase-type-A (1862 lux measured). MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.8515. Image taken on 29/10/2020.

Currently on display, one Vivianite (Figure 1.27) has suffered changes: some of the translucent dark green colour began to darken drastically, and it is also partially fragmented; changes began to occur with the fluorescent lamps. And one Spodumene (Figure 1.28) is suspected to have also changed: the pink colour seems to have faded slightly. The actual exhibition started in 2001, therefore the changes were slow. There is no photographic documentation of these 4 minerals before the colour change.

1.3.5.2. Temperature and relative humidity

Full monitoring and same timeframe of exposure of T and RH in the exhibition is presented in Table II.4 (Appendix II-II.4.1.). T values measured from all showcases are within the recommended limits, while RH values are higher than the recommended limits and with large fluctuations. Nevertheless, fluctuation decreases slightly inside showcases when compared to the room. These results were expected since the room is unfinished, there is no environmental control, and it has several windows and a door facing the exterior that does not make the correct insulation.

The exhibition room presented values of T between 14,5ºC (January) and 24,8ºC (July/September), while RH varies from 37,7% (September) to 82,0% (December). This resembles the data from the conditions outside MUHNAC's building (Chapter 1 - 1.1.3.). Therefore, this also proves that insulation between the interior and exterior of the building is far from ideal.

Figure 1.29 to Figure 1.33 show the monitoring of T and RH of the room and showcases within the same timeframe of exposure to conduct a better comparison of the showcases.

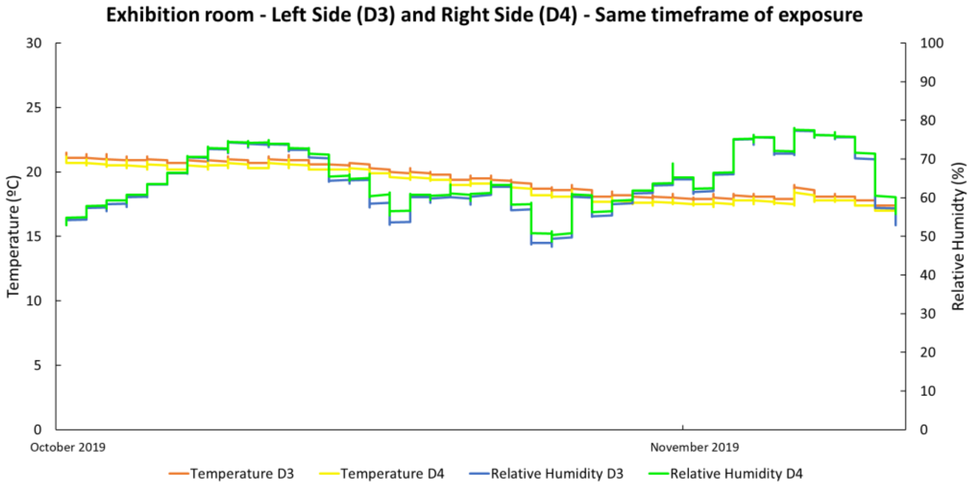


Figure 1.29 - Same timeframe of exposure monitoring values of T and RH from thermohygrometer in the exhibition room (D3). For D3: the average value and deviation of T is 19,4 ± 1,3 ºC and the average value and deviation of RH is 64,1 ± 7,4 %. Monitoring period: 23/10/2019 – 03/12/2019. For D4: The average value and deviation of T is 19,0 ± 1,3 ºC and the average value and deviation of RH is 65,0 ± 7,1 %. Monitoring period: 23/10/2019 – 03/12/2019.

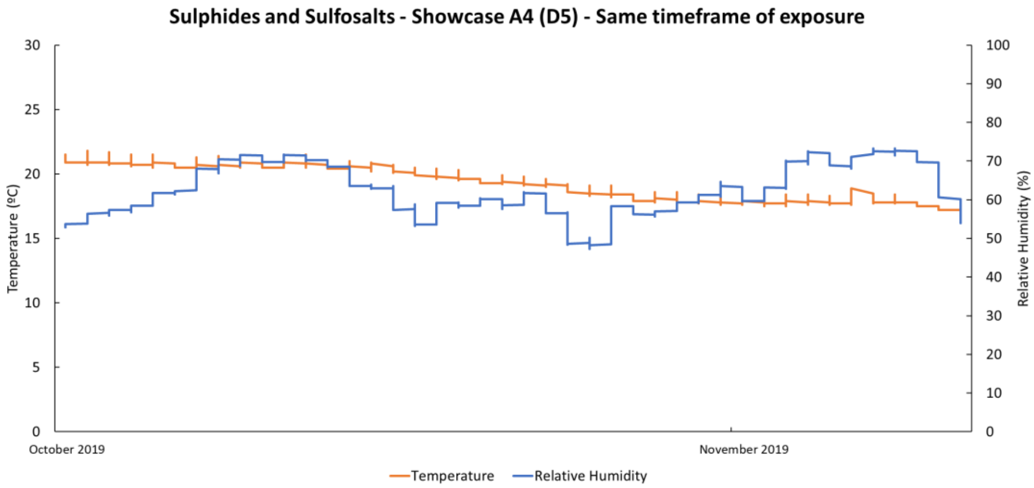


Figure 1.30 – Same timeframe of exposure monitoring values of T and RH from thermohygrometer inside showcase A4 (D5). The average value and deviation of T is 19,3 ± 1,3 ºC and the average value and deviation of RH is 62,4 ± 6,3 %. Monitoring period: 23/10/2019 – 03/12/2020.

The RH level inside the showcase with Pyrite and Marcasite (A4) presented an average of full monitoring 60,5 ± 6,2 % (minimum of 41,1% and maximum of 77,4%). This value is considered to be higher than the recommended by the literature as mention before (30% RH). Despite this RH measure, the two specimens do not show visual signs of deterioration.

The showcase holding native metals (such as Silver and Copper) (A3) was not monitored, but it is most likely to have the same conditions as the others showcases-type-A. Therefore, the RH for these minerals is higher than the recommended as describe above (between 35% and 55%), despite there being no signs of deterioration.

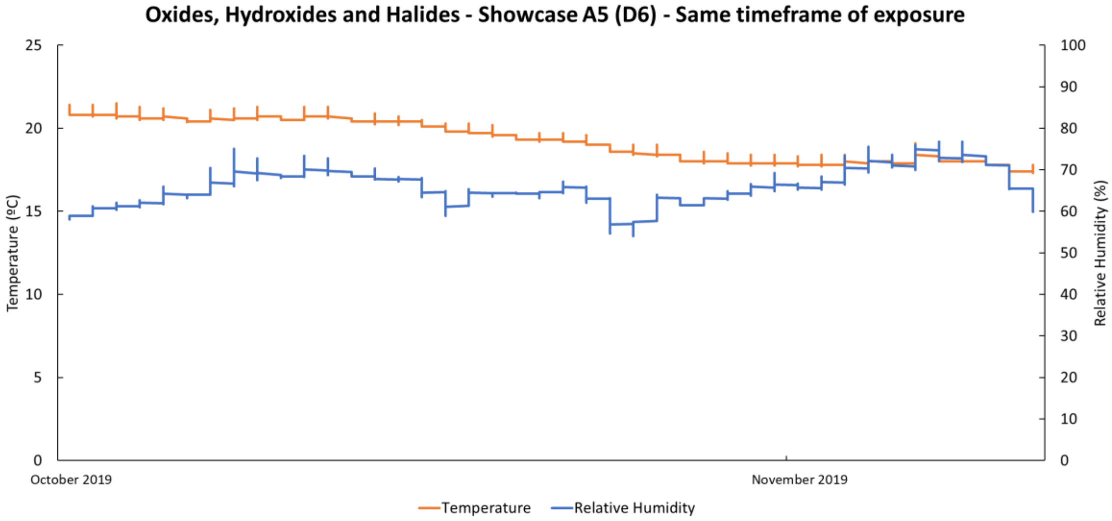


Figure 1.31 – Same timeframe of exposure monitoring values of T and RH from thermohygrometer inside showcase A5 (D6). The average value and deviation of T is 19,3 ± 1,2 ºC and the average value and deviation of RH is 66,0 ± 4,6 %. Monitoring period: 23/10/2019 – 03/12/2020.

According to the Curator, Halite (Figure 1.19) showed signs of deliquescence that started after changing from fluorescent light to LED. The specimen appeared to be slightly wet, and some crystals were loose. Currently, the showcase has a silica gel bag near the specimen to decrease and stabilize RH. The RH values monitored inside Halite showcase (A5) presented an average of full monitoring 67,1 ± 5,5 % (minimum of 48,9% and maximum of 80,7%). Even with the silica gel bag present, RH values are still very high. Nevertheless, the RH fluctuation is lower in this showcase when compared to others. This may be due to the silica bag.

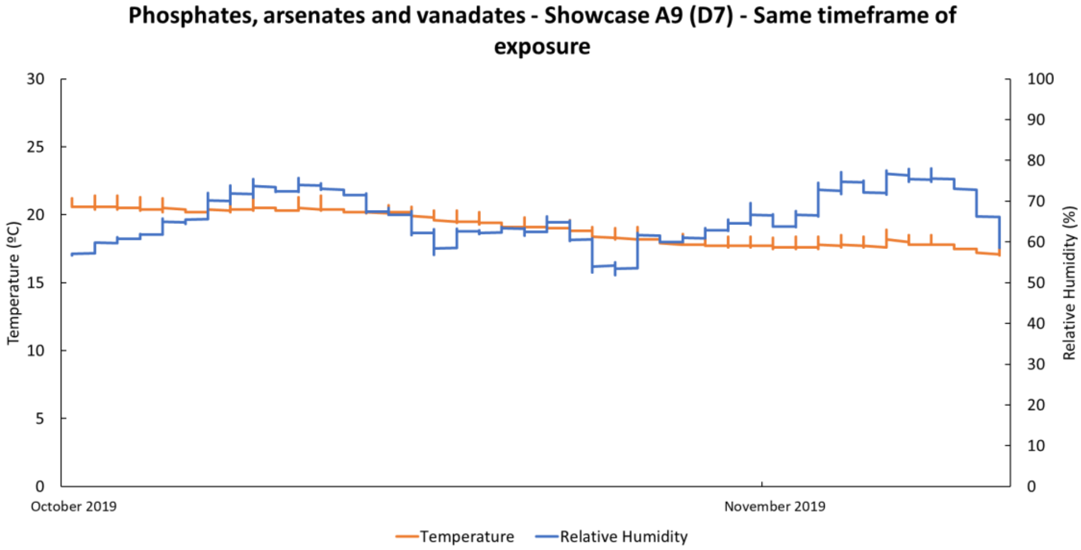


Figure 1.32 – Same timeframe of exposure monitoring values of T and RH from thermohygrometer inside showcase A9 (D7). The average value and deviation of T is 19,2 ± 1,2 ºC and the average value and deviation of RH is 66,2 ± 6,1 %. Monitoring period: 23/10/2019 – 03/12/2020.

The RH values inside the showcase with two Autunite (A9) presented an average of full monitoring 66,1 ± 6,8 % (min. 46,8% and max. 82,5%). Thus, it is not likely that the efflorescence will occur (Autunite efflorescence occurs at 40 ± 5% RH [32]). However, the RH is still higher than the recommended for general mineral collections, despite neither of these minerals' present visual signs of decay.

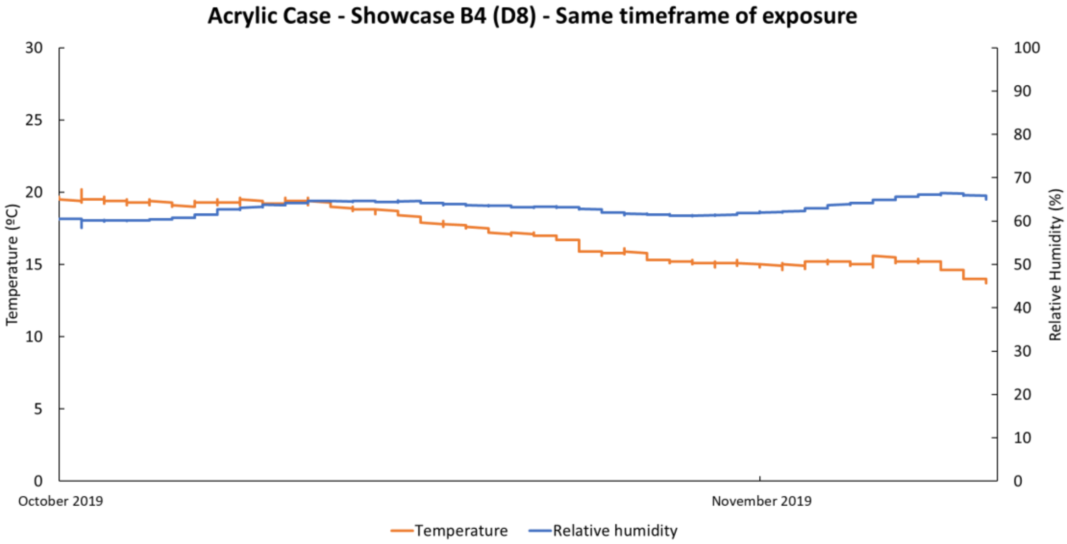


Figure 1.33 – Same timeframe of exposure monitoring values of T and RH from thermohygrometer inside showcase B4 (D8). The average value and deviation of T is 17,0 ± 1,9 ºC and the average value and deviation of RH is 63,0 ± 1,7 %. Monitoring period: 23/10/2019 – 03/12/2020.

The showcase-type-B (Figure 1.33) showed fewer variation of RH than showcases-type-A (Figure 1.30, Figure 1.31, Figure 1.32). This is also well represented in the full monitoring values. Thus, Showcases-type-B are better sealed and therefore it is likely that they will accumulate less dust as the Curator stated.

1.4. Conclusion

The MUHNAC's mineral collection has 10 756 minerals, wherein 170 are in "Minerals. Identify, classify" exhibition and 10 529 are in storage. The collection was arranged according to the Dana Classification and the most abundant minerals are from silicates mineral class.

The mineral collection was characterized by special mineral characteristics. There are 1 466 light-sensitive minerals, 773 are RH-sensitive, 249 were identified as potentially toxic minerals, 117 are asbestos, and 339 minerals are radioactive. Light-sensitive and RH-sensitive minerals on display are the most susceptible to damage due to the current conditions of the exhibition room.

Regarding the pollutants' value estimations, particulate matter <2,5 µm, is considered to be higher than the maximum limits proposed by Tétreault [27]. Therefore, in Chapter 2, the risk due to particulate matter will be considered for the exhibition room since the room does not have any filtration control system.

The condition survey carried out in storage included minerals with incorrect support, fragile minerals with projecting crystal structures and minerals currently decaying. While in the exhibition, the survey comprised minerals placed on high supports, fragile minerals, minerals with projecting crystal structures and minerals currently decaying. A general condition survey of Pyrite/Marcasite specimens was conducted.

The storage room presents RH and T conditions within the general limits recommended. However, Pyrite specimens inside the drawer present a RH slightly above the recommended for Pyrite. In the exhibition room, the T values are within the recommended values, but the RH values measured are higher than the recommended and have large fluctuations. The showcase-type-B presented to have lower value of illuminance targeting the mineral and fewer RH fluctuation than showcases-type-A and C.

2.1. Introduction

Risk assessment is the combination of risk analysis and risk evaluation [53]. Risk analysis includes the definition of what values are at risk, identification of all generic and specific risks for the collection, while risk evaluation aims the estimation of the magnitude of each risk [53]. The magnitude was calculated in order to provide a well-informed decision making, considering the type of mitigation strategies possible to implement.

The Cultural Property Risk Analysis Model (CPRAM) developed by the geologist Robert Waller from the Canadian Museum of Nature [53] was selected for this work. This author developed and applied the CPRAM to a mineral collection, an herbarium and a fish collection [53]. Moreover, the CPRAM model has been successfully applied to distinct collections such as a paper based collection kept in an archive storage [54], artifacts and specimens pertaining to the Royal British Columbia Museum [55]. In 2013, the American Museum of Natural History used this model to identify a complete picture of its collections priorities and to do the overall risk assessment of its research, exhibit and library/archive collections [56]. The CPRAM model was also applied to an oil painting collection on display in a historical house [57] and to the storage rooms of Lisbon Museum [58].

The CPRAM is a conceptual, semi-quantitative and risk-screening model [53]. The result value in this method does not need to be an exact number [59]; it is the relationship between the various magnitudes of risk that is really important. The model allows to calculate the Magnitude of Risk (MR) for a period of 100 years and hierarchize the specific risks, providing help in the decision making and management of the collection [59]. The model is founded on the ten agents of deterioration proposed by the Canadian Conservation Institute (CCI): physical forces, fire, water, thieves and vandals, pests, pollutants, light, incorrect temperature, incorrect relative humidity and dissociation [6].

2.2. Methodology

The magnitude of risk (MR) to collections is calculated by the product of Fraction Susceptible (FS), Loss in Value (LV), Probability (P) and Extent (E) [53]:

$$\boldsymbol{MR = FS \times LV \times P \times E}$$

FS is the most vulnerable fraction of the collection to loss of value. LV is the maximum possible reduction in utility of the FS. P is the likelihood of an incident may cause damage within a century (100-year period). E is the measure used to indicate which Fraction Susceptible will result in a loss of value over a century [53]. This parameters and MR vary between 0 and 1.

In this study, all parameters are calculated according to the minerals that are currently in storage and exhibition. Some specific risks only happen in the storage room, while others only occur in the exhibition room. The variable Extent is calculated as a function of the Fraction susceptible in order to simplify risk magnitude estimation. When there is no adequate basis to estimate the Extent, the experience of the mineral staff was taken into consideration. LV estimation assume all mineral are equally important.

Risks can be divided into three types according to its frequency and severity [53]: “Type 1” is considered a rare and catastrophic risk, such as an earthquake. “Type 2” is defined as sporadic and severe, such as incorrect handling. “Type 3”, is a constant and gradual risk, for example due to incorrect temperature. When the risk is type 1, E value is always maximum (E=1). For risk type 2 and 3, P value is always equal to 1, since the probability of an event to happen in 100 years is certain.

Figure 2.1 shows the criteria for estimation of LV values created and applied to the MUHNAC’s mineral collection.

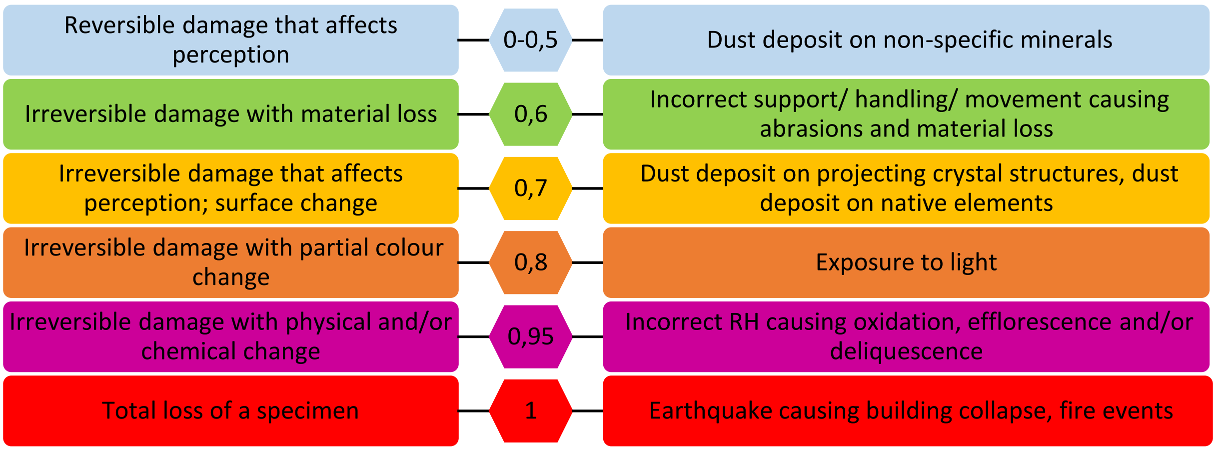


Figure 2.1 – Criteria for estimation of Loss in Value on the left and respective examples on the right.

Once the risks associated to the collections are identified and the assessment of the magnitude of each risk has been done, it is possible to hierarchize the risks and propose mitigation strategies.

2.3. Results and discussion

The ten agents of deterioration proposed by CCI were considered for the MUHNAC’s mineral collection. The risk magnitude was calculated for physical forces, fire, pollutants, light, and incorrect relative humidity. Detail explanation of MR calculation can be consulted in Appendix IV. The remaining agents of deterioration were not calculated, since those risks were minimal or non-existent for this mineral collection.

2.3.1. Physical forces

Physical forces is considered the most common agent of deterioration for minerals [49]. Physical damage can be seen through fissures, cracks, breaks, surface abrasion and material loss. Movement (e.g., building vibrations, operating drawers), incorrect handling (e.g. removal/placement of specimens), and incorrect support (e.g. minerals without padded support can jostle against the card tray or other minerals; minerals with projecting crystal structures on the lower area and without padded support are more prone to damage due to gravitational forces) are some examples of actions that cause physical damage. Some specimens are more sensitive than others, such as those with projecting crystals structures (e.g., Mesolite - Figure 1.16, Stibnite - Figure 1.18) or minerals with low hardness that can be scratched by a fingernail (e.g., Gypsum).

As it was mentioned in Chapter 1 - 1.1.4. , Lisbon is a region classified with high susceptibility to earthquakes (Appendix I - I.2.) [16], [17]. Since there are multiple occurrences of seismic activity in Portugal, two types of risk for earthquakes were considered: type 1 rare and catastrophic, and type 2 sporadic and severe [54]. Type 1 is considered as a strong earthquake with intensity equal or superior to 5 in Richter Magnitude Scale, similar to the 1755 earthquake. This type of earthquake can cause building collapse and/or toppling of cabinets/showcases. While type 2 is considered as a lighter earthquake with intensity <5, related to small quakes as discussed in Chapter 1 - 1.1.4. This type can cause movement, mixture and/or toppling of specimens.

Two types of damage were considered for physical forces: small abrasions/partial breakage and whole breakage of specimens. There is no record that the latter occurred due to incorrect handling and support. Therefore, the whole breakage of specimens will only be considered for earthquakes with intensity equal or superior to 5 in Richter Magnitude Scale. The general condition survey described above (Chapter 1 - 1.3.3.) contributed to the assessment of the specific risks considered. The estimation of the parameters and MR for the specific risks of earthquakes, incorrect handling, and incorrect support are discussed in Appendix IV – IV.1. and presented in Table 2.1.

Table 2.1 – MR calculation for the specific risk due to Physical Forces. The explanation tables presented can be found in Appendix IV-IV.1.

Specific risk		Type of risk	Risk magnitude calculation					Room
			FS	LV	P	E	MR	
PF/a)	Earthquake with intensity ≥5 in Richter Magnitude Scale causing building collapse and/or toppling of cabinets/showcases. (Table IV.6)	1	1	1	0,377	1	**0,377**	Storage
								Exhibition
PF/b)	Earthquake with intensity <5 in Richter Magnitude Scale causing movement and/or toppling of minerals. (Table IV.7)	2	0,794	0,6	1	0,08	**0,038**	Storage
			0,712	0,6	1	0,132	**0,056**	Exhibition
PF/c)	Incorrect handling causing abrasion. (Table IV.8)	2	1	0,6	1	0,063	**0,038**	Storage
			-	-	-	-	**-**	Exhibition
PF/d)	Incorrect support causing abrasion. (Table IV.9)	3	0,794	0,6	1	0,363	**0,173**	Storage
			0,024	0,6	1	0,25	**0,004**	Exhibition

2.3.1.1. Risk mitigation strategies

In the storage room, metal cabinets could be fixed to the floor/walls to prevent toppling in case of an earthquake with intensity ≥5 (analysis on centre of gravity and weight distribution of cabinets should be made). The program of repackaging all minerals with padded supports (Table 1.1 – Type E) should be continued to reduce abrasion. When specimens are overcrowded, a Stratocell® sheet or a cardboard barrier can be placed between specimens. Minerals that are too large to stay inside drawers should be moved to the cabinets with shelves. Regarding incorrect handling, labels should be clearly visible to reduce the need to handle several minerals to find a specific one (some labels are placed underneath the mineral or on the side of the card tray). Special care should be taken with drawers which are difficult to open (drawers should be regularly checked), minerals with projecting crystal structures, and the placement/removal of a mineral from the drawer. It is advisable to open the drawer entirely and horizontally to reduce the probability of the mineral hitting other surfaces when taking it out.

For the exhibition room, individual supports that are susceptible to fall could be fixed to the showcase base and the showcases itself can be fixed to the floor, respectively. This could reduce the possibility of toppling and movement of specimens due to earthquake events. Minerals with projecting crystal structures (e.g. Stibnite, Figure 1.18) should have a padded support in the most sensitive areas. Note that damage due to incorrect handling may also occur during cleaning procedures and exhibitions preparation, so special care should also be taken.

2.3.2. Fire

Fire events can be totally devastating by the complete consumption of the building or result in substantial damage by combustion, pollution (soot deposition), high temperature, water (to extinguish the fire), physical forces (crushing specimens due to the activity of the firefighters, collapse of the building structures), and thieves and vandals (opportunists during the chaos) [60]. This risk can be caused by unsafe use/practices (e.g., smoking, open flame activities, renovation work), arson, building system failure (e.g. malfunction of HVAC system, electrical panel boxes), and small apparatus malfunction (e.g. small boilers).

Figure 2.2 – An example of a fragmented Quartz affected by smoke and black soot and material loss from the fire. This specimen is no longer part of the collection; serves as exemplification of the fire damage. Image taken on 13/02/2020.

Figure 2.3 – An example of Calcite affected by smoke and black soot from the fire. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.1473. Image taken on 13/02/2020.

As it was mention in Chapter 1 - 1.1.5. , the last violent fire was in 1978 which led to the loss of two thirds of the mineral collection. The worst effects on the saved minerals were the fragmentation, water damage on labels and deposit of a dark layer on the surface of the specimens (Figure 2.2, Figure 2.3).

A fire of those dimensions is not expected to occur again since new facilities, policies and fire codes were implemented. Currently MUHNAC has reinforced concrete walls, several smoke detectors, a manual fire alarm, various fire extinguishers, 24h security vigilance and several hydrants surrounding the building. The electricity board on the exhibition room is turned off when it is closed to visitors, while in the storage room only the lights in the room are turned off (some equipment needs to keep functioning, such as the dehumidifier). The museum's central system is directly connected to the museum’s security booth, where there is a monitor that alerts to the sector in question. After analysing the situation, the Firefighter Station (*Campo de Ourique’s* Firefighter Station, approximately 4 minutes from MUHNAC) is then contacted.

The fire risk assessment was followed by Tétreault’s study [60], which was also applied by Fernandes [61] and Ramalhinho [62]. Regarding the sets of measures to prevent, detect and respond to a potential active fire within an institution, it is possible to establish a Control Level (CL) for a museum [60]. The CL can be established from a scale of 1 to 6 in which CL1 represents the least efficient protection against fire, while CL6 represents the best protection [60]. MUHNAC is considered as a CL1 museum (Figure IV.10 in Appendix IV-IV.2.). Thus, the frequency of a fire occurrence for CL1 is estimated to occur every 140 years and the extent of a fire confined to a room is 29% and to the building is 26% [60].

The estimation of the parameters and MR for the specific risks of fire ignites for an entire building consumption and a fire confined to a single room are discussed in Appendix IV – IV.2. and presented in Table 2.2.

Table 2.2 – MR calculation for the specific risk due to Fire. The explanation tables presented can be found in Appendix IV-IV.2.

	Specific risk	Type of risk	Magnitude risk calculation					Room
			FS	LV	P	E	MR	
F/a)	Fire ignites and consume entire building and contents. (Table IV.10)	1	1	1	0,186	1	**0,186**	Storage
								Exhibition
F/b)	Fire ignites in a single room, consume specimens and causing soot damage. (Table IV.11)	1	1	1	0,207	0,9	**0,186**	Storage
			1	1	0,207	1	**0,207**	Exhibition

2.3.2.1. Risk mitigation strategies

Sprinklers systems could be implemented for storage and exhibition. Sprinklers have the disadvantages of promoting water damage; however, modern systems are designed to operate only in the presence of a heat source and will close off once the heat source has been neutralised. In the storage, wooden windows should be removed, and wooden doors should be replaced by fire doors. This proposal is not recommended for the exhibition room since it would significantly influence the historic aesthetic of the building. It is advisable the periodic verification of the smoke detectors, alarm system, fire extinguishers and electric board.

2.3.3. Pollutants

Particulate matter, or dirt, can be divided in two main types: formation of an intrinsic material, for example metallic corrosion products; and foreign material to the specimen, also referred as dust and contains particulates such as soot and mould [63]. Within the second type, it is crucial to understand that over a period of time, dust can become combined with the surface by a physically, chemically and/or electrostatically processes [63].

Particulate matter will impact aesthetical observation, visitor's perception and apparent colour change (Figure 2.4, Figure 2.5). Minerals which have projecting crystal structures are easily damaged by dust cleaning and most of them are not cleaned (e.g., Anhydrite and Asbestos). If particulate matter is allow to accumulate, it may initiate or accelerate corrosion since the particles can absorb moisture and acids (especially damaging for native elements) [38].

Figure 2.4 – Quartz amethyst with particulate matter inside Showcase Type C. Image taken on 09/01/2021.

Figure 2.5 – Quartz amethyst partially clean inside Showcase Type C. Image taken on 09/01/2021.

Showcases are regularly cleaned with a vacuum cleaner and dried cloth. Most minerals are cleaned with a soft brush and a vacuum cleaner. The assessment of this risk considered the particulate matter accumulation in different types of specimens, inside distinct showcases. However, there was no adequate basis for estimating of the Extent on particulate matter accumulation on showcases, so the experience of the mineral staff was taken into consideration. The scale on Figure 2.6 was proposed for the estimation of the parameter Extent. The parameters and MR estimations for the specific risks of pollutants are detailed in Appendix IV – IV.3. and presented in Table 2.3.

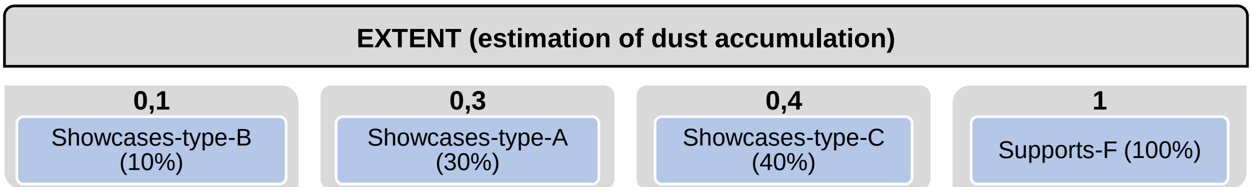


Figure 2.6 – Proposed scale for Extent estimation.

Table 2.3 – MR calculation for the specific risk due to Pollutants. The explanation tables presented can be found in Appendix IV- IV.3. .

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	**LV**	**P**	**E**	**MR**	
P/a)	Particulate matter deposit in non-specific-minerals inside showcases-type-A. (Table IV.12)	3	-	-	-	-		Storage
			0,888	0,5	1	0,3	**0,132**	Exhibition
P/b)	Particulate matter deposit in non-specific-minerals inside showcases-type-B. (Table IV.13)	3	-	-	-	-		Storage
			0,024	0,5	1	0,1	**0,001**	Exhibition
P/c)	Particulate matter deposit in specimens inside showcase-type-C. (Table IV.14)	3	-	-	-	-		Storage
			0,006	0,5	1	0,4	**0,001**	Exhibition
P/d)	Particulate matter deposit in specimens on supports-F. (Table IV.15)	3	-	-	-	-		Storage
			0,012	0,5	1	1	**0,006**	Exhibition
P/e)	Particulate matter deposit in minerals with projecting structures inside showcases-type-A. (Table IV.16)	3	-	-	-	-		Storage
			0,029	0,7	1	0,3	**0,006**	Exhibition
P/f)	Particulate matter deposit in minerals with projecting structures inside showcases-type-B. (Table IV.17)	3	-	-	-	-		Storage
			0,006	0,7	1	0,1	**0,0004**	Exhibition
P/g)	Particulate matter deposit in native elements inside showcase-type-A. (Table IV.18)	3	-	-	-	-		Storage
			0,035	0,7	1	0,3	**0,007**	Exhibition

2.3.3.1. Risk mitigation strategies

In the exhibition, an air filtration system and better insulation of windows and showcases should be implemented to reduce particulate matter accumulation. Minerals with projecting crystal structures inside showcase-type-A are more prone to damage since they cannot be cleaned – these showcases should have priority to decrease particulate matter accumulation. Minerals on supports-F need be regularly monitored and cleaned or moved inside a showcase. Note that the carpet may be part of the particulate matter production. Therefore it should be considered to change the type of floor. Electrostatic dust collectors can be applied to monitored particulate matter deposition.

2.3.4. Light

Many minerals can experience colour changes or be deteriorated by the action of light [40], [43], [64]. Light-sensitive minerals can be faded by exposure to light, others become discoloured, and others can be transformed into other compounds [49]. A number of sulphides, halides and chromates are susceptible to deterioration by exposure to light and oxygen [40]. Most of the processes involved in colour alterations are not fully understood and are still under research [30], [43].

Different impurities or imperfections can influence stability (e.g. some brown topaz are stable to light, while others fade rapidly) [30]. However, not all colour changes are permanent, after a period of proper storage (e.g. replaced in the dark) some minerals may be restore their original colour [30], [34].

The light risk assessment considered Nassau's study on light-sensitive minerals [30]. The author divides these minerals into three groups:

- Light-induced colour changes (LC) without any other physical or chemical changes - may or may not be reversible (e.g., the faded colour of blue Celestite may return to its original colour if stored in the dark): 24 minerals on exhibition;
- Light-induced decompositions producing significant bulk physical or chemical changes (LD) - irreversible effect (e.g., Cinnabar becomes darker with the conversion to black Metacinnnabarite; red Realgar transformation to yellow Pararealgar - Figure 1.25): 2 minerals on exhibition;
- Light-accelerated surface reactions with air, moisture, and/or pollutants (LA) - irreversible effect (e.g., Vivianite darkens on exposure to light and air, and it can also disintegrate - Figure 1.27): 6 minerals on exhibition.

For this generic risk, the three groups described above will be considered in the same specific risk to simplify risk magnitude estimation. As discussed above in Chapter 1 - 1.3.2. and 1.3.5.1. , there are 32 light-sensitive minerals on display, from which 1 has already suffered damage and 1 is suspected to. Also, the 2 minerals that suffered changes in a previous exhibition will also be considered for Extent estimation. The parameters and MR estimations for the specific risks of the three type of light damage are discussed in Appendix IV – IV.4. and presented in Table 2.4.

Table 2.4 – MR calculation for the specific risk due to Light. The explanation tables presented can be found in Appendix IV-IV.4.

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	LV	P	E	MR	
L/a)	Light-induced colour changes, decompositions, and light-accelerated surface reaction with the atmosphere. (Table IV.19)	3	-	-	-	-	**-**	Storage
			0,188	0,8	1	0,481	**0,072**	Exhibition

2.3.4.1. Risk mitigation strategies

Light-sensitive minerals should not be on display. If it is necessary to display, the light lamps could be changed so the lux value will not be superior to 50 lux as discussed above. Reducing the intensity of illuminance can minimise the damage, although note that light remains cumulative [34]. Minerals can also be placed further from the light source to lower the illuminance that reaches them or only be visible when a visitor approaches the showcase (e.g., implementation of light sensors or a button to illuminate a light-sensitive mineral). The change of showcases could also be evaluated (showcases with light focus outside the case, such as showcase-type-B may present a good solution). Nevertheless, it is fundamental that all light-sensitive minerals be photographed and documented to evaluate eventual changes and make a decision to prevent further damage.

2.3.5. Incorrect relative humidity

Some minerals are susceptible to suffer chemical and physical changes due to the incorrect RH. Hydrates and pyrites can crumble/weep above or below a critical RH level [49]. The most common damages in minerals due to incorrect RH are corrosion/oxidation, efflorescence, and deliquescence reactions.

Corrosion includes any transformation a specimen may undergo by reaction with atmospheric constituents other than water vapour (such as carbon dioxide, sulphur oxides, organic acids, dust) [32], [38]. The corrosion of native metals (e.g. Silver, Copper, Antimony) occurs due to high levels of RH [40], [52]. This reaction can lead to surface tarnishing to formation of serious pitting [40]. Pyrite oxidation is considered the most well-known corrosion process in minerals [32]. Also known as "pyrite decay", "pyrite rot" and "pyrite disease", it occurs when the mineral reacts with atmospheric oxygen and water [32], [48], [50], [65]. The reaction, which is fully explained in Appendix III, is accelerated when RH is above 60% [65]–[67]. However, not all specimens containing Pyrite will decay [46]. Specimens with compact, large, and very well-formed crystals seem to be more stable than pyrite occurring in assemblages and fossil material, microcrystals or small spherules/nodules [45], [46], [65]. Oxidated Pyrite specimens are often easily recognisable through visual observations: loss of surface shine (dull/grey), development of powdery efflorescence (white/yellow/grey/green), sulphurous smell, expansion cracks [8], [40], [46]–[49], [65], [67], [68]. The effects can also result in acid burns on storage media and labels due to sulphuric acid, and in extreme situations, into complete destruction of specimens [46]–[48], [65]. Examples of Pyrites in good condition and in poor condition are illustrated in Figure 1.20 and Figure 1.21.

Incorrect RH may also initiate efflorescence on some minerals. Efflorescence occurs through the loss of water of crystallisation from a hydrated mineral in response to a lowering of the ambient RH below its equilibrium water vapour pressure [3], [40], [69]. The loss of the water molecules causes the mineral to shrink in size, form slight fractures and splits in crystal structures to the complete disintegration of a crystal into a formless mass of microcrystalline powder [32], [69]. Some examples of specimens that that can undergo efflorescence are Autunite and Borax. Autunite can efflorescence at 40% RH [32]. This efflorescence does not decrepitates crystals, but instead forms Meta-autunite crystal due to dehydration of Autunite crystal – crystals open along the cleavage plane in response to shrinkage [32]. Borax dehydrates to Tincalconite at 50% RH and crystals become chalky and friable [32], [49].

Certain minerals can undergo deliquescence when exposed to high RH values. It occurs when specimens absorb moisture where ambient RH is above the stability limit of the mineral present [32], [40]. Consequently, specimens can spontaneously dissolve, appear as a stain in absorbent surfaces, become rounded/flattened or be reduced to mere crusts [32]. Some examples of minerals that will dissolve quickly in high RH values are Halite, Melanterite and Trona [40]. Halite can deliquescence at 75% RH [32], [49], Melanterite at 95% [32].

The mineral collection condition survey conducted showed that 204 RH-sensitive minerals had signs of deterioration, wherein 84 are native elements, 91 are pyrite/marcasite and 29 are minerals that undergo humidity-related phase transitions.

The specific risks will be divided into three chemical deteriorations considering corrosion of native metals, oxidation of pyrite/marcasite, and minerals that undergo humidity-related phase transitions (such as efflorescence and deliquescence). Native elements and Pyrite/Marcasite on exhibition were not considered since the specimens are currently in good condition. Thus, the specific risk for these reactions are discussed in Appendix IV–IV.5. and MR calculated in Table 2.5.

Table 2.5 – MR calculation for specific risk due to incorrect RH. The explanation tables presented can be found in Appendix IV-IV.5.

Specific risk	Type of risk	Magnitude risk calculation					Room
		FS	**LV**	**P**	**E**	**MR**	
IRH/a) Incorrect RH resulting in corrosion of native metals. (Table IV.20)	3	0,028	0,95	1	0,282	**0,008**	Storage
		-	-	-	-	**-**	Exhibition
IRH/b) Incorrect RH resulting in oxidation of pyrite/marcasite. (Table IV.21)	3	0,025	0,95	1	0,343	**0,01**	Storage
		-	-	-	-	**-**	Exhibition
IRH/c) Incorrect RH resulting humidity-related phase transitions of minerals. (Table IV.22)	3	0,019	0,95	1	0,142	**0,003**	Storage
		0,029	0,95	1	0,2	**0,006**	Exhibition

2.3.5.1. *Risk mitigation strategies*

Acquisition of thermohygrometers for the storage room should be the first step to keep monitoring environmental control. One thermohygrometer should be placed in the room (for digital data), and the thermohygrograph's sheet should be changed more often. Two thermohygrometers can be placed inside drawers: one for monitoring the blocks on the left side and another for the right side. Moreover, one thermohygrometer should be placed in the hallway outside the storage and another inside the "Geology Storage Room 2". Minerals that can undergo chemical changes should be regularly checked for changes. Pyrite/Marcasite in decay can be addressed by conducting treatments and encapsulating specimens in microclimate conditions. Other minerals (native elements and non-specific minerals) currently decaying need to be evaluated and assessed for treatments.

In the exhibition room, new methods need to be applied to help control RH values and fluctuations. New thermohygrometers with the same location as the ones placed for this study should be added to continue monitor atmospheric conditions. In addition, a thermohygrometer should also be place in showcase A3 (native elements) and another in showcase C1. Since the room does not have finished construction, the process to keep the room in proper atmospheric conditions becomes difficult. Investment in dehumidifiers or a ventilation system similar to the storage can be expensive and non-sustainable to the museum. Furthermore, the entrance door is always open when the exhibition is open to the public. The long-term proposal is to finish the room infrastructure and purchase a central heating, ventilation and air conditioning (HVAC) system for the entire museum. Some alternatives for quick response are as follows: use of caulking tape for doors/windows to improve the room insulation; control RH inside showcases with microenvironments suitable for general mineral collections. Desiccants, such as pre-condition silica gel or, PRO SORB®[2] in cassettes or sachets are usually used inside museum showcases. As stated before, the RH level acceptable for mineral collections is 50 ± 5% RH. Thus, this should be the RH levels inside showcases. Minerals that require a specific RH are currently stable (such as Pyrite and Native metals), nevertheless it is recommended that these specimens be regularly monitored for possible changes instead of creating a microclimate suitable for each mineral's stability. Another proposal is the replacement of showcases-type-A for showcases-type-B since the latter showed better insulation. However, showcase-type-A can be considered to have a better museographic display. All RH-sensitive minerals should be regularly monitored for visual changes. Regarding the Halite mineral on exhibition, digital weight measuring should be taken periodically to control more accurately halite deterioration.

Again, it is fundamental that all RH-sensitive minerals be photographed and documented to evaluate eventual changes and make a decision to prevent further damage.

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[2] PROSOBR® (https://llfa.eu/climate-control/prosorb.html, consulted on October 2020)

2.3.6. Assessment of the magnitudes of risk

The risk magnitude results of the mineral collection are presented in Figure 2.7.

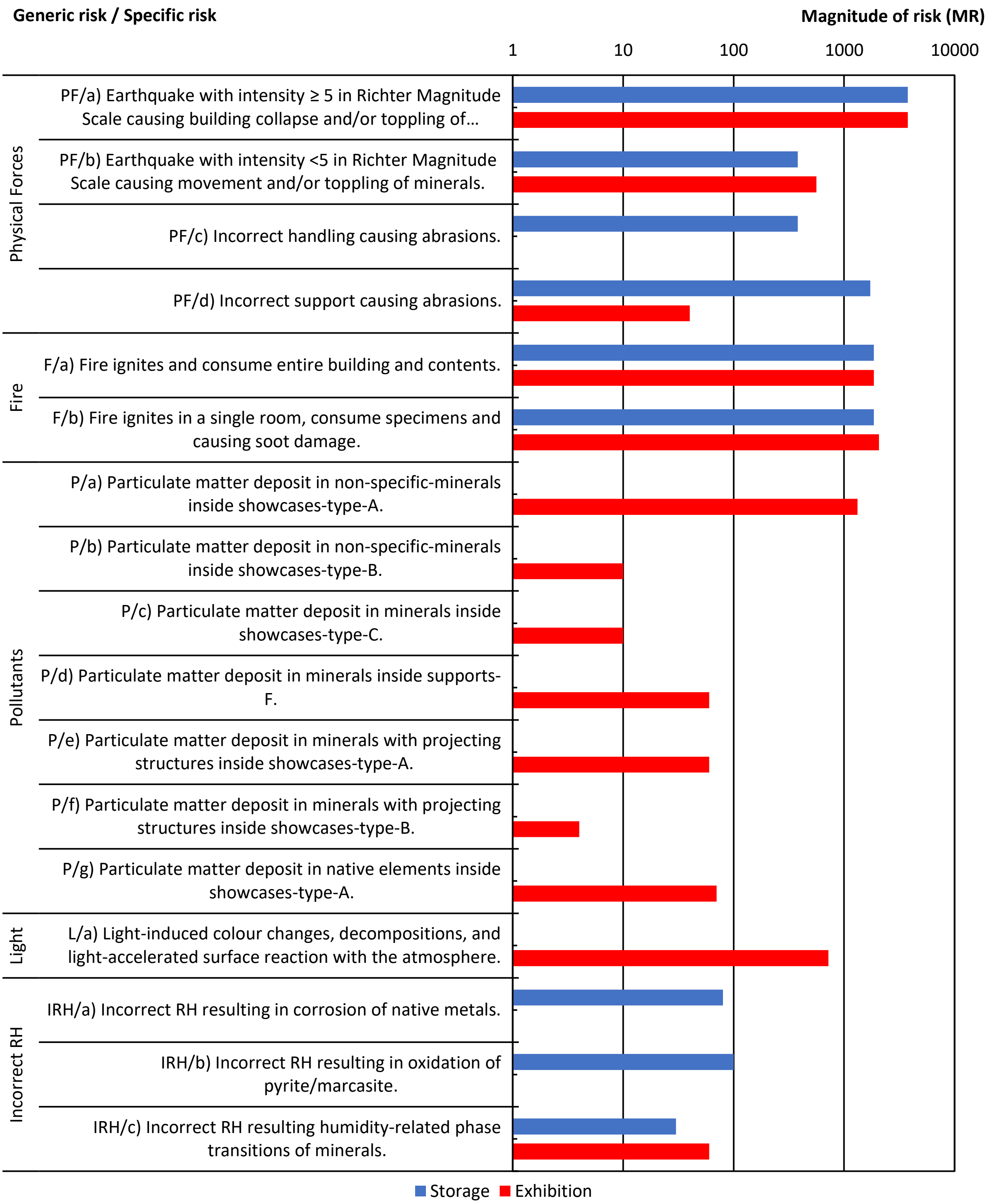

Figure 2.7 – Risk magnitudes calculated for MUHNAC's mineral collection in storage and exhibition. The MR values were multiplied by 10 000 and a logarithmic scale with base 10 was applied to the axis.

2.4. Conclusion

The application of the CPRAM model to MUHNAC's mineral collection made it possible to identify, characterize and quantify specific risks for this collection. The risk assessment highlighted the most significant risks to establish the priority of mitigation strategies.

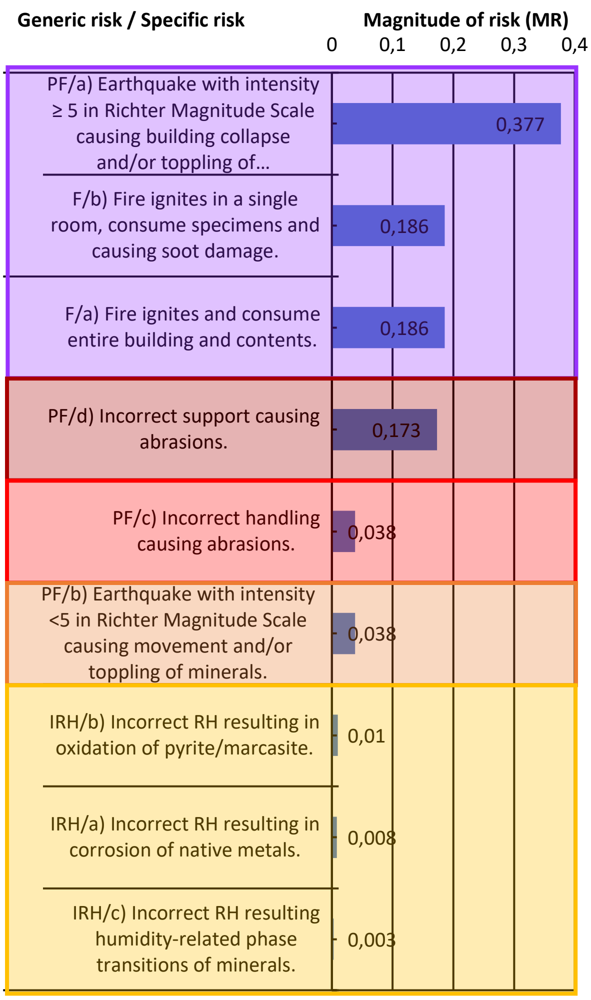

Figure 2.8 – Risk magnitudes calculated in storage by descending order.

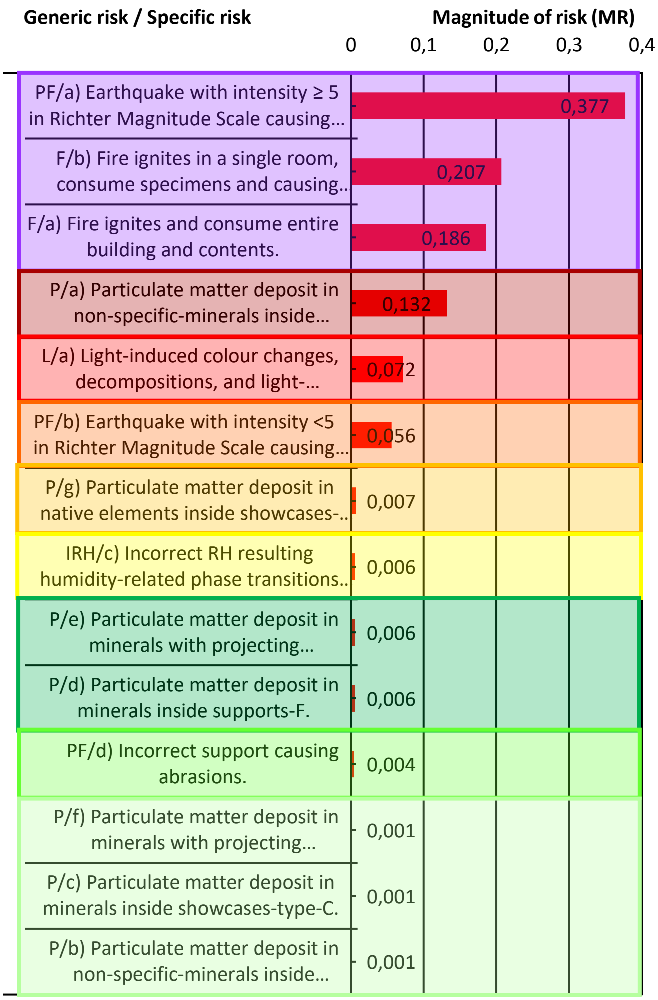

Figure 2.9 - Risk magnitudes calculated in exhibition by descending order.

The highest risks to this collection are due to an earthquake with intensity ≥5 on Richter Magnitude Scale, and fire events. To mitigate these risks, cabinets/showcases and tall supports should be fixed to the walls/floor, and fire doors (when possible) and sprinklers could be implemented in the museum.

Within the storage room (Figure 2.8), the priority should be to continue repackaging minerals with padded supports to reduce abrasion (especially for minerals with projecting crystal structures) (PF/d), PF/b)), conduct a treatment on deteriorated Pyrite/Marcasite specimens (IRH/b)). RH-sensitive minerals that are not currently deteriorating should continue to be regularly checked for changes.

The minerals in the exhibition (Figure 2.9) presented more specific risks than in storage. Particulate matter deposits in non-specific minerals inside showcases-type-A (P/a)) contribute to more than 80%

of the total risks to the mineral collection. This suggests that effort directed at reducing this specific risk will be most significant in reducing overall risks: it can be addressed by investing in an air filtration system and better insulation of showcases to reduce particulate matter accumulation. The lights should be changed to reduce illuminance or specific display techniques for light-sensitive minerals need to be implemented (L/a)). High critical supports can be fixed to the showcase's bases, as well as showcases itself to prevent movement from a possible earthquake with intensity <5 (PF/b)) (centre of gravity and the weight distribution must be studied). RH values should be controlled by finishing the room construction, improving the insulation of doors/windows, invest in a dehumidifier, and/or create individual microclimates inside showcases (IRH/c)). RH-sensitive minerals should continue to be regularly checked for possible changes, including native elements and Pyrite/Marcasite minerals, although they are not in decay. Showcases-type-B proved to have lower lux values, lessened fluctuations of RH, and are suspected to have less particulate matter accumulation. Replacing showcases-type-A for showcases-type-B may be a good solution as it reduces several risks simultaneously, although showcases-type-A can be considered to have a better museographic display. It is important to highlight that all minerals in the collection should be photograph for object documentation and to identify possible changes.

The generic risk of thieves and vandals was not considered in both rooms since there are no records of stolen/vandalized minerals in these rooms. However, the security within the storage and exhibition can still be improved by acquiring surveillance cameras, and an alarm system with motion detectors when the museum closes. Vandalism can also be reduced by requesting visitors to leave their belongings at the museum entrance, placing limitation barriers for supports-F and hiring exhibition staff.

3.1. Introduction

Risk to safety and health may also arise in collections containing potentially toxic, radioactive and asbestos minerals. The staff in charge of the mineral collections is responsible for protecting themselves, other museum staff and visitors from possible potential health risks. It is crucial to understand the potential danger and how to proceed with these hazardous specimens. Careful handling procedures should be carried out with all specimens (not only the specimens known to be hazardous), especially considering some minerals specimens are not fully characterised (some elements may not be identified in the mineral name). Card trays should be handled rather than specimens themselves. All cabinets housing these minerals should be considered in the museum emergency planning [36], [70]. Identification and labelling of the hazard, use of appropriate personal protective equipment (PPE) when handling, proper storage materials and ventilation systems are some of the procedures to follow. Advice on radiation and asbestos protection, and knowledge on the regulations implemented by the country should be sought.

The main routes of exposure from hazardous specimens are through inhalation, ingestion and absorption [71] (Figure 3.1). Therefore, minerals should be handled as minimum as possible.

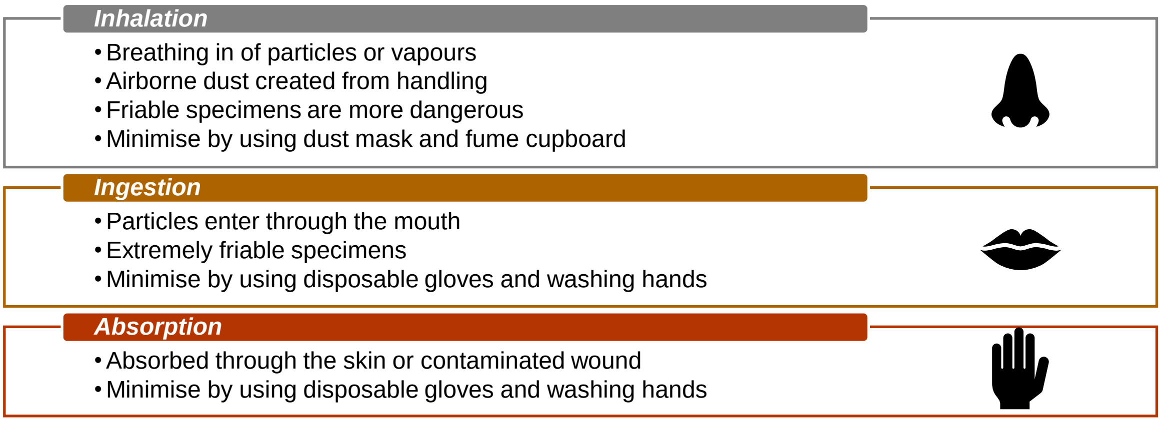

Figure 3.1 – Different routes of exposure from hazardous specimens after Freedman (2012) [71].

These minerals should always be kept dust-free due to possible exposure of particles to air space, especially friable/powdery specimens.

3.2. Methodology

Potentially hazardous minerals were divided in three groups: potentially toxic, asbestos, and radioactive minerals. Both asbestos and radioactive minerals are also toxic, however, these two types of hazards are assessed individually due to their specific hazardous problems.

A Hazardous Mineral Survey was conducted in May 2020 using Google Forms (Appendix V - V.5.). The questionnaire was developed to gather information regarding the management of hazardous specimens in mineral collections. It was applied to Portuguese and international institutions. A total of 44 of 101 institutions answered the survey. The results contributed to the assembly of the management of these specimens in the case study collection.

New mineral acquisitions should be checked if they are listed in the hazardous minerals references lists and the ionising radiation emission must be measured. The management comprised the eight following steps presented in Table 3.1. A mapping of hazardous minerals locations inside storage/exhibition was assembled for emergencies events (Figure V.22, Figure V.30, Figure V.31). Detailed information on background research, results and discussion of hazardous minerals are presented in Appendix V.

Table 3.1 – Methodology applied for hazardous minerals

Step	Potentially toxic minerals	Asbestos minerals	Radioactive minerals
1	Background research of hazardous minerals and respective safe storage and exhibition.		
2	Identification of toxic, asbestos and radioactive minerals in the mineral collection database through the references lists.		
3	Establishing procedures for safe handling of specimens: workstation, PPE (Appendix V - V.1.).		
4	-	Asbestos assessment. Detailed description of asbestos (species, texture, surface, and quantity of loose fibers).	Radioactive minerals assessment. Radiation levels measurement of all minerals in the collection surveyed by a Geiger counter. Attribution of Low, Weakly and Significantly radioactivity level scale.
5	Verify if storage materials are contaminated with particles (Figure V.13). Respective decontamination of areas: waste was wrapped in tissue paper before disposal and placed inside a Minigrip with respective hazard label. The disposal hazard waste was collected by licensed operators.		
6	Photographic documentation and mapping of hazardous specimens inside storage/exhibition (Figure V.22, Figure V.30, Figure V.31).		
7	Encapsulation of native mercury, mercury-containing specimens (cinnabar)[1], asbestos[2] and radioactive minerals with zipper bags (Mingrip®). Card trays were re-size and provided padded supports when necessary.		
8	Labelling of card trays of toxic minerals (Figure V.16, Figure V.17). Mercury and mercury-containing were also labelled in drawers and Mingrips® (Figure V.14, Figure V.15).	Labelling of drawers, card trays and Mingrips® containing asbestos (Figure V.18 to Figure V.20) and radioactive minerals (Figure V.26 to Figure V.28). Minerals on exhibition were also signalled (Figure V.21, Figure V.29).	

[1] Cinnabar minerals inside the same drawer as native metals, such as gold, silver and copper were encapsulated. As study by Waller, Andrew and Tétreault [23], a reaction between mercury vapour and these metals can form amalgams [23], [29].
[1] Some asbestos were not encapsulated since it presented compact/bladed texture.

3.3. Conclusion

The hazardous minerals management led to the identification and labelling of 249 toxic minerals (16 drawers), of which 10 were encapsulated; 117 asbestos (44 drawers/shelves), wherein 54 were encapsulated and 1 placed inside a *Cristal*® box; and 339 radioactive minerals (89 drawers/shelves), which 150 were encapsulated and 105 placed inside *Cristal*® boxes.

The labels serve the purpose of warning museum staff and visitors to exercise precautions when handling hazardous specimens. Safety procedures and PPE proposed should be carried out when handling these minerals. The specimens' encapsulation was conducted with the aim of improving human health safety by restricting the spread of contamination and lowering the concentration of hazardous emissions. Protocols for monitoring mercury vapour (MUHNAC is currently in process of acquiring equipment to measure mercury vapour), asbestos fibres concentration and radon concentration should be implemented and conducted by licensed operators. These evaluations allow to verify whether the values are within the limits of the regulation in Portugal, and if the present ventilation system is suitable. If radon concentration values are still high, it should be assessed whether the radioactive minerals ought to be transferred to a separate and designated radioactive room.

A Microsoft® Excel worksheet was created which included information regarding mineral data, previous/new storage material, asbestos and radioactive assessments, and photographic documentation. A mapping of hazardous minerals locations in storage and exhibition was assembled for emergency purposes.

All the information collected will be added to the museum collection conservation plan and collection and storage emergency plan (PEAR).

Figure 4.1 shows a summary of the results obtained from the study conducted. Characterization of MUHNAC's building, mineral collection in storage and exhibition, classification system analysis, attribution of special mineral characteristics, condition survey and determination of environmental conditions in both rooms (light, T and RH) were discussed. The CPRAM model was applied to the collection and risk mitigation strategies were proposed. Management on potentially hazardous minerals was also surveyed for human health and safety purposes. Thus, it is expected that this study can contribute to research growth on the care and preservation of mineral collections, and help institutions conduct standard methodologies, and thereby promote the preservation of their mineral collections for future generations, as well as the safeguard of professionals and visitors.

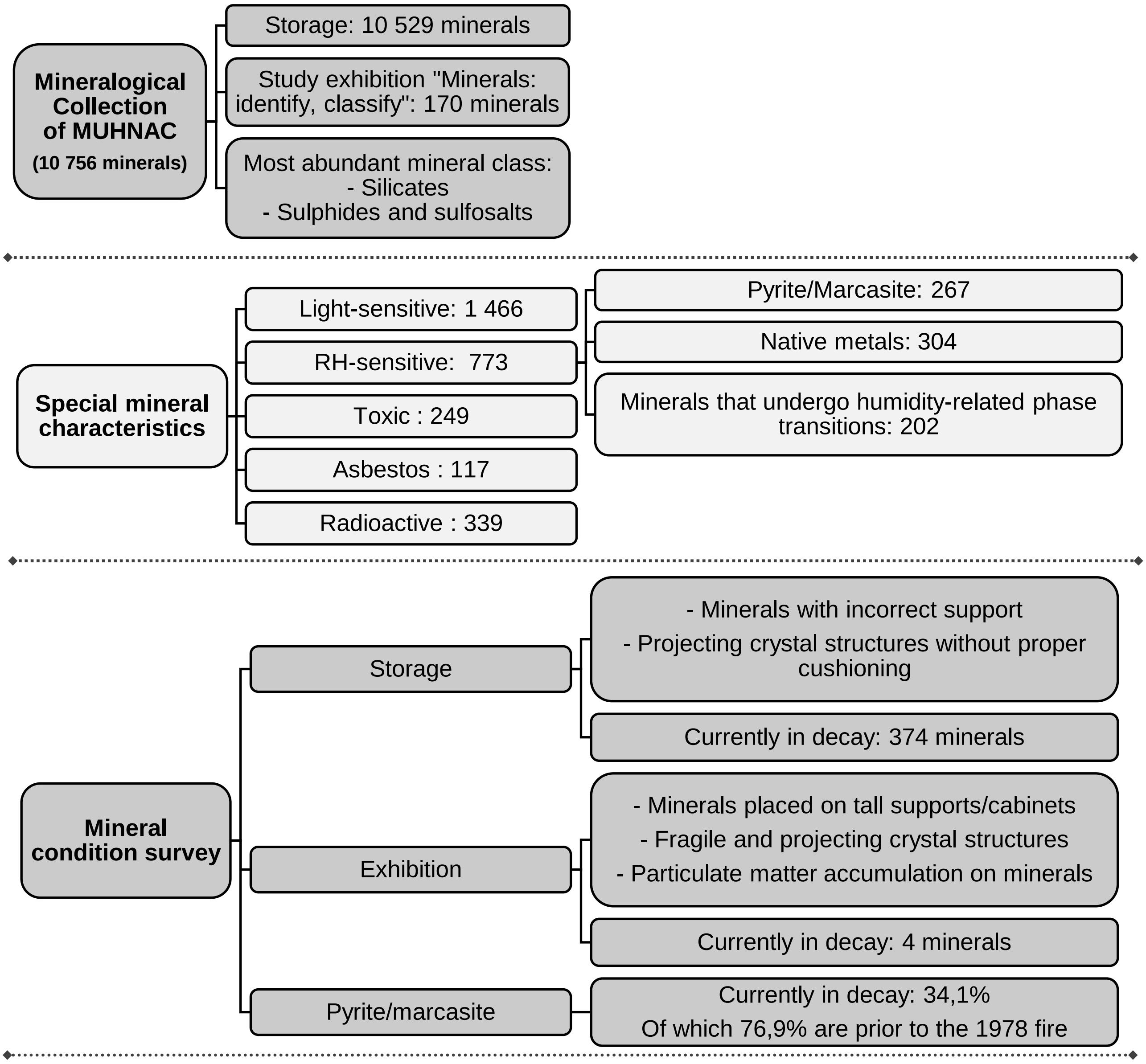

Figure 4.1 – General conclusions of the study.

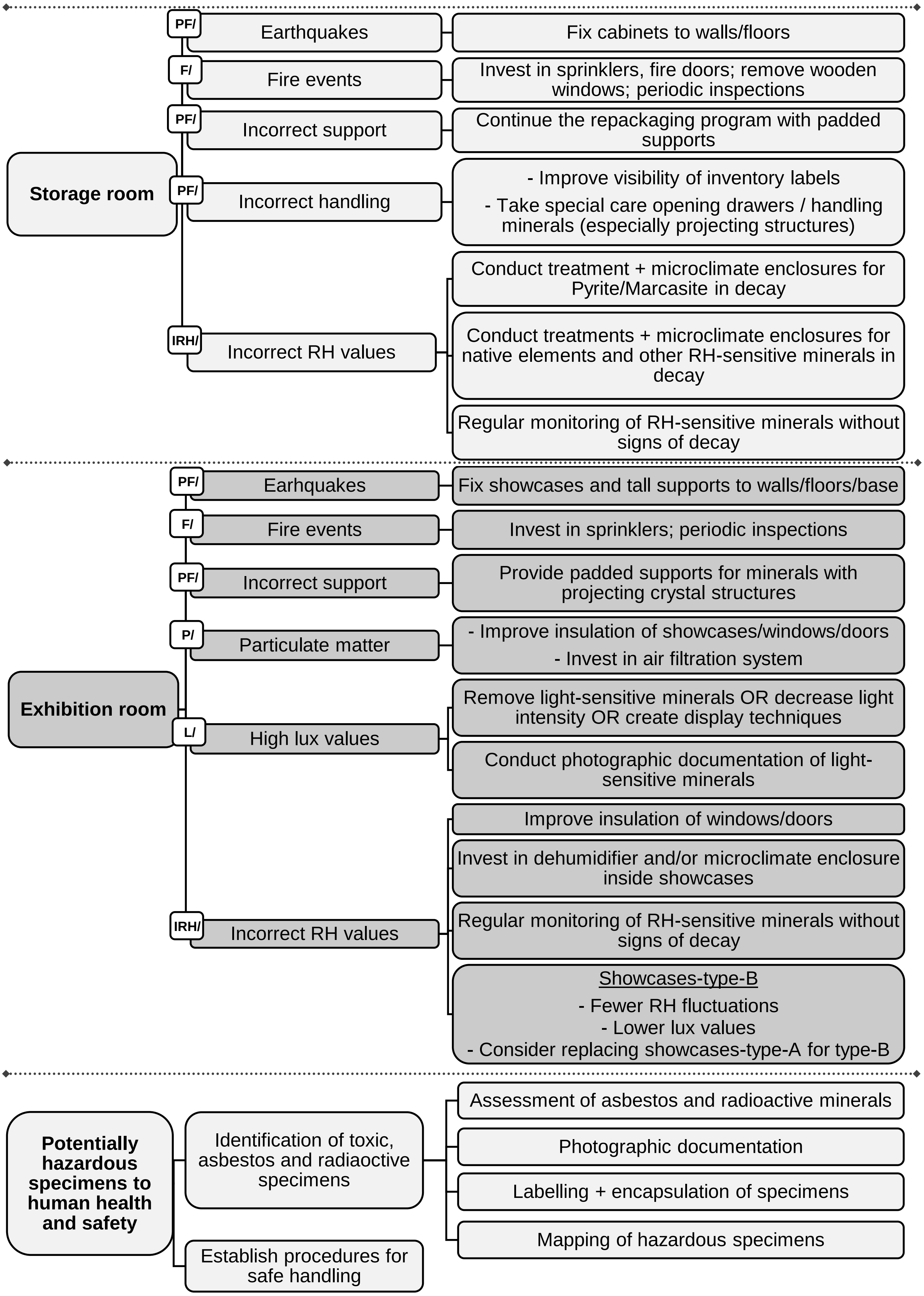

Figure 4.1 – Continued.

Further research

- Determine international standard recommendations for the care of mineral collections regarding: T and RH standard values for specific minerals, illuminance standard values, light systems to display light-sensitive minerals, ventilation requirements (T, RH, dust filtration and requirements for hazardous minerals);
- Damage definition and determine objective/analytical methodologies to measure damage. A few considerations are: weight measurements for material loss/gain; colour analysis device for minerals with different textures or comparing to a colour scale; use of dust collectors to rate particulate matter deposits on showcases; detect decay products with analytical methods (e.g. Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, X-ray diffraction (XRD), Digital Image Correlation (DIC));
- Establish a standard protocol for condition survey of mineral collections. Some reflections on condition surveys can be seen in Buttler [7] and Sievwright [72] studies.
- Concerning incorrect RH affecting Pyrite/Marcasite, a project similar to “Project Airless” [51], [66], [67], [73] should be conducted in MUHNAC’s mineral collection. The objective of this project aims to identify, clean, treat, photograph, re-pack within microenvironments and prevent pyrite decay from fossils and mineral specimens in the Earth Science collections.
- Assess if the information related to Pyrite/Marcasite’s chemical composition, provenance, crystals form and size can contribute to understanding if certain specimens can be more stable than others.
- Monitoring and quantification of gaseous pollutants concentration considered by Waller, Andrew and Tétreault [23]. A research on recommended maximum pollutant concentrations for mineral collections should also be conducted.

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Appendix I – Characterization of the building and surrounding area

I.1. Climate

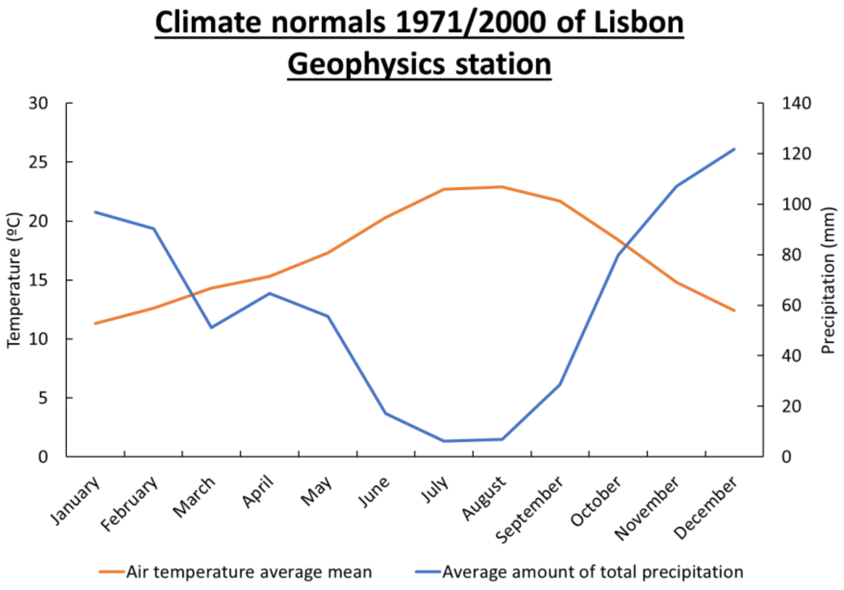


Figure I.1 – Climate normals 1971/2000 of Lisbon Geophysics station [15].

I.2. Seismic activity

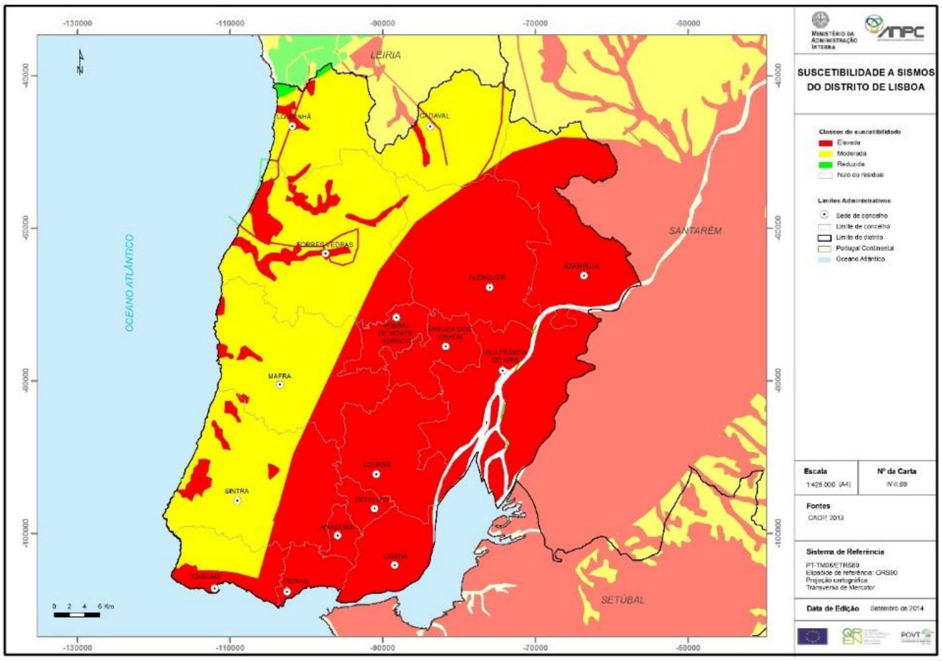


Figure I.2 – Earthquake susceptibility of Lisbon district [17]

Appendix II – Relative humidity and temperature monitoring on storage and exhibition

II.1. Recommended values of temperature and relative humidity according to literature

Table II.1 – General and examples of specific reference values of T and RH for geological collections and some specific minerals

Mineral	Recommended Temperature	Recommended Relative Humidity	Reference
Geological collections	20 ± 2ºC	50 ± 5%	[40]
	15 – 20 ºC	50 %	[2]
	15 ± 5ºC	50 ± 5%	[41]
	16 – 22ºC	45 – 55%	[43]
	15 – 25ºC	45 – 55%	[44]
Mineral collections	18 – 23ºC	45 – 55%	[42] recommended by Thomson (1978) and Howie (1992?)
Majority of sensitive minerals to efflorescence (unstable must be stored in individual microclimates)	15 ± 5ºC	50 ± 5%	[69]
Sensitive minerals and other materials	The exact condition will often be specific to the mineral. Microclimates should be considered for minerals which are extremely sensitive to moisture and/or temperature		[43]
Pyrite	-	≤ 50% over periods of several years (short periods of storage ≥ 60% results in rapid deterioration)	[40], recommended by Howie in 1984 and 1994
	-	≤ 50% or < 60% as possible At 30% Individual boxes kept in 30 - 40% using silica gel Larger cases and cabinets < 60%	[45]
	-	< 60% Preferably nearer 30%	[32] recommended by Howie (1992)
		< 50% Ideally at 30%	[46] recommended by Howie (1992)
	-	30% (Howie 1992) <30% high carbon content 40% without microclimate 40-43% (treatment and storage at Hancock Museum)	[47]
	-	< 60 %	[8]
	16 – 22ºC	20 – 30% If pyrite begins to oxidize, it can continue < 55%	[43]
	-	≤ 45%, if reaction has not started ≤ 30%, if reaction has started	[44]
	-	Always < 60% Preferably about 30% More realistically 45%	[48] recommended by Howie (1992)
	-	< 50%	[49]
	-	Always < 60% Preferably 30% More realistically 45%	[50] recommended by Howie (1992)

	-	Conditioned in < 30% RH to only control RH. Conditioned in 40-50% RH, if treated with ammonia vapour.	From Project Airless [51]
Halite	< 20ºC	Deliquescence at 75%	[32]
	-	Can liquefy above 75%	[49]
Borax	< 20ºC	Deliquescence at 99% Dehydrates to tincalconite at 50% (efflorescence)	[32]
	-	Can dehydrate to become tincalconite at less than 50%	[49]
Metals	-	35% - 55% (mixed collections) < 35% (active deterioration)	[52]

As seen in Museums, Libraries and Archives Council [43], there is an extensive environment guidance of RH and T for geological records (documents, negatives, and others) compared to the few recommendations for the geological collections. The exact appropriate condition will be specific to the mineral. For geological collections, the minimum value for T is 10ºC and the maximum 25ºC; the values proposed by Standards in the Museum Care of Geological Collections is the closest within the other limits, 16-22ºC. There is a consensus agreement of RH values: 50 ± 5%. Halite and Borax have a consensus recommendation.

However, RH values for Pyrite differ from the references. Most references recommend RH levels always below 50% or 60%, others also recommend to kept RH at 20-30%, below 30%, at nearly 30%, and below 45%. The majority recommend a RH level of 30% and are followed by Howie [45].

For further information regarding specific environmental limits for individual minerals (minerals known to undergo humidity-related phase transitions at levels between 5% and 90%), see Waller's study [32].

II.2. Recommended values of illuminance according to literature

Table II.2 – Summary of levels of light illuminance recommended for geological collections and light-sensitive minerals. m*ax.*, stands for maximum

Specimens	Light illuminance levels	Reference
General guideline for geological collections	200 – 350 lux	[41]
	Store in dark Display max. 300 lux	[43]
Light-sensitive minerals	Store in light proof boxes 50 – 200 lux 50 lux for particularly sensitive specimens	[34] after Thomson and Staniforth (1985)
	Store in dark Display max. 50 lux	[43]

Geological collections include paleontological, petrological and mineralogical collections. Therefore, most objects do not suffer light damage, thus higher values of lux can be applied. Light-sensitive minerals, such as Realgar and Vivianite, will suffer colour change if not stored with the correct illuminance, hence the lux values should be lower. 50 lux is the minimum illuminance for displays recommended by Thomson [28]. With the information in Table II.2 light-sensitive minerals should be store in dark and if on display, should have 50 lux for viewing.

Light damage is cumulative, and some factors need to be considered: illuminance values, time of exposure, type of radiation, object sensitivity, synergy reaction with the atmosphere and pollutants. Another factor to reflect is the reciprocity law, which states that high illuminance levels over a short period of time cause the same degree of damage as low illuminance levels over a long period of time. Regarding the acceptable limits of annual light exposure, highly sensitive objects should have a maximum annual light exposure of 10 000 lux/h per year [74]. Light-sensitive minerals were considered as highly sensitive objects.

II.3. Storage room monitoring

II.3.1. Temperature and relative humidity

Table II.3 – Full monitoring and same timeframe of exposure of T and RH values measured by thermohygrometers placed in the storage room

Thermohygrometer	Time of exposure	Temperature (ºC)			Relative Humidity (%)		
		Min.	Max.	Avg. ± STDEV	Min.	Max.	Avg. ± STDEV
Storage room (D1)	23/10/2019 – 27/10/2020 Figure II.3	16,9 January	25,4 September	20,8 ± 2,7	39,1 January	55,4 June	47,6 ± 2,6
	23/10/2019 – 09/01/2020 Figure 1.23	-	-	20,2 ± 1,5	-	-	46,7 ± 2,6
Pyrite drawer (D2)	19/03/2019 – 27/10/2020 [1,2] Figure II.4	17,3 January	25,1 September	22,3 ± 2,1	45,7 June December	52,1 September	48,0 ± 1,5
	23/10/2019 – 09/01/2020 Figure 1.24	-	-	21,8 ± 2,0	-	-	47,9 ± 1,7

[1] T values between 09/01/2020 – 06/05/2020 were discard due to thermohygrometer malfunction as result of low battery.
[2] T and RH values between 06/05/2020 – 21/07/2020 were not measured due to the thermohygrometer running out of battery.

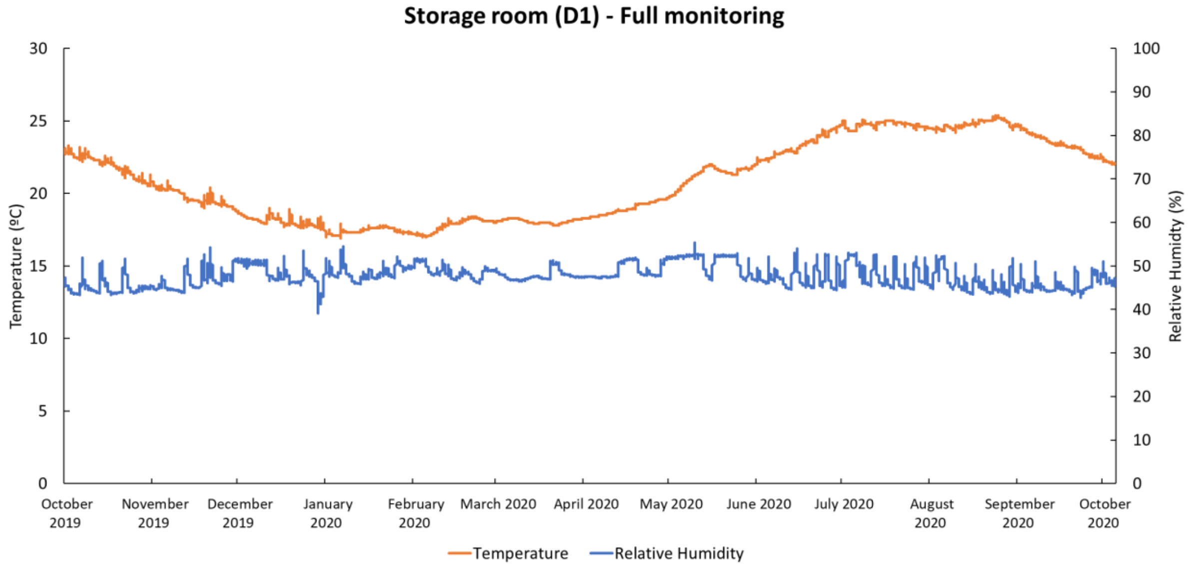


Figure II.3 – Full monitoring values of T and RH from thermohygrometer (D1) in the storage room. The average value and deviation of T is 20,8 ± 2,7 ºC and the average value and deviation of RH is 47,6 ± 2,6 %. Monitoring period: 23/10/2019 – 27/10/2020.

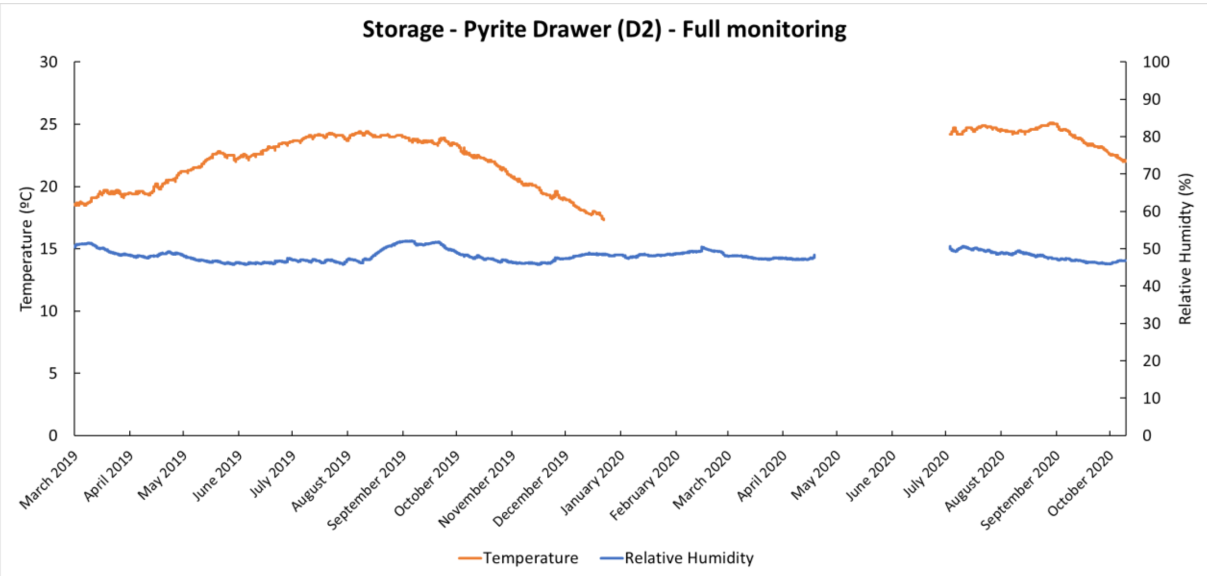


Figure II.4 – Full monitoring values of T and RH from thermohygrometer (D2) inside a drawer in the storage room. The average value and deviation of T 22,3 ± 2,1 ºC and the average value and deviation of RH is 48,0 ± 1,5 %. Monitoring period: 19/03/2019 – 27/10/2020.

II.4. Exhibition room monitoring

II.4.1. Temperature and relative humidity

Table II.4 – Full monitoring and same timeframe of exposure of T and RH values measured by thermohygrometers placed in the exhibition room

Thermohygrometer	Time of exposure	Temperature (ºC)			Relative Humidity (%)		
		Min.	Max.	Avg. ± STDEV	Min.	Max.	Avg. ± STDEV
Room left side (D3)	23/10/2019 - 27/10/2020 (Figure II.5)	15,0 January	25,2 September	19,5 ± 3,2	39,9 September	81,9 December	63,7 ± 7,7
	23/10/2019 – 03/12/2020 (Figure 1.29)	-	-	19,4 ± 1,3	-	-	64,1 ± 7,4
Room right side (D4)	23/10/2019 - 27/10/2020 (Figure II.5)	14,5 January	24,8 July September	19,1 ± 3,2	37,7 September	82,0 December	64,4 ± 7,6
	23/10/2019 – 03/12/2020 (Figure 1.29)	-	-	19,0 ± 1,3	-	-	65,0 ± 7,1
Showcase A4 (D5)	19/03/2019 - 27/10/2020 [1,2] (Figure II.6)	14,4 January	25,8 July	21,0 ± 2,7	41,1 October	77,4 December February	60,5 ± 6,2
	23/10/2019 – 03/12/2020 (Figure 1.30)	-	-	19,3 ± 1,3	-	-	62,4 ± 6,3
Showcase A5 (D6)	19/03/2019 - 21/07/2020 (Figure II.7)	15,0 January	24,6 September	19,3 ± 2,8	48,9 June September	80,7 February	67,1 ± 5,5
	23/10/2019 – 03/12/2020 (Figure 1.31)	-	-	19,3 ± 1,2	-	-	66,0 ± 4,6
Showcase A9 (D7)	19/03/2019 - 21/07/2020 (Figure II.8)	14,7 January	24,7 September	19,2 ± 2,8	46,8 June	82,5 February	66,1 ± 6,8
	23/10/2019 – 03/12/2020 (Figure 1.32)	-	-	19,2 ± 1,2	-	-	66,2 ± 6,1
Showcase B4 (D8)	19/03/2019 – 27/10/2020 [3] (Figure II.9)	13,7 December	24,3 July	19,8 ± 3,0	56,1 June	73,1 May	64,3 ± 3,8
	23/10/2019 – 03/12/2019 (Figure 1.33)	-	-	17,0 ± 1,9	-	-	63,0 ± 1,7

[1] T values between 09/01/2020 – 03/05/2020 were discard due to thermohygrometer malfunction as result of low battery.
[2] T and RH values between 03/05/2020 – 21/07/2020 were not measured due to the thermohygrometer running out of battery.
3 T values between 04/12/2020 – 20/01/2020 were discard due to thermohygrometer malfunction as result of low battery

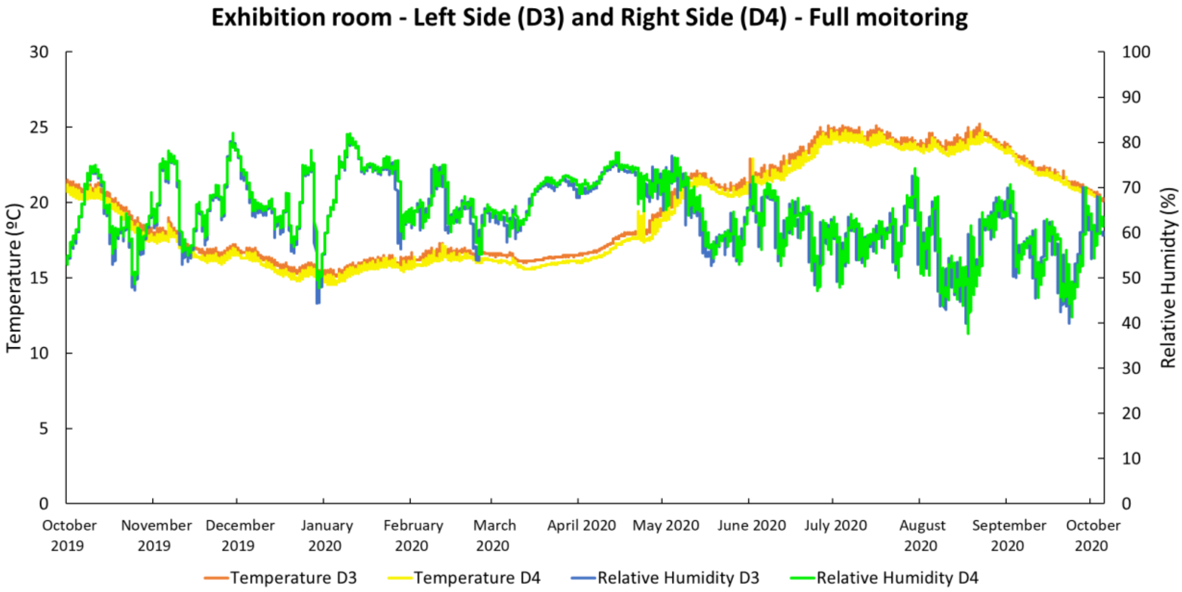


Figure II.5 – Full monitoring values of T and RH from the 2 thermohygrometer (D3, D4) placed in the exhibition room. For D3: the average value and deviation of T is 19,5 ± 3,2 ºC and the average value and deviation of RH is 63,7 ± 7,7 %. Monitoring period: 23/10/2019 – 27/10/2020. For D4: the average value and deviation of T is 19,1 ± 3,2 ºC and the average value and deviation of RH is 64,4 ± 7,6 %. Monitoring period: 23/10/2019 – 27/10/2020.

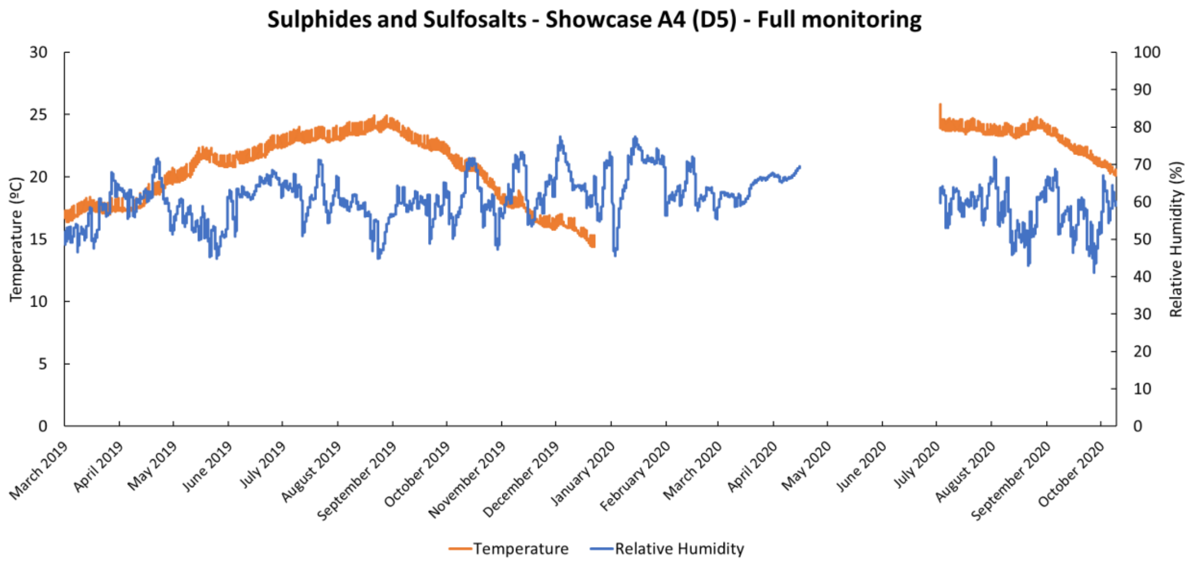


Figure II.6 – Full monitoring values of T and RH from thermohygrometer (D5) inside showcase A4. The average value and deviation of T is 21,0 ± 2,7 ºC and the average value and deviation of RH is 60,5 ± 6,2 %. Monitoring period: 19/03/2019 – 27/10/2020.

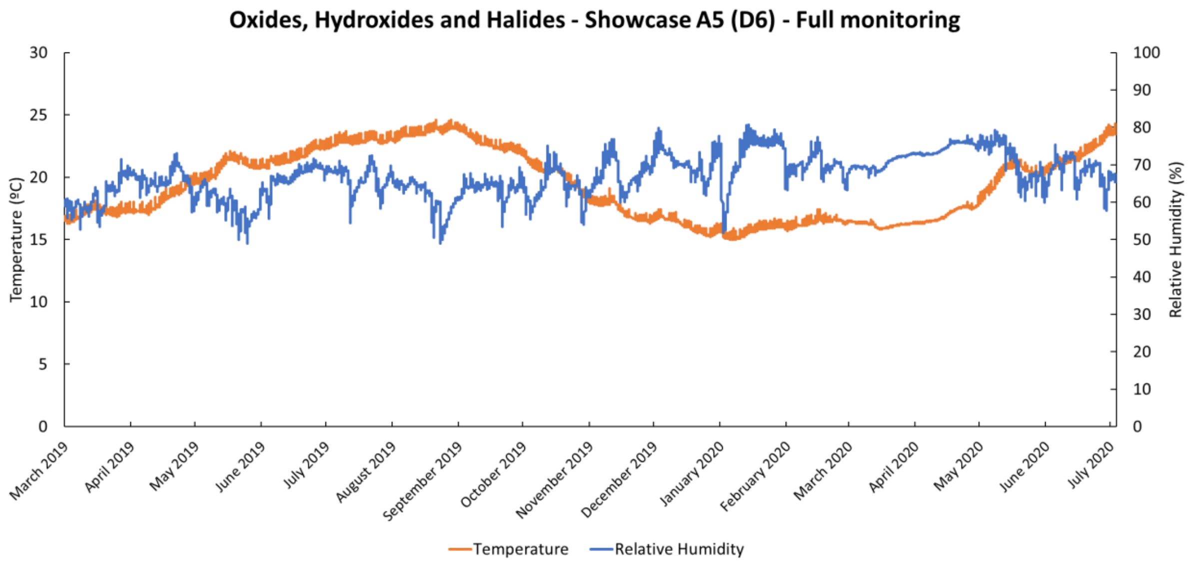


Figure II.7 – Full monitoring values of T and RH from thermohygrometer (D6) inside showcase A5. The average value and deviation of T is 19,3 ± 2,8 ºC and the average value and deviation of RH is 67,1 ± 5,5 %. Monitoring period: 19/03/2019 – 21/07/2020.

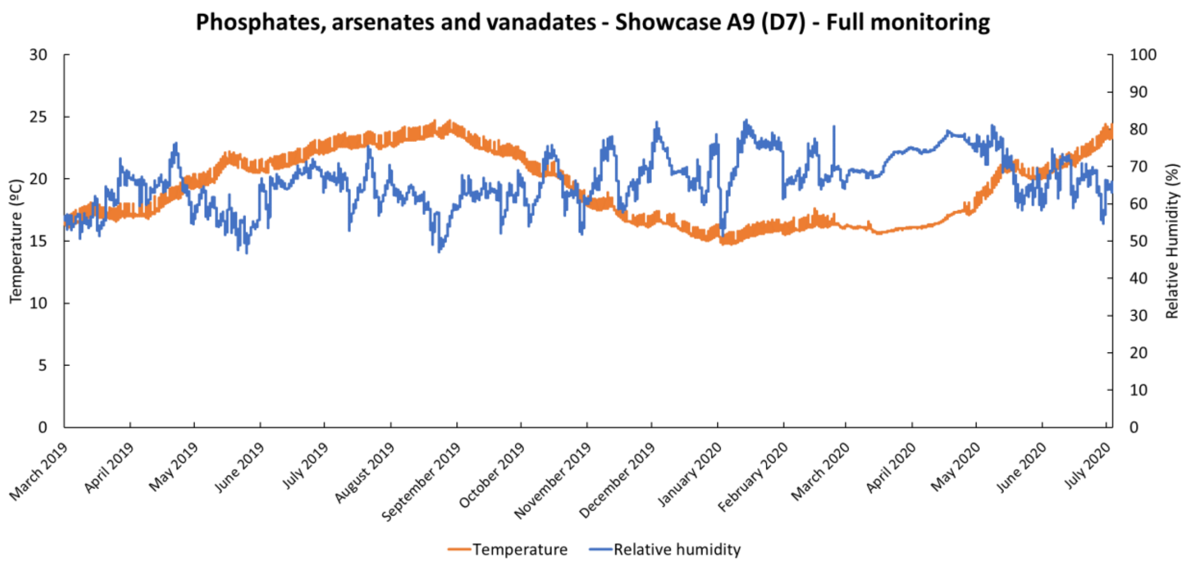


Figure II.8 – Full monitoring values of T and RH from thermohygrometer (D7) inside showcase A9. The average value and deviation of T is 19,2 ± 2,8 ºC and the average value and deviation of RH is 66,1 ± 6,8 %. Monitoring period: 19/03/2019 – 21/07/2020.

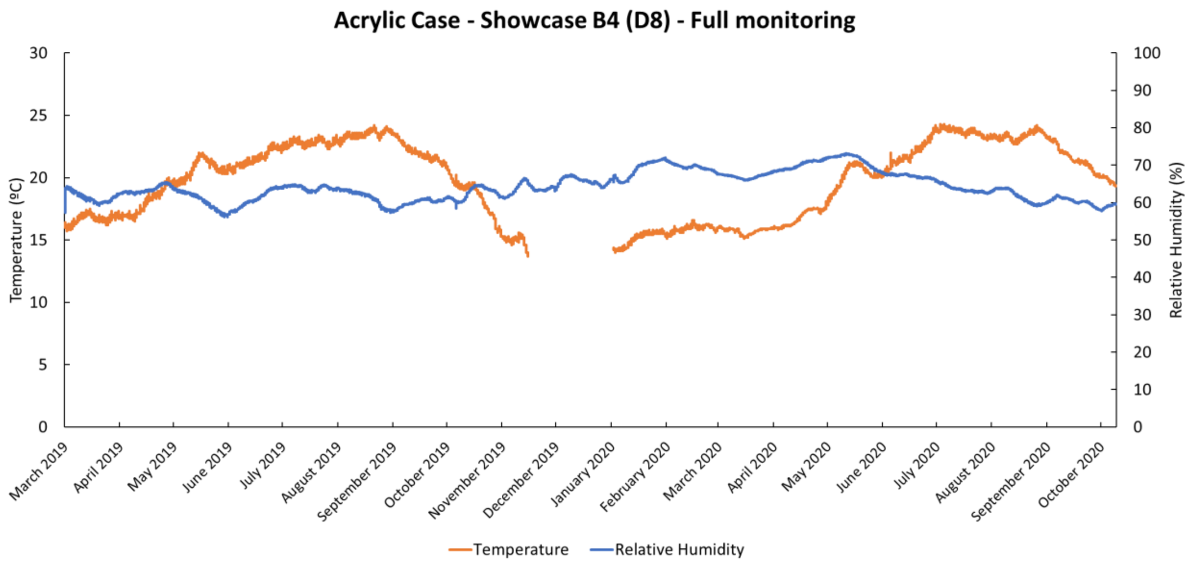


Figure II.9 – Full monitoring values of T and RH from thermohygrometer (D8) inside showcase B4. The average value and deviation of T is 19,8 ± 3,0 ºC and the average value and deviation of RH is 64,3 ± 3,8 %. Monitoring period: 19/03/2019 – 27/10/2020.

II.4.2. **Illuminance**

Table II.5 – Illuminance monitoring in the exhibition room. Monitoring on light-sensitive minerals was taken in September 2020. Lux values in showcase-type-A were measured on top of the mineral. Minerals with marked with “ ** ” already suffered changes or it is suspected to. Specific effect of light information was taken from [30]. “C” stands for Colourless

Showcase /Support	Light-sensitive mineral (current colour)	Specific effect of light (turns to)	Location	Lux values	Annual light exposure (lux hours per year)
A1	Celestite (blue)	C	Wood support	1107 lux	2 316 951
A2	Fluorite (purple)	C or pink	Acrylic support	507 lux	1 061 151
	Purpurite (Purple)	Darkens	Wood support	740 lux	1 548 820
A4	Cinnabar in quartz (Cinnabar: red)	Black metacinnabarite	Base	335 lux	701 155
	Galena with calcite (Calcite: orange)	Fades	Wood support	490 lux	1 025 570
	Stibnite (dark)	Dark and/or iridescent	Shelf	1009 lux	2 111 837
A5	Cuprite (greenish, reddish)	Darkens, Cu liberated	Base	329 lux	688 597
	Fluorite (green / blue)	Purple or C or pink	Wood support	458 lux	958 594
	Corundum var.sapphire (blue)	C	Shelf	971 lux	2 032 303
A6	Cobaltocalcite (pink)	Darkens	Wood support	408 lux	853 944
	Calcite (pink)	Fades	Shelf	990 lux	2 072 070
	Calcite (orange)	Fades	Shelf	1106 lux	2 314 858
A7	Crocoite (red)	Darkens	Base	352 lux	736 736
	Celestite (blue)	C	Wood base	473 lux	989 989
	Anhydrite (blue)	C	Shelf	1705 lux	3 568 565
A9	-	-	Base	354 lux	740 922
	Vanadinite (red)	Darkens	Wood support	358 lux	749 294
	Turquoise (blue)	Fades	Wood support	783 lux	1 638 819
	** Vivianite (green)	Darkens, can disintegrate	Highest wood support	626 lux	1 310 218
	Fluorapatite (Fluorite greenish)	Purple	Shelf	1644 lux	3 440 892
A10	Zircon (brown / red)	Grey or blue	Acrylic support	456 lux	954 408
	Topaz (incolour / brown / orange)	C or blue, rapid or C or blue, slow	Wood support	559 lux	1 169 987
A11	Beryl (pinkish)	Paler pink	Wood support	669 lux	1 400 217
	Beryl (blue)	C or pink	Wood support	532 lux	1 113 476
	Beryl (blue)	C or pink	Wood support	517 lux	1 082 081
	Rhodonite (red)	Darkens	Shelf	1237 lux	2 589 041
	** Spodumene (pink)	C	Shelf	1862 lux	3 897 166
A12	Orthoclase with smoky quartz (Smoky quartz: dark)	Greenish yellow and then C	Acrylic support	428 lux	895 804
	Pink quartz	C	Wood support	378 lux	791 154
	Smoky quartz	Greenish yellow and then C	Wood support	716 lux	1 498 588
	Amethyst quartz	Fades	Wood support	339 lux	709 527
B1	Smoky quartz (dark)	Greenish yellow and then C	Interior, on top of the mineral Outside, on top of acrylic case	90,4 lux 129 lux	189 207 269 997
C1	Geode amethyst quartz	Fades	Interior, lower area Interior, middle area Interior, upper area	156 lux 202 lux 413 lux	326 508 422 786 864 409
F1	(not light-sensitive mineral)	-	On top of the mineral	69,8 lux	146 091
F2	(not light-sensitive mineral)	-	On top of the mineral Middle area of the mineral	74,4 lux 113 lux	155 719 236 509

Note: The annual light exposure was calculated considering the light intensity emitted to the object (lux value) and the time of exposure to light (hours).The museum is open around 299 days per year and the exhibition is open 7 hours per day. Therefore the showcases are turned on 2093 hours per year. The equation used was the following: *2093 hours* X *lux value*.

Appendix III – Pyrite oxidation

Pyrite (FeS_2, also known as "fool's gold", iron pyrites) grows in varying crystalline forms, such as cubic, octahedral or pyritohedral crystals [32], [45], [46], [48]. Marcasite (FeS_2) has the same chemical formula, but crystallises in a different form (orthorhombic) and is also subject to oxidation the same way as pyrite [46].

Oxidation process: When pyrite decay occurs, the iron disulphide (FeS_2) reacts with oxygen in the atmosphere and breaks down to ferrous sulphate ($FeSO_4$) and sulphur dioxide (SO_2) [46]. At higher levels of RH sulphur dioxide can be oxidised to form sulphuric acid (H_2SO_4) [23], [46]. Powder efflorescence can be a health hazard [65], therefore gloves and dust mask should be worn to protect against sulphuric acid. The change of the iron sulphide to the bulkier iron sulphate causes internal stress and can disintegrate due to iron sulphate being greater in volume than iron sulphite pyrite [8], [45], [49]. According to the authors [46], [48], [65], [73], the following chemical process takes place:

$$4FeS_2 \;+\; 13O_2 \;+\; 2H_2O \;\gg\; 4FeSO_4 \;+\; 2H_2SO_4 \;+\; 2SO_2$$

Pyrite	Oxygen	Water	Ferrous Sulphate	Sulphuric Acid	Sulphur Dioxide

Hydrogen sulphide (H_2S) is one of the most significant reduced sulphur gases [23]. Following the reaction of pyrite oxidation described above, the migrating sulfuric acid (H_2SO_4) will react with monosulphide minerals to produce hydrogen sulphide (H_2S) according to the following chemical reaction [23]:

$$FeS \;+\; H_2SO_4 \;\gg\; H_2S \;+\; FeSO_4$$

Pyrite	Sulphuric acid	Hydrogen sulphide	Ferrous Sulphate

A few days of exposure to an incorrect RH may be sufficient to trigger the decay process [48]. The damage inflicted on a specimen is considered irreversible, however some by-products can be removed and neutralized with proper treatment [46], [48], [50], [73]. It is important to known that treated specimens are still susceptible to further oxidation [48]. An even though the treatment results, the specimens does not return to their original state (treated areas change colour/shine, fissures are visible, etc). Thereafter, it is best prevented by careful environmental control [46].

The production of replicas (mould and cast) should be considered if not possible to delay the pyrite oxidation in order to preserve minerals for future study [46], [48], [50], [75]. Photogrammetry digital 3D model can be produce with good digital photographs with different angles [50], [76]. CT scanning, MicroCT scanning or laser scanning could be used to develop a three-dimensional digital model to be printed in 3D [50].

IV.1. Physical forces

Table IV.6 – PF/a) Earthquake with intensity ≥5 in Richter Magnitude Scale causing building collapse and/or toppling of cabinets/showcases (considered equal for storage and exhibition)

FS	• All the collection is equally susceptible (FS=1).
LV	• An earthquake with these dimensions can cause building collapse, toppling of storage/showcase units resulting in crushing or breakage of specimens. The loss of value of a specimen can be total, since the damage can result in total breakage and deformation of specimens. (LV = 1).
P	• The 1755 Lisbon earthquake (265 years ago) will be considered for this specific risk (P = (1/265) x 100 = 0,377).
E	• The value considered for the Extent is the default value for type of risk 1 (E = 1).
MR = 0,377	

Table IV.7 – PF/b) Earthquake with intensity <5 in Richter Magnitude Scale causing movement and/or toppling of minerals

FS	• In the storage room, lighter specimens in drawers can be more susceptible to movement and damage. There are 8364 minerals which do not have padded supports ($FS_{storage}$ = 8364/10529 = 0,794). • In the exhibition room, specimens that are more likely to move/fall due to their support were considered. Inside showcases-type-A, there are 116 specimens which have a considered tall acrylic/wood supports or are placed on the glass shelf. There are 3 susceptible specimens placed inside showcases-type-B. There is 1 mineral inside showcase-type-C. And the mineral in support-F (F1) in placed on an iron structure smaller than the mineral itself ($E_{exhibition}$ = 121/170 = 0,712).
LV	• An earthquake with these dimensions can cause movement of specimens, therefore causing abrasion and possibly breakage of crystals structures. ($LV_{storage}$ = 0,6). • In the exhibition, the earthquake can cause movement of specimens, toppling of individual wood supports, breakage of glass shelves. These situations can led to abrasion and material loss of specimens ($LV_{exhibition}$ = 0,6).
P	• Probability will be considered equal for storage and exhibition rooms. The value considered for the Probability is the default value for type of risk 2 (P = 1).
E	• There are 666 minerals with projecting crystal structures which are more susceptible to movement ($E_{storage}$ = 666/8364 = 0,08). • There are 16 minerals considered more prone to damage for being fragile minerals if moved/fall. ($E_{exhibition}$ = 16/121= 0,132)
$MR_{storage}$ = 0,038 // $MR_{exhibition}$ = 0,056	

Table IV.8 – PF/c) Incorrect handling causing abrasions (only happens in the storage)

FS	• All the collection is equally susceptible ($FS_{storage}$ =1).
LV	• Handling accidents during use by borrowers, visitors and staff can cause scratching, marring, breaking. The placement and removal of a mineral from the drawer can also cause damage. There are no records of specimen/drawers being dropped in storage and are taken care by the same staff. Thus, it will be considered a LV of partial damage. Small abrasions are considered to have a LV equal to 0,6 ($LV_{storage}$ = 0,6).
P	• The value considered for the Probability is the default value for type of risk 2 ($P_{storage}$ = 1).
E	• There are 666 minerals with projecting crystal structures without a more appropriate cushioning that are more susceptible to damage when removing for observation ($E_{storage}$ = 666/10529= 0,063).
	$MR_{storage}$ = 0,038

Table IV.9 – PF/d) Incorrect support causing abrasions.

FS	• Considering only the specimens inside the metal drawers, since the smaller specimens are more fragile. There are 8364 minerals which do not have padded supports ($FS_{storage}$ = 8364/10529 = 0,794). • In the exhibition, Stibnite (A4), Halite (A5), Anhydrite (A7) and Scolecite over apophyllite (A12) are minerals with sensitive projecting structures which can develop changes in the lower area ($FS_{exhibition}$ = 4/170 = 0,024).
LV	• Inadequate support can cause minerals to fall, jostling surface or other minerals, deformation caused by stress from media storage and abrasions by touching the drawers. These damages occur especially when drawers are being used. ($LV_{storage}$ = 0,6). • In the exhibition room, the susceptible minerals can suffer material loss and deformation in the lower area. ($LV_{exhibition}$ = 0,6)
P	• Probability will be considered equal for storage and exhibition rooms. The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• In storage, there are 1636 minerals with inadequate space between other minerals which can promote bumping into one another (overcrowded), 700 mineral have inadequate size of support that can cause minerals to fall, jostling surface or other minerals, 37 minerals are oversized to be kept inside drawers and 666 mineral have projecting structure without an proper padded support ($E_{storage}$ = 3039/8364 = 0,363). • In exhibition, at least one specimen in the exhibition is currently suffering severe damage to the bottom (Stibnite) ($E_{exhibition}$ = 1/4= 0,25).
	$MR_{storage}$ = 0,173 // $MR_{exhibition}$ = 0,004

IV.2. Fire

Table II: Control Levels (CL) for Fire Prevention and Response. (See also notes in Appendix 1.)

CL*	Avoid	Block	Detect	Respond	Training	Procedures
1			a) Local smoke alarms provided, tested monthly and batteries replaced annually. b) A telephone is available.	a) Fire station available full time. b) Portable fire extinguishers provided.		a) Open-flame fire safety procedures in place. b) Visual inspection of portable fire extinguishers is conducted quarterly.
2		a) Fire resistive construction. b) Collection storage rooms fire-rated for 1 to 2 hours. c) Enclosed emergency staircase provided in multi-level buildings.	Under "Detect", CL1b plus: a) Fire alarm system installed throughout the building, with an annual inspection.	All items under "Respond" in CL1 plus: a) Water supply available to firefighters.	a) A few staff members are trained in the use of portable fire extinguishers.	All items under "Procedures" in CL1 plus: a) Annual inspection of portable fire extinguishers.
3		All items under "Block" in CL2 plus: a) Exhibit rooms protected from other areas with a minimum 1 hr fire-rated separation. b) Fire doors equipped with automatic closing devices.	All items under "Detect" in CL2 plus: a) Fire alarm system monitored full time. b) Automatic smoke detection provided in collection-holding areas.	All items under "Respond" in CL1 plus a) Municipal or private fire hydrants provided. b) Standpipe system with fire department connections is provided.	a) Portable fire extinguisher training provided every 5 years.	All items under "Procedures" in CL2 plus a) Monthly testing of fire alarm system. b) Building's electrical system inspected every 10 years for building more than 40 years old.
4	a) Avoid high crime-rated areas. b) Avoid having the institution on properties attached to structures classified "industrial" or "storage", or containing high hazard contents. c) Avoid close proximity to wooded areas and fire-prone bush.	Items "Block" in CL2b,2c,3a and 3b plus: a) Noncombustible building. b) Automatic HVAC shutdown provided.	All items under "Detect" in CL3 plus: a) Dedicated and supervised telephone line provided for the fire alarm system.	All items under "Respond" in CL3 plus: a) Automatic fire suppression system provided in collection storage rooms with a high fuel load, with annual inspection of automatic fire suppression system(s).	a) Staff trained in fire prevention methods. b) Portable fire extinguisher training provided every 3 years.	All items under "Procedures" in CL3 plus: a) Monthly fire safety inspections conducted. b) Active fire safety committee and Emergency Response plan in place. c) Building's electrical system inspected every 10 years. d) Fire prevention procedures for facility rental and user groups in place. e) Hot work permit required. f) Building systems (mechanical/electrical) preventive maintenance program in place and reviewed every 3 years.
5	All items under "Avoid" in CL4 plus: a) Avoid sharing occupancy of your building (including attached building) with an unprotected occupant.	All items under "Block" in CL4 plus: a) Combustible / flammable liquids kept in approved storage cabinets.	All items under "Detect" in CL4 plus: a) Separate fire alarm zones provided for collection storage rooms. b) Trained security personnel provided full time.	All items under "Respond" in CL3 plus: a) Automatic fire suppression system provided in collection storage rooms and exhibit rooms, with annual inspection of automatic fire suppression system(s).	All items under "Training" in CL4 plus: a) Team trained in emergency response. b) Portable fire extinguisher training provided for new staff.	All items under "Procedures" in CL4.
6	All items under "Avoid" in CL5	All items under "Block" in CL5	All items under "Detect" in CL5	All items under "Respond" in CL3 plus: a) Automatic fire suppression system provided throughout the building, with annual inspection of automatic fire suppression system(s).	All items under "Training" in CL5 plus: a) Emergency measures exercise performed at least every 5 years.	All items under "Procedures" in CL4 plus: a) Electrical inspection conducted following renovations and/or new projects. b) Formal fire department site visits are conducted annually.

* Control Level 1 represents the least efficient protection against fire, while Control Level 6 represents the ultimate reasonable protection for an institution.

Figure IV.10 – Table of control Levels for fire prevention and response according to Tetreault [60]. Control strategies within MUHNAC is underline in green.

Table IV.10 – F/a) Fire ignites and consume entire building and contents (considered equal in the storage and exhibition)

FS	• All the collection is susceptible to damage by fire (FS = 1)
LV	• The loss in value can be total (LV = 1).
P	• According to Tetreault (2008) and the MUHNAC's control strategies (CL 1), it is expected an occurrence of a fire every 140 years [60]. For CL2, the percentage of spread throughout the building is 26% (P = [(1/140) X 100] X 0,26 = 0,186).
E	• For type 1, by default, the Extent is one. (E = 1).
MR = 0,186	

Table IV.11 – F/b) Fire ignites in a single room and consume specimens in the room the factors (factors FS, LV and P considered equal in the storage and exhibition)

FS	• All specimens on storage are susceptible (FS = 1).
LV	• The loss of value can be total (LV = 1).
P	• According to Tetreault (2008) and the MUHNAC's control strategies (CL1), it is expected an occurrence of a fire every 140 years [60]. For CL1, the percentage of a fire being confined to a division is 29% (P = [(1/140) X 100] X 0,29 = 0,207).
E	• For type of risk 1, by default, the Extent is one. However, a fire that occurs in the exhibition is more prone to spread more quickly due to the room characteristics (carpet floor, wooden showcases, several wooden doors and windows). Thus, the extent in the storage will be considered lower than in the exhibition ($E_{storage}$ = 0,9). • In the exhibition room, the Extent will follow the default of type 1 risk ($E_{exhibition}$ = 1)
$MR_{storage}$ = 0,186 // $MR_{exhibition}$ = 0,207	

IV.3. Pollutants

Table IV.12 – P/a) Particulate matter deposit in non-specific-minerals inside showcases-type-A (only happens in the exhibition)

FS	• There are 151 minerals considered inside showcases-type-A ($FS_{exhibition}$ = 151/170 = 0,888).
LV	• Particulate matter can have impact on mineral colour/shine and visitor's perception. Therefore excessive dust accumulation may influence exhibition value if allowed to accumulate ($LV_{exhibition}$ = 0,5).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-type-A is considered the third showcase that accumulates more dust ($E_{exhibition}$ = 0,3).
$MR_{exhibition}$ = 0,132	

Table IV.13 – P/b) Particulate matter deposit in non-specific-minerals inside showcases-type-B (only happens in the exhibition)

FS	• There are 4 non-specific minerals considered inside showcases-type-B ($FS_{exhibition}$ = 4/170 = 0,024).
LV	• Particulate matter can have impact on mineral colour/shine and visitor's perception. Therefore, excessive dust accumulation may influence exhibition value if allowed to accumulate ($LV_{exhibition}$ = 0,5).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-typeB is considered the fourth showcase that accumulates more dust ($E_{exhibition}$ = 0,1).
$MR_{exhibition}$ = 0,001	

Table IV.14 – P/c) Particulate matter deposit in minerals inside showcases-type-C (only happens in the exhibition):

FS	• There is 1 mineral considered inside showcases-type-C ($FS_{exhibition}$ = 1/170 = 0,006).
LV	• Particulate matter can have impact on mineral colour/shine and visitor's perception. Therefore excessive dust accumulation may influence exhibition value if allowed to accumulate ($LV_{exhibition}$ = 0,5).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-type-C is considered the second showcase that accumulates more dust ($E_{exhibition}$ = 0,4).
$MR_{exhibition}$ = 0,001	

Table IV.15 – P/d) Particulate matter deposit in minerals on supports-F (only happens in the exhibition)

FS	• There are 2 minerals with inside supports-F: Garnierite (F1) and Quartz (F2) ($FS_{exhibition}$ = 2/170 = 0,012).
LV	• Particulate matter can have impact on mineral colour/shine and visitor's perception. Therefore excessive dust accumulation may influence exhibition value if allowed to accumulate ($LV_{exhibition}$ = 0,5).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Supports-F is considered the first showcase/support that accumulates more dust ($E_{exhibition}$ = 1).
$MR_{exhibition}$ = 0,006	

Table IV.16 – P/e) Particulate matter deposit in minerals with projecting structures inside showcases-type-A (only happens in the exhibition)

FS	• There are 5 minerals with projecting structures inside showcases-type-A that if left with dust, it is difficult to clean it without damaging it: Stibnite (A4), Halite (A5), Actinolite (A11), Chrysolite (A12), and Scolecite over apophyllite (A12) ($E_{exhibition}$ = (5/170) = 0,029).
LV	• If specimens with projecting structures are clean, material loss may occur. With the continuous accumulation of dust, it can also affect mineral colour/shine and visitor's perception ($LV_{exhibition}$ = 0,7).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-type-A is considered the third showcase that accumulates more dust ($E_{exhibition}$ = 0,3).
$MR_{exhibition}$ = 0,006	

Table IV.17 – P/f) Particulate matter deposit in minerals with projecting structures inside showcases-type-B (only happens in the exhibition)

FS	• There is 1 mineral with projecting structures inside showcases-type-B that if left with dust, it is difficult to clean it without damaging it: Anhydrite (B3). ($E_{exhibition}$ = (1/170) = 0,006).
LV	• If specimens with projecting structures are clean, material loss may occur. With the continuous accumulation of dust, it can also affect mineral colour/shine and visitor's perception ($LV_{exhibition}$ = 0,7).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-type-B is considered the fourth showcase that accumulates more dust ($E_{exhibition}$ = (0,1).
$MR_{exhibition}$ = 0,0004	

Table IV.18 – P/g) Particulate matter deposit in native elements inside showcases-type-A (only happens in the exhibition)

FS	• There are 6 native metals inside showcases-type-A (A3): 1 native copper, 1 native silver, 1 native silver and copper , 1 native arsenic, 2 native bismuth ($E_{exhibition}$ = (6/170) = 0,035).
LV	• Particulate matter can damage native elements because they absorb moisture and acids, and therefore encouraging corrosion and other reactions on mineral's surface ($LV_{exhibition}$ = 0,7).
P	• The value considered for the Probability is the default value for type of risk 3 (P = 1).
E	• Showcase-type-A is considered the third showcase that accumulates more dust ($E_{exhibition}$ = (0,3).
$MR_{exhibition}$ = 0,007	

IV.4. Light

Table IV.19 – L/a) Light-induced colour changes, decompositions, and light-accelerated surface reaction with the atmosphere (only happens in the exhibition)

FS	• There are 24 minerals that can suffer colour changes, 2 minerals can undergo physical and chemical decay, and 6 minerals are light-accelerated surface reactions with air, moisture, and/or pollutants. ($FS_{exhibition}$ = 32/170 = 0,188).
LV	• Exposure to light can cause irreversible damage that can compromising stability and exhibition ($LV_{exhibition}$ = 0,8).
P	• The value considered for the Probability is the default value for type of risk 3 ($P_{exhibition}$ = 1).
E	• In the past 26 years, 4 minerals have suffered colour changes due to the light exposure conditions: pink Halite, Realgar, Vivianite and Spodumene. ($E_{exhibition}$ = [(4 X 100)/26]/32 = 0,481).
$MR_{exhibition}$ = 0,072	

IV.5. Incorrect relative humidity

Table IV.20 – IRH/a) Incorrect values of relative humidity resulting in corrosion of native metals (only happens in storage)

FS	• Of the 10529 minerals on storage, 298 specimens are native metals ($FS_{storage}$ = 298/10529 = 0,028).
LV	• These reactions can led to irreversible damage and depleting of specimens (LV = 0,95).
P	• For type of risk 3, by default, the Probability is one (P = 1).
E	• Of the 298 specimens on storage, 84 specimens have/show signs deterioration ($E_{storage}$ = 84/298 = 0,282).
$MR_{exhibition}$ = 0,008	

Table IV.21 – IRH/b) Incorrect values of relative humidity resulting in oxidation of pyrite/marcasite (only happens in storage)

FS	• Of the 10529 minerals on storage, 265 specimens are pyrite and marcasite ($FS_{storage}$ = 265/10529 = 0,025).
LV	• These reactions can led to irreversible damage and depleting of specimens (LV = 0,95).
P	• For type of risk 3, by default, the Probability is one (P = 1).
E	• Of the 265 specimens, 91 specimens have/show signs of deterioration ($E_{storage}$ = 91/265 = 0,343).
$MR_{storage}$ = 0,01	

Table IV.22 – IRH/c) Incorrect RH resulting humidity-related phase transitions of minerals.

FS	• Of the 10529 minerals on storage, 197 specimens are RH-sensitive. ($FS_{storage}$ = 197/10529 = 0,019). • In the exhibition, 5 specimens are RH-sensitive: 1 Halite (A5), 1 Autunite (A9), 1 Sabugalite in autunite (A9) and 2 Torbernite (A9) ($FS_{exhibition}$ = 5/170 = 0,029).
LV	• LV will be considered equal for both rooms. These reactions can led to irreversible damage and depleting of specimens (LV = 0,95).
P	• For type of risk 3, by default, the Probability is one for both rooms (P = 1).
E	• Of the 197 specimens, 28 specimens have or show signs of deterioration. ($E_{storage}$ = 28/197 = 0,142). • In the exhibition room, only 1 (Halite) has already changed due to incorrect RH ($E_{exhibition}$ = 1/5 = 0,2).
$MR_{storage}$ = 0,003 // $MR_{exhibition}$ = 0,006	

V.1. Workstation for handling hazardous minerals

Figure V.11 – Assembled workstation for handling hazardous minerals.

Figure V.12 – Adaptation of Minigrip® bags (resized, closed holes).

The following materials and personal protective equipment (PPE) were used to safe handle hazardous minerals and to properly store these minerals (Figure V.11). These procedures were chosen according to the literature consulted.

- Disposable nitrile gloves, lab coat, dust mask FPP2 OR 3M™ Full Face Mask, paperboard for worktable, tray with disposable paper tissue to place mineral/card trays Geiger counter, photographic camera;
- Minigrip® re-sized in the inferior area (sealed 2 times, Figure V.12) with an IMPULSE SEALER MODEL FS-400C 220V AC 50/60Hz POWER 600W (level 2);
- Paper duct tape (TimeMed Labeling System) to close Minigrip® holes (exterior and interior) (Figure V.12);
- Labels for individual storage of toxic, mercury, asbestos and radioactive;
- Identified hazard (mercury, asbestos, radioactive) Minigrip® for latter safe disposal of particles/waste material (Figure V.13).
- Note: all minerals were inserted inside the Minigrip® with the zipper on top to reduce possible damage due to minerals rubbing in the bag. If the card tray was large, then the Minigrip® needed to be inserted horizontally.

Figure V.13 – Detail of card tray contaminated with asbestos particles.

V.2. Toxic minerals

Certain minerals can be considered moderately to highly toxic to human health by ingestion, inhalation or prolonged/repeated skin contact [31]. Howie [31] presents a compilation of toxic minerals after different authors. This list includes the mineral name, toxic element(s) present and which via route is likely to be highly toxic. Some of the most common toxic elements present in minerals are: Antimony (Sb), Arsenic (As), Cadmium (Cd), Chromium (Cr), Lead (Pb), Mercury (Hg), Thallium (Tl), Vanadium (V) [31], [36], [37], [40], [43], [70], [77]. As, Pb, Hg and Tl should be regarded as highly toxic [31], [77]. Some examples of toxic minerals are: Arsenolite, Chromite, Cinnabar, Descloizite, Native Mercury, Native Lead, Realgar.

The risk of acute poisoning is unlikely to the curator / conservator if precautions during handling are taken [31], [40], [77]. For example, Silicon (Si) is considered to be toxic (via inhalation of prolonged exposure to airborne particles), however the potential risk to the curator is normally minimal because it is not common to grind and polish specimens in museums [71]. Various factors influence the potential risk, such as solubility (minerals that are water soluble are more hazardous than a non-soluble type [36], [40], [71]), grain size, friability, activities (e.g. handling, cleaning).

Native mercury and mercury-containing minerals should be stored in a well-sealed containers (e.g. screw top glass jars, Stewart plastic boxes) [78]. This method will reduce the rate of volatilisation and contain the mercury vapour [78]. These mineral can also be stored in vapor barrier envelope, in order to reduce mercury vapor emission [8]. It is important to take note, that the concentration of these gases can become higher if cabinets / boxes are left closed for extended periods of time [23], [70]. Thus, the containers need to be open in a well ventilated area [78].

V.2.1. **Results and discussion**

V.2.1.1. *<u>Personal protective equipment (PPE) and health and safety handling procedures</u>*

If correct handling is carried out with toxic minerals, it is unlikely dramatic poisoning will occur, however some minerals contain very toxic elements and therefore should always be handled with suitable gloves [77]. The following materials/procedures were compiled from the literature and the Hazardous Mineral Survey:

- Latex or neoprene gloves [31], [77].
- Surgical gloves [79]
- Disposable gloves for minerals containing arsenic, lead [71]
- Rubber gloves for known strong poison mineral [40], [43] (after Hazardous Mineral Survey)
- Neoprene gloves [70] (after Hazardous Mineral Survey)
- Face mask or respirator [79]
- Work should be carried out in a fume cupboard [43], [71]
- Goggles [71]
- Disposable lab coats or apron can reduce the risk of particulates being transported from one location to another [71]
- Hands should be wash after handling.

V.2.1.2.*Labels and storage materials*

All drawers and individual storage with mercury and mercury-containing minerals were labelled with a simple pictogram with exclamation mark and toxic element (Figure V.14, Figure V.15, Figure V.16). Native mercury and some mercury-containing specimens were encapsulated inside labelled Minigrip® bags - labels were placed outside the card tray and Minigrip® (Figure V.15). For the remain toxic minerals, only their individual card trays were identified with the toxic element(s) present - labels were placed outside and inside the card tray (Figure V.17).

Figure V.14 – Example of an identified drawer with mercury-containing minerals inside (left). Label used for drawers with mercury and mercury-containing minerals (right)[3].

[3] The background image of mercury labels taken from https://betaeq.com.br/index.php/2019/09/13/metais-liquidos-inovacao-nas-ligas-metalicas/ (consulted on September 2020)

Figure V.15 – Example of an identified native mercury and cinnabar mineral inside a Minigrip® (left). Image taken on 22/10/2020. Label used for individual storage of mercury and mercury-containing minerals (right). Labels were placed outside the card tray and outside the Minigrip®.

Figure V.16 – Example of an identified Cinnabar mineral. Image taken on 29/10/2020. Labels were placed outside and inside the card tray.

Figure V.17 – Example of label for a potentially toxic minerals containing Arsenic element (e.g. Adamite mineral).

V.3. Asbestos minerals

Asbestos is the generic commercial name used to refer silicate fibres of the serpentine and amphibole groups of minerals [35], [80]. Minerals of serpentine group have long, twisty and curly fibres (e.g. Chrysotile) [71]. While the minerals from amphibole group (e.g. Crocidolite) have straight, sharp, needle-like, brittle fibres and are considered more hazardous than the serpentine group [71], [81]. Asbestos is a natural geological material wildly recognized as a serious hazard substance that can cause serious diseases, such as asbestosis, lung cancer and mesothelioma [35], [37], [82]. These minerals can release individual flexible fibres that can be inhaled and dangerous to human health [43], [70]. Health risks of asbestos inhalation depends on several factors including how friable the specimen is, how carefully is handled [70], how much asbestos dose an individual was exposed to and how long an individual was exposed to [81]. The appearance of the first symptoms after the first contact with asbestos usually may reach from 10 to 30 years to show [83].

Asbestos was widely used in construction in nineteenth century [37], [80] and twenty century in Portugal. Before knowing the toxicity of this material, it was used in industrial applications such as roofing, thermal and electrical insulation, cement pipe and sheets, flooring, gaskets, friction materials, coating and compounds, plastics, textiles, paper, mastics, thread, fibre jointing and millboard [80]. It was also used as component of drywall, fire blankets, fireproof clothing for firefighters and gas mask filters [37]. The asbestos industrial used is now banned within the United Kingdom and European Union, while in the United States the use and management of asbestos is regulated [35], [37], [80].

Some minerals defined as asbestos are: Actinolite, Amosite (variety of Grunerite), Antrophyllite, Chrysolite, Crocidolite (variety of Riebeckite), Erionite, Grunerite, Richterite, Riebeckite, Tremolite, Winchite [35]–[37], [70]. Amosite and Crocidolite are considered to be the most hazardous [37], [70].

Drawers and card trays holding these specimens, as well as their labels should be vacuumed to remove any trace of asbestos particles [71]. Some fibres can be placed in plastic vials. However, the card trays and heavily contaminated drawers should be treated as asbestos waste [35]. After this process, the asbestos specimens needed to be encapsulated. They can be sealed in a transparent proactive covering and then be stored in new clean card trays [35]. It is advisable to transfer minerals in grade fume cupboards or sealed tent with air extraction so specimens can be sealed safely [71].

Both in Portugal and the European Union, the exposure limit value of airborne concentration of asbestos is fixed at 0,1 fibres per cubic centimetre (cm^3) as an 8 hour time-weighted average (TWA) according to the Article 4º of Decreto-Lei n.º266/2007 of 24 July and Article 8º of Council Directive 2009/148/EC of 30 November 2009 [84], [85].

V.3.1. **Results and discussion**

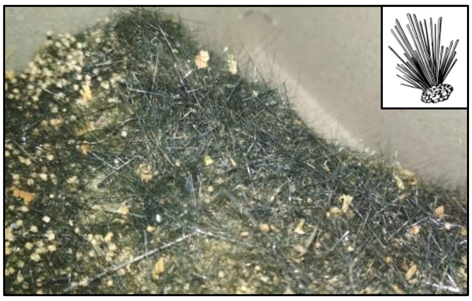
V.3.1.1. *Personal protective equipment (PPE) and health and safety handling procedures*

- Disposable gloves (e.g., PVC, latex, nitrile, polythene);
- Disposable full-body cover (after Hazardous Mineral survey);
- Full-body cover and washable boots [86];
- Laboratory coat [77];
- Dust mask [71], [77] especially if it is suspected that fibres will become airborne [36];
- Disposable masks EN 149 FFP3 or half face mask respirator EN405 and filter replace when dirty [86];
- Goggles [71];
- Negative-pressure filtered desktop cabinet or glove box or fume cupboard for handling/sampling/processing asbestiform materials (after Hazardous Mineral Survey).

V.3.1.2. *Asbestos assessment*

Asbestos were assessed according to the Hunterian Museum geological asbestos risk assessment [35]. The visual examination was adapted and included the following subjects: mineral species present, habit/texture, surface condition, and quantity of loose fibers present in storage materials (Table V.23).

Table V.23 – The Hunterian geological asbestos risk assessment [35] (adapted)

Subject	Definition and score
Species	1 - No asbestiform groups/species 2 - Serpentine group 3 - Amphibole group 4 - Amosite/riebeckite and erionite
Texture	1 - Massive/visible individual crystals/cleavages (bladed) [4]  3 - Silky/acicular or for not visible (packed) potential asbestos  2 - Elongate/glassy acicular  4 - Finely fibrous/asbestiform/filiform or woolly 
Surface	1 - Hard/clean/glassy surfaces, already sealed in a container; minor breaks/abrasions 2 - Significant breaks/abrasions/porosity, or not visible (packed) potential asbestos 3 - Fragile: loose dust and fragments present
Quantity of loose fibers	1 - None to trace 2 - Medium 3 - Significant

V.3.1.3. *Labels and storage materials*

All drawers and individual storage housing asbestos specimens were signalled with the labels below (Figure V.18, Figure V.19, Figure V.20). The proposed label for asbestos minerals on exhibition is presented in Figure V.21. The mapping of asbestos minerals inside the storage and exhibition are shown in Figure V.22 and Figure V.31, respectively.

Most asbestos specimens were only stored on open card trays, therefore not having an appropriated safe storage container. Thus, all specimens which had acicular and fibrous/woolly texture were encapsulated inside Minigrip® bags to control the release of fibres (Figure V.19). A potential issue with zipper bag enclosure is that the bag can suck inwards. If the tray is too shallow, the barrier film can press down tight against a specimen. To avoid this, side cards were added to the card trays to

[4] Drawings of bladed, acicular and fibrous were taken from https://www.britannica.com/science/mineral-chemical-compound/Crystal-habit-and-crystal-aggregation (consulted on March 2020)

make a couple of centimetres higher than the top of the specimen. Specimens that had a compact bladed structure and no particles were visible inside the card were not encapsulated, only identified in the card tray (Figure V.20).

Figure V.18 – Example of an identified drawer with asbestos minerals inside (left). Label used for drawers with asbestos minerals (right) [5].

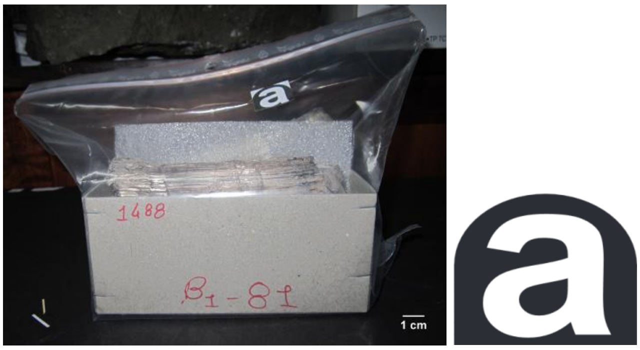


Figure V.19 – Example of an identified asbestos mineral inside a Minigrip® (left). Image taken on 13/10/2020. Label used for individual storage of asbestos minerals (right). Labels were placed outside the card tray and outside the Minigrip®.

Figure V.20 – Example of an identified asbestos mineral not encapsulated since it has a compact structure and no particles were visible inside the card tray. Image taken on 13/10/2020. Labels were placed outside and inside the card tray.

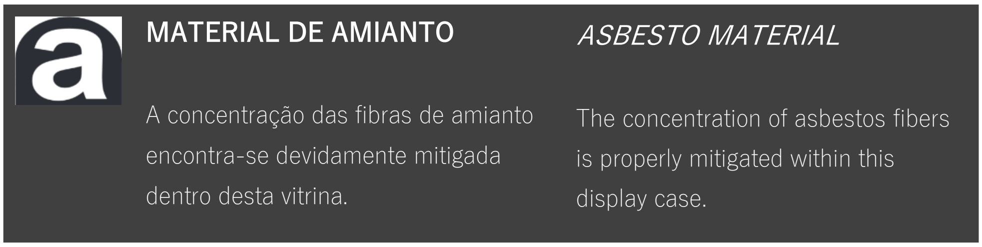


Figure V.21 – Label used for asbestos minerals in the exhibition room.

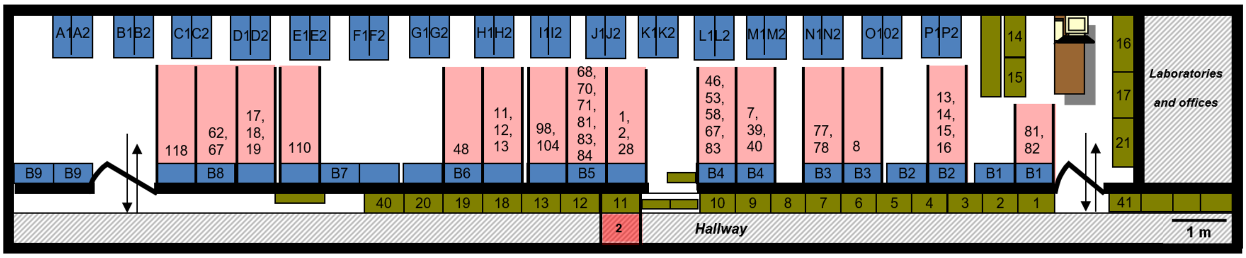


Figure V.22 – Mapping of asbestos minerals inside the storage. Numbers represent drawers' respective number.

[5] Asbestos labels image were taken from https://agdemolicoes.wordpress.com/tag/amianto/ (consulted on September 2020).

V.4. Radioactive minerals

V.4.1. Previous work

In 2013-2015 a study on radioactive minerals was conducted by Silva [87]. This was the first work aimed to identify, mapping, determination of the dimension, assessment of storage materials, compile and analyse the previous radon measurements of uranium minerals in MUHNAC's mineral collection [87]. Also, a set of first recommendations for good conservation practices and safety were implemented [87].

Initially most of radioactive minerals were stored in open card trays [87]. Gradually these specimens were being placed in “Le parfait” jars (jam jars), cylindric tubes with rudimentary plastic or in plastic containers Cristal® with lid (Polystyrene, PS) [87]. Mostly since 2015, these specimens have being placed in Minigrip® zipped bags (Polyethylene, PE) or in duct-tape sealed plastic sleeve [87].

As reported in Silva's work, between 2013 and 2015, the emission of radon gas resulting from the presence of radioactive specimens in the collection was monitored by Professor Fernando Barriga with the support of *Campus Tecnológico e Nuclear* (CTN) [87]. The monitorization was conducted in two phases: 2013-2014 (01/10/2013 to 07/01/2015 – 98 days) and 2014-2015 (27/11/2014 to 23/03/2015 – 88 days). The results on the exhibition room presented radon values within the protection thresholds for radon: 48 Bq/m^3 and 155 Bq/m^3 in 2014. Inside the “Geology Storage Room 2” the radon values were significantly higher: 181 Bq/m^3 and 231 Bq/m^3. While for the “Geology Storage Room 1”, the concentration was had constant high values in 2014 and 2015:

- Where most of radioactive minerals are concentrated (Block 9, South-side): 1302 Bq/m^3 in 2014 and 1375 Bq/m^3 in 2015.
- In the opposite location and closer to the working area (Block 1, North-side): 1134 Bq/m^3 in 2014 and 1117 Bq/m^3 in 2015.

As cited by Silva (2016), the radon concentration in the “Geology Storage Room 1” is considered high. In the European Union, the reference level for the annual average activity of radon concentration in the air within the workplace must not be higher than 300 Bq/m3 according to the Article 54º of *Council Directive 2013/59/Euratom* of 5 December 2013 [88]. In Portugal, the reference protection limit of radon concentration is 400 Bq/m^3 according to the *Ministérios do Ambiente, Ordenamento do Território e Energia, da Saúde e da Solidariedade, Emprego e Segurança Social* Portaria n.º353-A/2013 of 4 December [89].

V.4.2. **Present work**

Minerals that contain considerable amounts of uranium (U) and thorium (Th) are radioactive [36], [40], [43], [90]. Examples of common radioactive minerals include Autunite, Brannerite, Carnotite, Gummite, Monazite, Pitchblende, Thorianite, Thorite, Torbernite, Uraninite, Uranophane, Uranocircite [8], [39], [90]. However, certain minerals can have radioactive elements in, but are not itself radioactive, such as Bismuth that can be associated with uranium ores [71].

As stated by different authors [8], [36], [40], [91], [92], the main potential health risk from radioactive specimens are through:

- External exposure to beta particles and gamma radiation due to proximity to a source outside the body. Irradiation of the skin and the rest of the body;
- Inhalation of radioactive particulate material when handling specimens, due to production of airborne dust;
- Ingestion of radioactive particulate material by transfer from contaminated hands to the face/mouth;
- Radon gas emanation.

Radioactivity is a property that some atoms have to spontaneous break down their unstable nuclei, successively transforming themselves into atoms of other elements, involving the release of “ionizing radiation”, until they reach a stable and not radioactive form [26], [93]. The ionizing radiation is the emission of alpha particles, beta particles and gamma rays [26].

Radon (^{222}Rn) is a noble gas, colourless, odourless and tasteless radioactive gas that can be release as a by-product of the radioactive disintegration of Radium (226Ra), an element of the chain of uranium (U) decay series [90], [92], [94]. Radon will decay itself quickly and will led to a series of “radon-daughters” products [40], [90], [92], [94]. These products are longer-lived than the radon gas and are hazardous if allowed to accumulate [40], [90]. The radon daughter products are electrostatically charged and for that have an affinity with dust particles [95]. As a hazard, it can be inhaled and deposited in the lungs, submitting them to ionizing radiation and therefore increasing the risk of cancer [92], [95]. Radon also has the property of being heavier than air, therefore it will settle in the lowest part of the media storage/room [90]. These products can cause internal irradiation when inhaled [40].

The concentration of radon gas in a room is measured in becquerels per cubic metre (Bq m^{-3}) and depends on the ventilation rate of the store and the quantity of radon gas associated with the collection [33]. The dose of radiation received by a person is measured in Sieverts (Sv), milisieverts (mSv) or microsieverts (μSv) [36] – usually these can be measured per hour or per year.

Standard values of radon gas concentration limits from different sources are listed in Table V.24. Radon concentration values vary between 100 to 400 Bq m^{-3}, which 400 Bq m^{-3} is the maximum value in Portugal.

Table V.24 – Standard and acceptable values for annual radon concentration in the air from different countries (becquerels per cubic metre)

Source	Local	Radon concentration (Bq m^{-3})	Reference
World Health Organization	General	100 – 300[1]	[96]
Health and Safety Executive	United Kingdom	300	[97]
Environmental Protection Agency	United States of America	148 (4 pCi/L)[2]	[98]
Official Journal of the European Union	European Union	300	[88]
Diário da República	Portugal	400	[89]

[1] If this level cannot be reach under the prevailing country-specific conditions, the reference level should not exceed 300 Bq m^{-3}

[2] Conversion: 1 pCi/L is equal to 37 Bq m^{-3}

Faithfull [99] stated that a specimen can be classed as being "significantly radioactive" if it gives a maximum surface dose rate of greater than 7,5 µSv hr^{-1} (corresponding to the "adequate shielding level" specified by UK legislation) or it can be classed as being "weakly radioactive" if it gives a maximum surface dose rate between 1 to 7,5 µSv hr^{-1} [99]. Figure V.23 shows this methodology and the adaptation for this study.

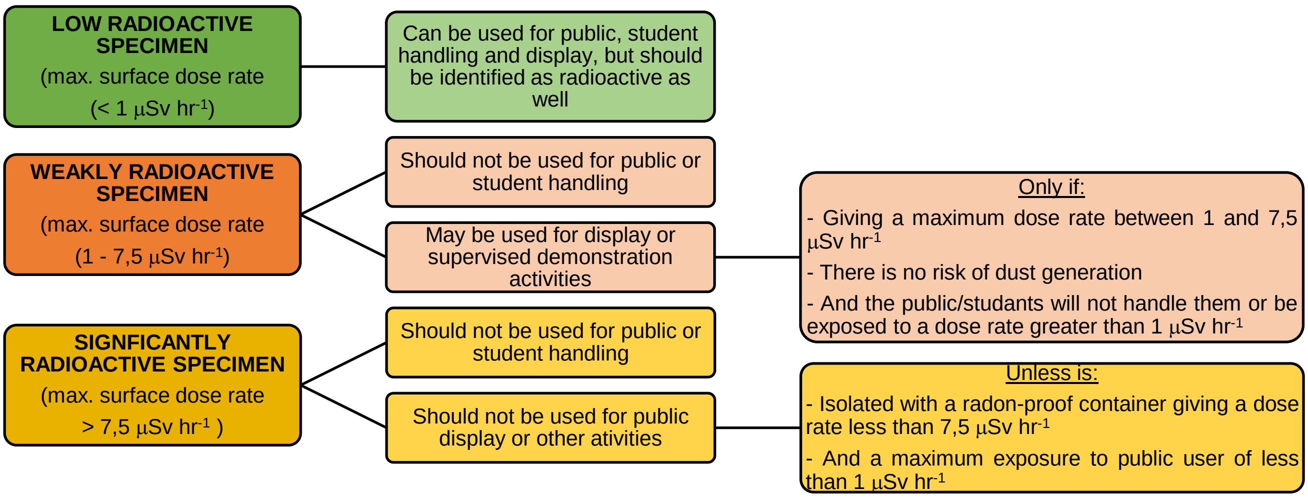


Figure V.23 – Weakly and significantly radioactive specimen specifications according to UK regulations and methodology used in Hunterian Museum Collections [99] (adapted). Low radioactive specimen was added for this study.

Radiation protection is to keep all exposure to radiation "As Low As Reasonably Achievable" (ALARA) [92], [100]. Figure V.24 represents the general rules for minimising radiation exposure followed by Museums Libraries and Archives Council [43] and Horak, Price and Faithfull [39].

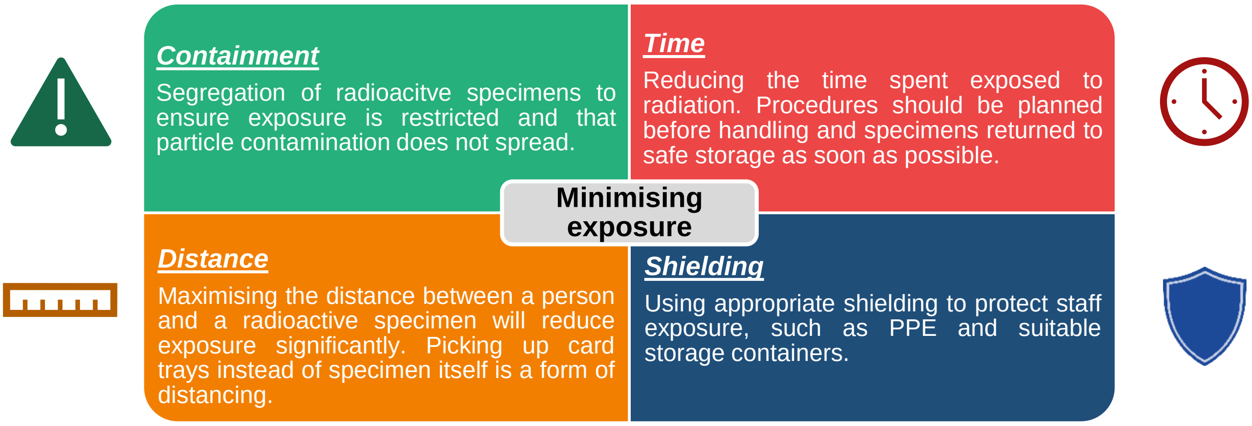


Figure V.24 – Minimising exposure requirements followed by Mick Stanley for MLA (2004) and Horak, Price and Faithfull (2013).

To measure radiation levels, a *Geiger counter* (*Geiger-Müller tube*) can determine the level of radiation by measuring alpha particles, beta particles, gamma radiation [26], [90], [91], [100], [101]. The Geiger counter is used to identify radioactive minerals, loose materials on work surfaces, protective clothing and storage containers [91].

The use of dose limits are intent to protect workers and general public from the effects of ionising radiation [102]. In Portugal, the *Direção-Geral da Saúde* states there are different dose limits for different groups of people: exposed employees, trainees and students, exposed working pregnant or lactating women and members of the public [93]. All the work areas where radiation dose rate exceeds 1 mSv per year of the limit dose should be classified as "controlled zone" or "supervised zone" [93]. Price et al. [39] compared the dose rate limits provided by the law in the UK with the dose rate measured by a dose rate meter: "The current dose limit for the general public is 1 mSv per year. A person would have to be exposed to a specimen of $1\mu Svh^{-1}$ for greater than 1000 hours or a $7.5\ \mu Svh^{-1}$ specimen for more than 133 hours, to obtain their maximum yearly dose". According to Ionizing Radiation Regulation of UK, an area should be designated as a "Radiation Controlled Area", if the dose rate exceeds 7,5 µSv per hour [33], [40], [97]. Thus, a person would exceed the annual dose rate if exposed to a place with $8{,}5\ \mu Svh^{-1}$.

V.4.3. **Results and discussion**

V.4.3.1. *Personal protective equipment (PPE):*

- Disposable gloves (e.g., PVC, latex, nitrile, polythene) [31], [39], [71], [77], [91], [92], [103];
- Washable gloves (e.g., rubber) [77], [92], [99], [104];
- Laboratory coat or disposable apron [39], [71], [91], [92];
- Lead-lined coat (after Hazardous Mineral survey);
- Respirator protection with High Efficiency Particulate Air (HEPA) filter [31], [91]; Respirator with filters for radionuclide dusts [103]; Particulate filter mask [71], [92];
- Reusable half face mask respirator (after Hazardous Mineral survey);
- Eye protection (e.g., safety glasses) [92], [103],

V.4.3.2.*Health and safety handling procedures:*

- Before the specimens are handled, the containers should be opened in a well-ventilated area (at least an hour - freshly opened drawers should not be breath directly over), such as outdoors or in a fume cupboard, to allow the radon daughters to be diluted to a very low concentration and prevent accidental inhalation [3], [77], [92], [100], [105],[100].
- Place mineral in a shallow tray instead being directly on the workstation surface;
- Examples of shielding: thick transparent acrylic (to shield from Beta radiation) [39], lead glass screen barrier (after Hazardous Mineral Survey);
- Card trays should be handled rather than specimens themselves [39];
- Tongues can be used for handling strongly radioactive material (after Hazardous Mineral survey);
- Radioactive specimens should not be handled when hands are cut or skin broken [31], [106];
- Hands should be wash before and after handling;
- Surfaces/trays should be cleaned with damp cloth until all contamination has been removed [39];
- Store significant radioactive minerals in the back of cabinets;
- If specimens are dispersed with a few per drawer, the local concentration of radiation can be reduce [33], [39]

V.4.3.3.*Assessment of radioactive minerals*

Certain minerals are not considered radioactive, but can sometimes contain radioactive elements, making it difficult to identify them [39]. In order to be certain that all minerals containing radioactive elements were detected, all the specimens of the mineral collection were surveyed with a radiation detector.

A nuclear radiation monitor Radalert 100™ (hand-held Geiger counter that measures alpha, beta and gamma radiation) was used to measure the dose rate of radioactivity from: outside the building, entrance of the mineral storage room, different locations inside the storage, outside of closed drawers, storage material surface (e.g., zipper bag) and the minerals itself without any storage material (Figure V.25). The measurements were made three times in the same place to obtain more accurate values.

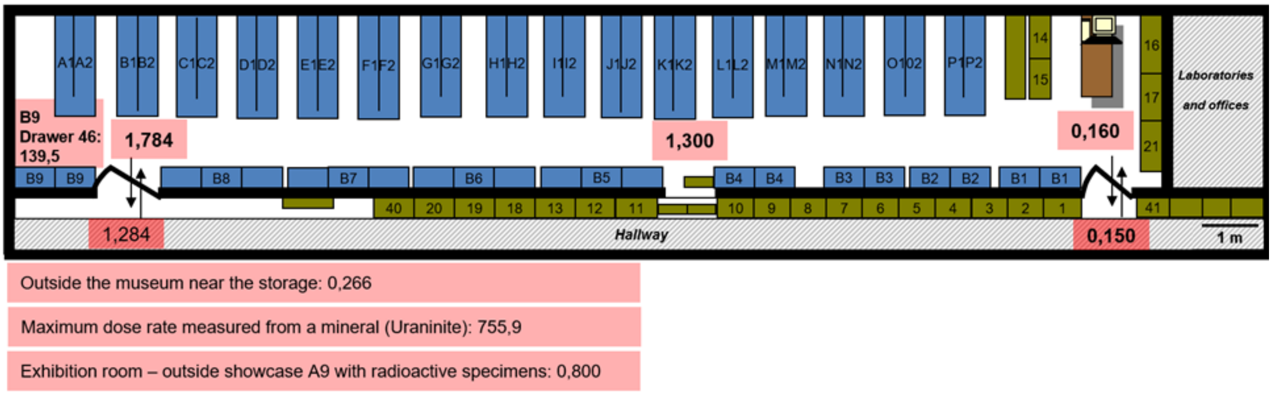


Figure V.25 – Dose rate of radioactivity measurements (μSv hr-) inside the storage room and other locations. Measured at 20/11/2020

The radiation dose rate inside the storage room exceeds 8,5 μSvh^{-1} near B9. Thus, it should be considered whether this room should be classified as a "controlled zone" or "supervised zone" as described above.

The radioactive minerals considered for this study have a maximum surface dose rate superior to 0 μSv/hr. The MUHNAC's mineral collection comprises 339 radioactive specimens. Following the considerations explained above by Faithfull [99], radioactive minerals were classed as Low, Weakly and Significant radioactive. There are 73 "Low radioactive" specimens, 57 "Weakly radioactive" and 209 "Significantly radioactive". The specimens which had the highest dose rate at the surface were Uraninite (755,9 μS/hr), Fourmarierite (709,4 μS/hr), Uraninite with Curite (694,7 μS/hr), Guilleminite (630,1 μS/hr), Cuprosklodowskite with Vandenbrandeite (619,7 μS/hr), Swamboite (567,4 μS/hr).

V.4.3.4.*Labels and storage materials*

All drawers and individual storage material were identified with the labels mentioned by Silva [87] (Figure V.26, Figure V.27, Figure V.28). Not all minerals had a proper safe storage container were encapsulated or inside boxes and some had small zipper bags that could be teared. For that, all minerals that did not have a proper container were encapsulated inside Minigrip® bags (Figure V.27) and Cristal® boxes with lid sealed with duct-tape (Figure V.28). Minerals placed inside Cristal® boxes were conducted by João Paulo Lopes. The proposed label for radioactive minerals on exhibition is present in Figure V.29. The mapping of radioactive minerals inside the storage and exhibition are shown in Figure V.30 and Figure V.31, respectively. A label with the most recent dose rate measurement and its' respective date can be added to the container in the future.

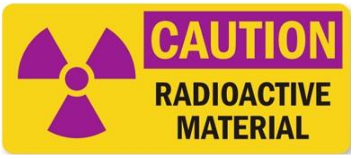


Figure V.26 – Example of an identified drawer with radioactive minerals inside (left). Label used for drawers with radioactive minerals (right)[6].

[6] Radioactive labels were taken from https://www.mysafetysign.com/Laser-Warning-Labels/Radioactive-Material/SKU-L-0576-XV.aspx (consulted on September 2020).

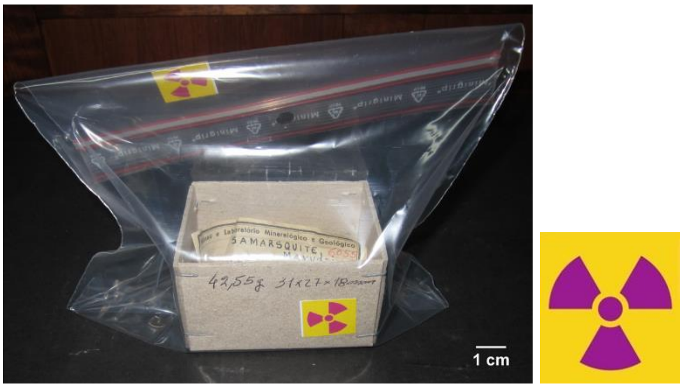


Figure V.27 – Example of an identified radioactive mineral inside a Minigrip® (left). Image taken on 24/09/2020. Label used for individual storage of radioactive minerals (right). Labels were placed outside the card tray and outside the Minigrip®.

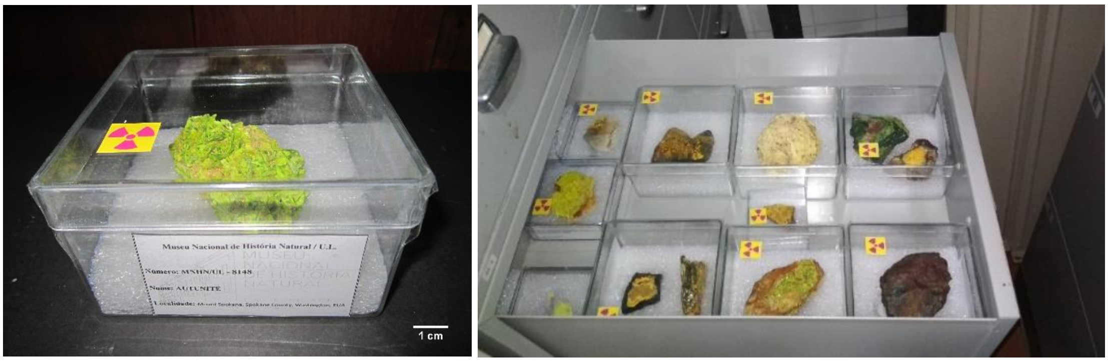


Figure V.28 – Example of an identified radioactive mineral inside a *Cristal*® box (left) and organization inside a drawer (right). Images taken on 08/10/2020. Label was placed outside the *Cristal*® boxes.

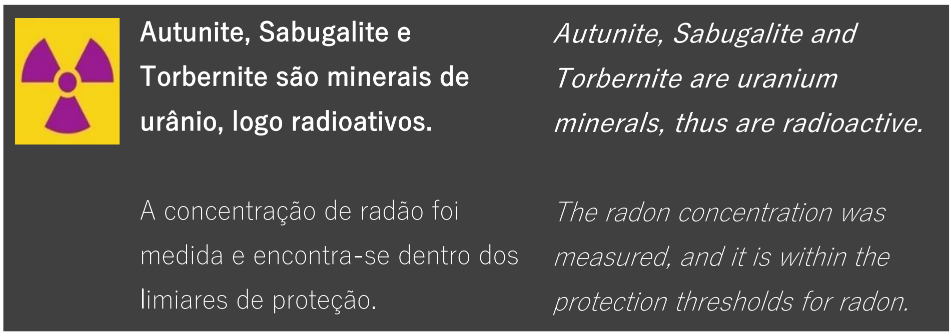


Figure V.29 – Label used for radioactive minerals in the exhibition room.

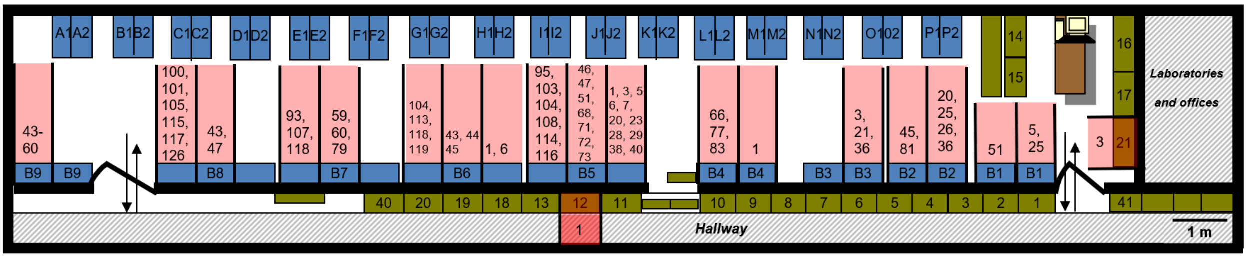


Figure V.30 – Mapping of radioactive minerals inside the storage. Numbers represent drawers' respective number.

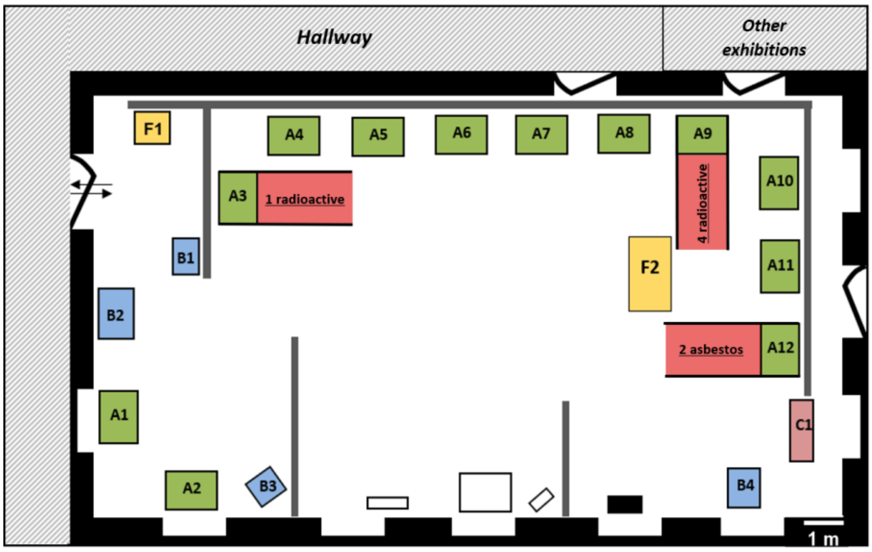
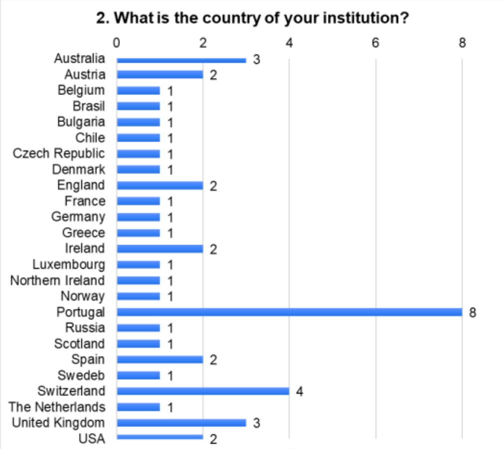
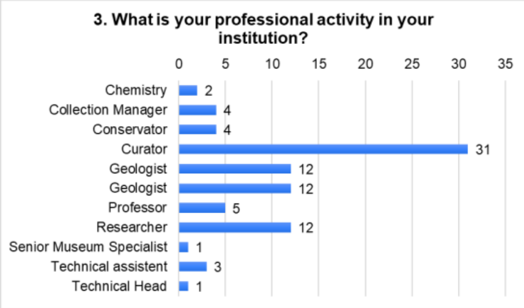
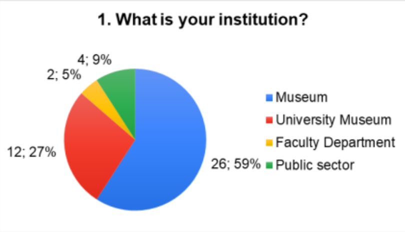


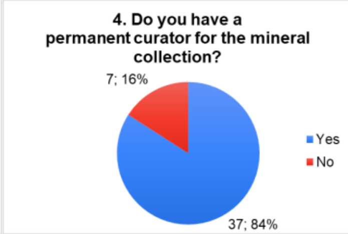
Figure V.31 – Mapping of radioactive and asbestos minerals inside the exhibition. Numbers represent quantity of minerals inside the showcase.

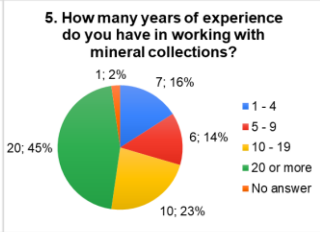
V.5. Hazardous Mineral Survey

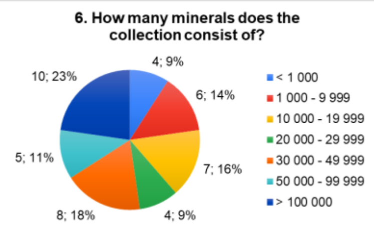


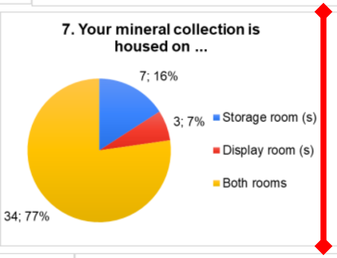


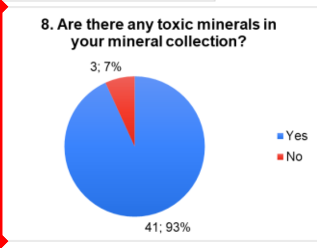


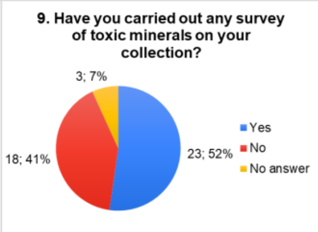


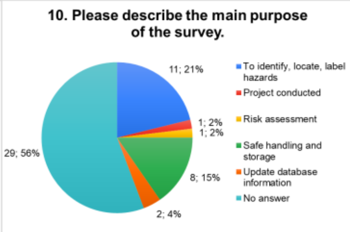


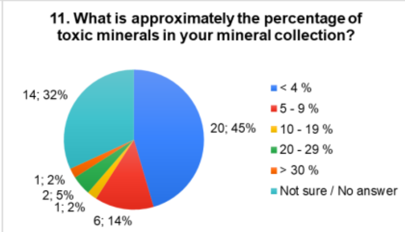


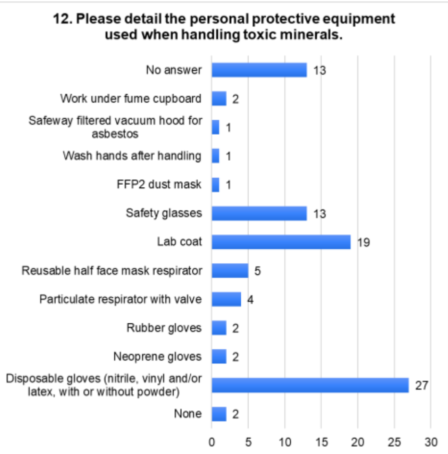


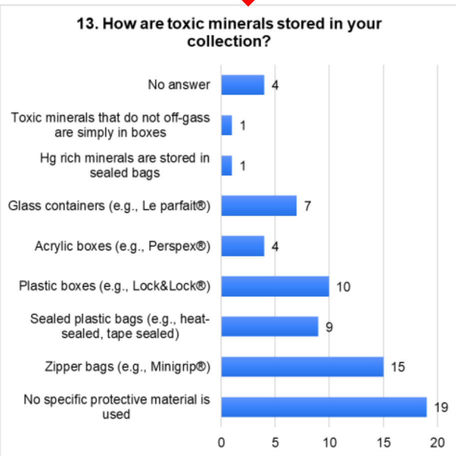


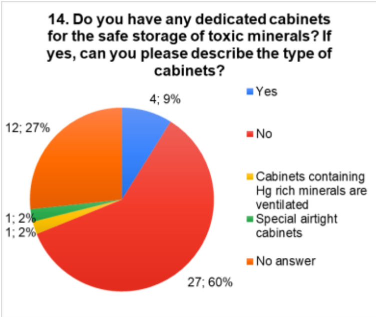


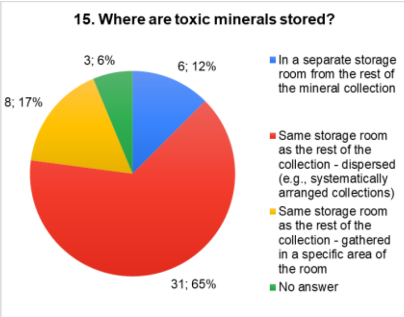


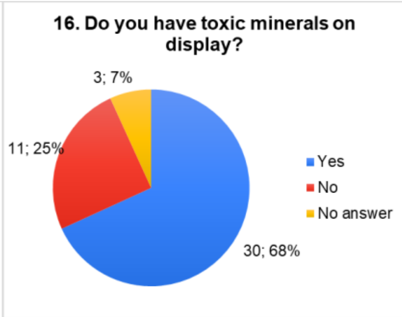




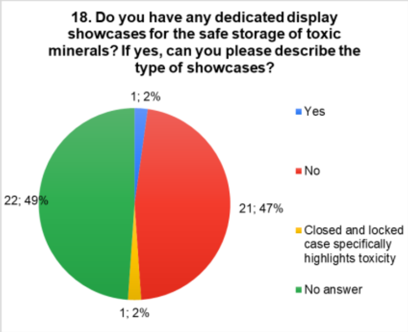


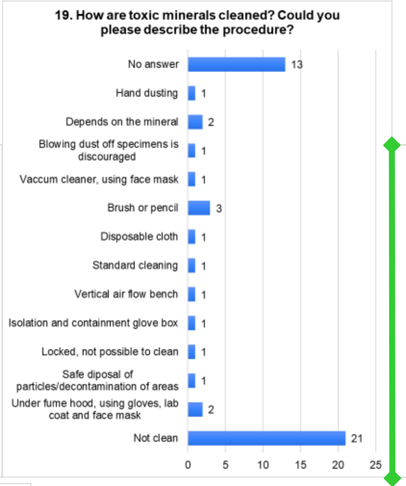


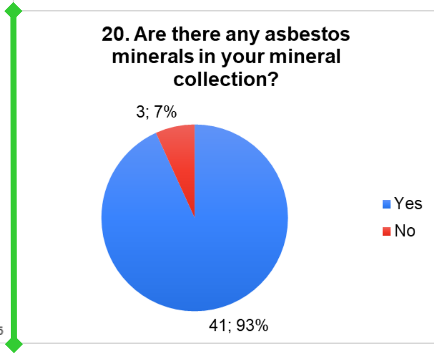


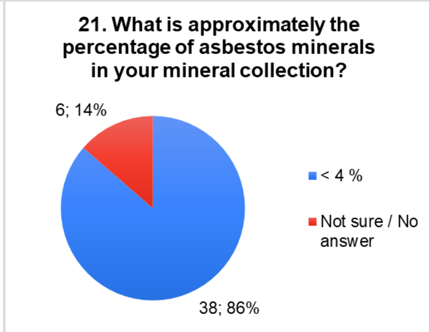


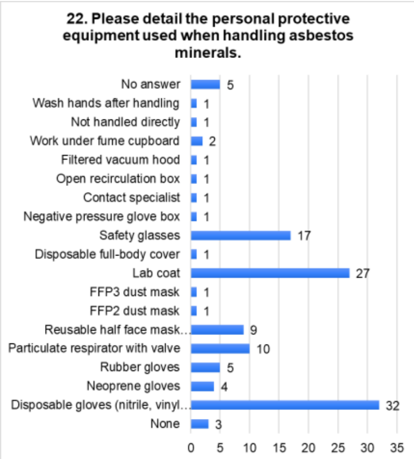

17. How are toxic minerals displayed in your collection?
No answer 14
Closed showcases 15
Glass boxes 4
Acrylic boxes 3
Plastic boxes 2
No specific protective material is used 9
0 5 10 15 20

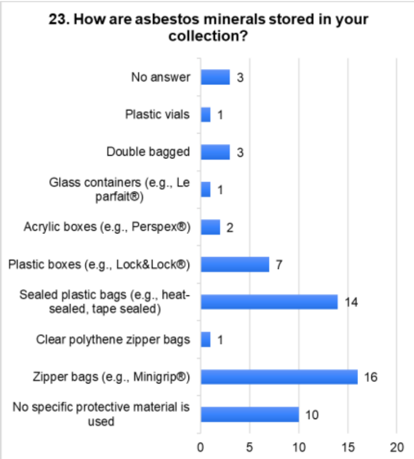

18. Do you have any dedicated display showcases for the safe storage of toxic minerals? If yes, can you please describe the type of showcases?
1; 2%
22; 49%
21; 47%
1; 2%
Yes
No
Closed and locked case specifically highlights toxicity
No answer

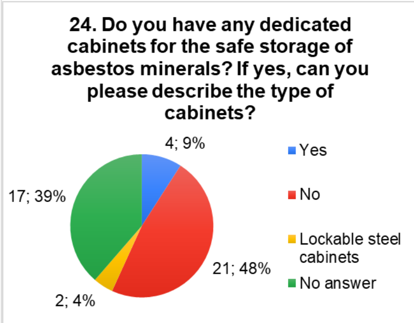

19. How are toxic minerals cleaned? Could you please describe the procedure?
No answer 13
Hand dusting 1
Depends on the mineral 2
Blowing dust off specimens is discouraged 1
Vaccum cleaner, using face mask 1
Brush or pencil 3
Disposable cloth 1
Standard cleaning 1
Vertical air flow bench 1
Isolation and containment glove box 1
Locked, not possible to clean 1
Safe diposal of particles/decontamination of areas 1
Under fume hood, using gloves, lab coat and face mask 2
Not clean 21
0 5 10 15 20 25

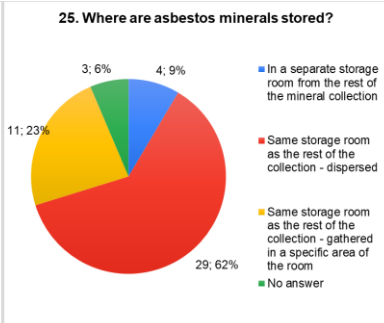

20. Are there any asbestos minerals in your mineral collection?
3; 7%
41; 93%
Yes
No

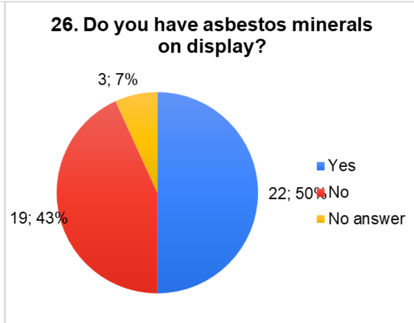

21. What is approximately the percentage of asbestos minerals in your mineral collection?
6; 14%
38; 86%
< 4 %
Not sure / No answer

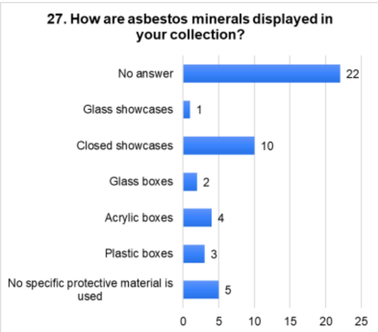

22. Please detail the personal protective equipment used when handling asbestos minerals.
No answer 5
Wash hands after handling 1
Not handled directly 1
Work under fume cupboard 2
Filtered vacuum hood 1
Open recirculation box 1
Contact specialist 1
Negative pressure glove box 1
Safety glasses 17
Disposable full-body cover 1
Lab coat 27
FFP3 dust mask 1
FFP2 dust mask 1
Reusable half face mask... 9
Particulate respirator with valve 10
Rubber gloves 5
Neoprene gloves 4
Disposable gloves (nitrile, vinyl... 32
None 3
0 5 10 15 20 25 30 35

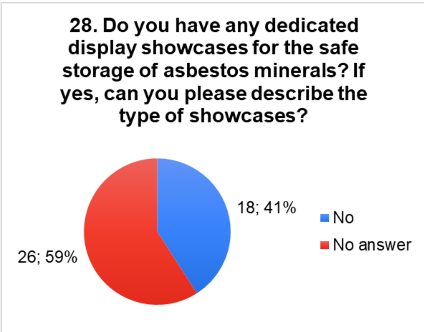

23. How are asbestos minerals stored in your collection?
No answer 3
Plastic vials 1
Double bagged 3
Glass containers (e.g., Le parfait®) 1
Acrylic boxes (e.g., Perspex®) 2
Plastic boxes (e.g., Lock&Lock®) 7
Sealed plastic bags (e.g., heat-sealed, tape sealed) 14
Clear polythene zipper bags 1
Zipper bags (e.g., Minigrip®) 16
No specific protective material is used 10
0 5 10 15 20


24. Do you have any dedicated cabinets for the safe storage of asbestos minerals? If yes, can you please describe the type of cabinets?
4; 9%
17; 39%
21; 48%
2; 4%
Yes
No
Lockable steel cabinets
No answer

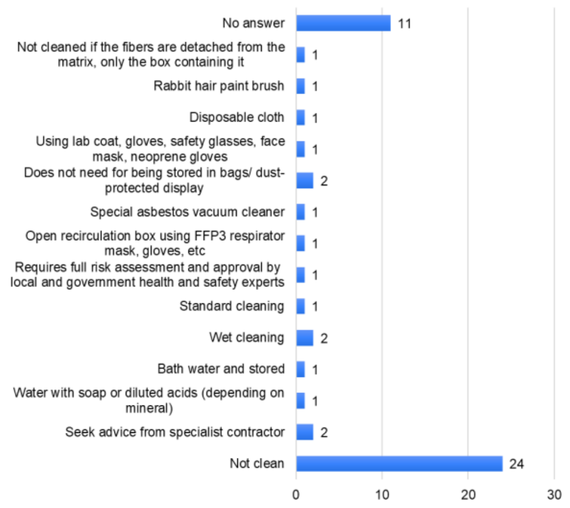

25. Where are asbestos minerals stored?
3; 6%
4; 9%
11; 23%
29; 62%
In a separate storage room from the rest of the mineral collection
Same storage room as the rest of the collection - dispersed
Same storage room as the rest of the collection - gathered in a specific area of the room
No answer


26. Do you have asbestos minerals on display?
3; 7%
19; 43%
22; 50%
Yes
No
No answer

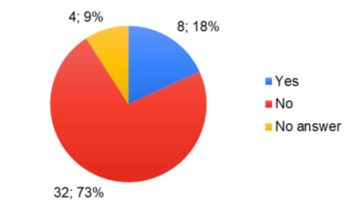

27. How are asbestos minerals displayed in your collection?
No answer 22
Glass showcases 1
Closed showcases 10
Glass boxes 2
Acrylic boxes 4
Plastic boxes 3
No specific protective material is used 5
0 5 10 15 20 25


28. Do you have any dedicated display showcases for the safe storage of asbestos minerals? If yes, can you please describe the type of showcases?
18; 41%
26; 59%
No
No answer

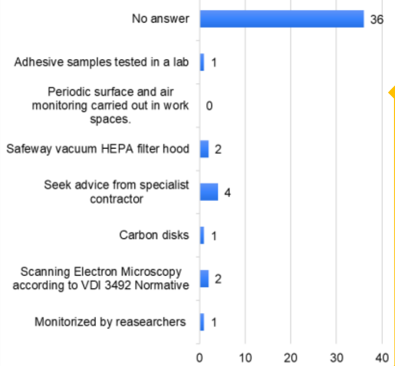
29. How are asbestos minerals cleaned? Could you please describe the procedure?



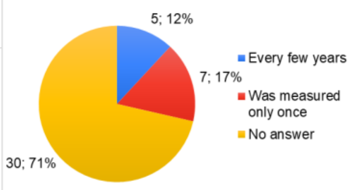
30. Is the concentration of asbestos fibres in the air monitored?



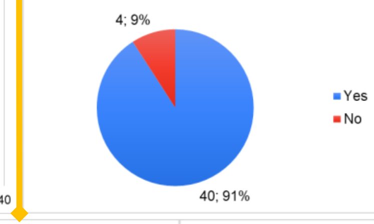
31. Could you please describe the procedure and equipment used for monitoring the airborne concentration of asbestos in the air?



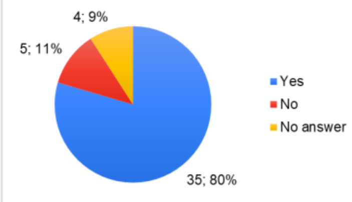
32. How regularly do you measure the airborne concentration of asbestos?



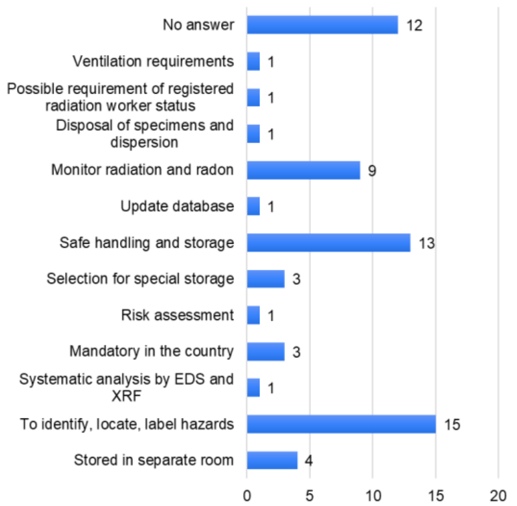
33. Are there any radioactive minerals in your mineral collection?



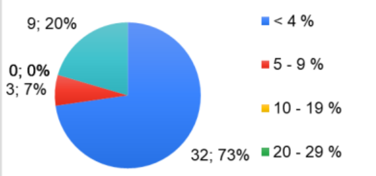
34. Have you carried out any survey of radioactive minerals on your collection?



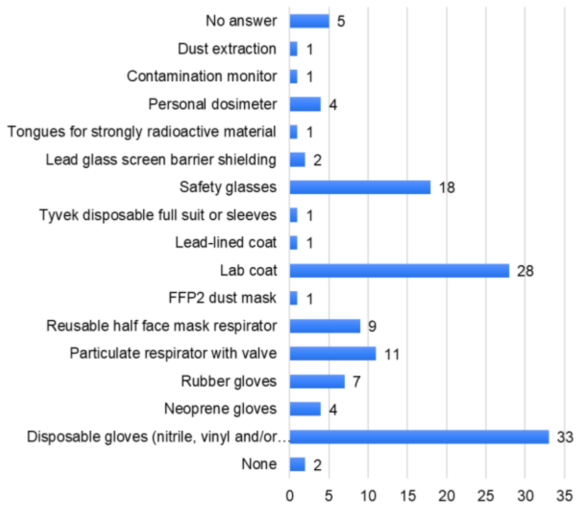
35. Please describe the main purpose of the survey.



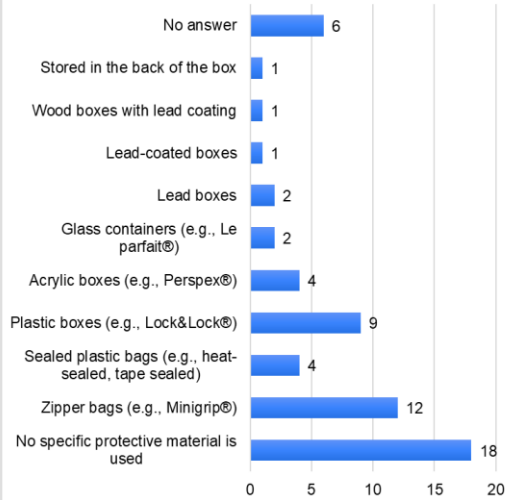
36. What is approximately the percentage of radioactive minerals in your mineral collection?

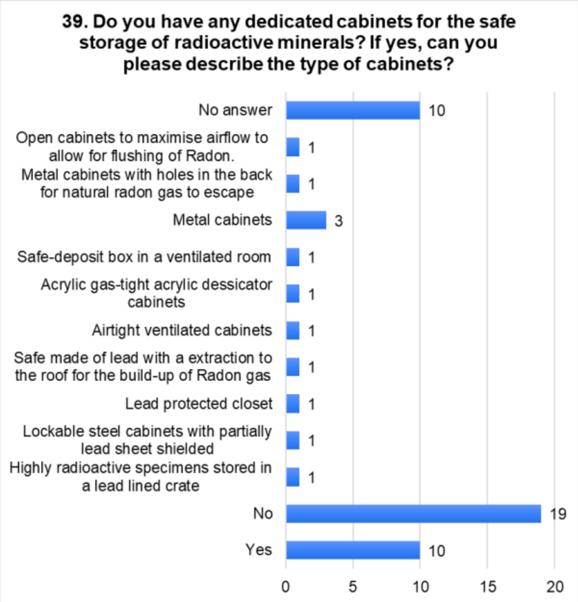


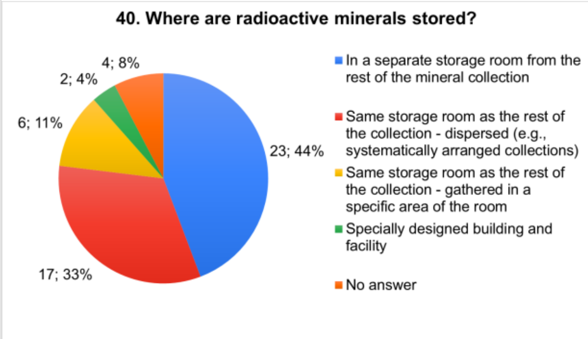
37. Please detail the personal protective equipment used when handling radioactive minerals.

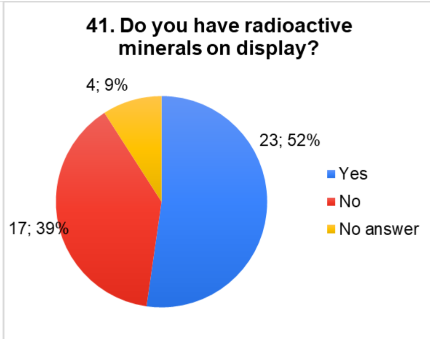


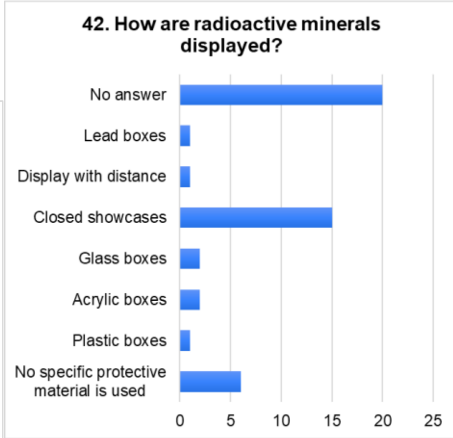
38. How are radioactive minerals stored in your collection?



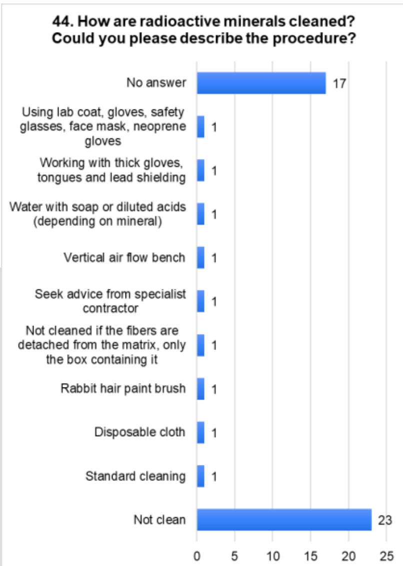

39. Do you have any dedicated cabinets for the safe storage of radioactive minerals? If yes, can you please describe the type of cabinets?
No answer
10
Open cabinets to maximise airflow to allow for flushing of Radon.
1
Metal cabinets with holes in the back for natural radon gas to escape
1
Metal cabinets
3
Safe-deposit box in a ventilated room
1
Acrylic gas-tight acrylic dessicator cabinets
1
Airtight ventilated cabinets
1
Safe made of lead with a extraction to the roof for the build-up of Radon gas
1
Lead protected closet
1
Lockable steel cabinets with partially lead sheet shielded
1
Highly radioactive specimens stored in a lead lined crate
1
No
19
Yes
10
0
5
10
15
20

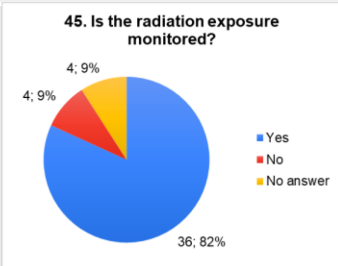

40. Where are radioactive minerals stored?
4; 8%
2; 4%
6; 11%
23; 44%
17; 33%
In a separate storage room from the rest of the mineral collection
Same storage room as the rest of the collection - dispersed (e.g., systematically arranged collections)
Same storage room as the rest of the collection - gathered in a specific area of the room
Specially designed building and facility
No answer

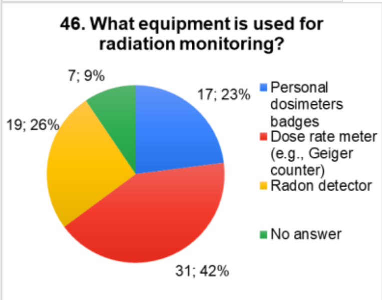

41. Do you have radioactive minerals on display?
4; 9%
23; 52%
17; 39%
Yes
No
No answer

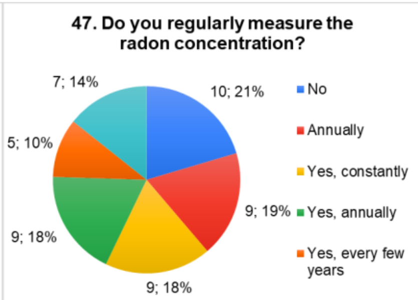

42. How are radioactive minerals displayed?
No answer
Lead boxes
Display with distance
Closed showcases
Glass boxes
Acrylic boxes
Plastic boxes
No specific protective material is used
0
5
10
15
20
25

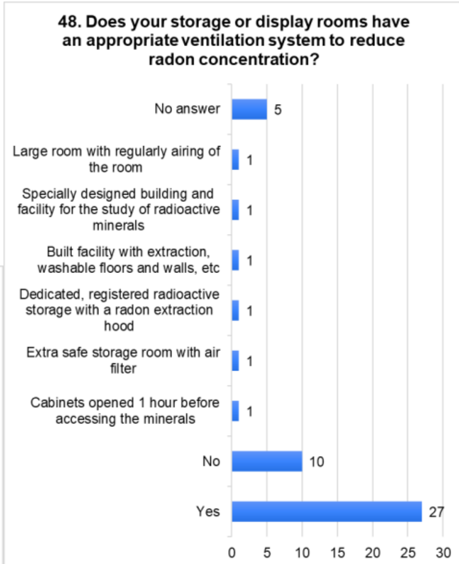

43. Do you have any dedicated display showcases for the safe storage of radioactive minerals? If yes, can you please describe the type of showcases?
2; 4%
14; 31%
28; 61%
1; 2%
1; 2%
Yes
No
Lead glass shielding and barriers according to legislation
Showcases with extra protective glass
No answer


44. How are radioactive minerals cleaned? Could you please describe the procedure?
No answer
17
Using lab coat, gloves, safety glasses, face mask, neoprene gloves
1
Working with thick gloves, tongues and lead shielding
1
Water with soap or diluted acids (depending on mineral)
1
Vertical air flow bench
1
Seek advice from specialist contractor
1
Not cleaned if the fibers are detached from the matrix, only the box containing it
1
Rabbit hair paint brush
1
Disposable cloth
1
Standard cleaning
1
Not clean
23
0
5
10
15
20
25


45. Is the radiation exposure monitored?
4; 9%
4; 9%
36; 82%
Yes
No
No answer


46. What equipment is used for radiation monitoring?
7; 9%
17; 23%
19; 26%
31; 42%
Personal dosimeters badges
Dose rate meter (e.g., Geiger counter)
Radon detector
No answer


47. Do you regularly measure the radon concentration?
7; 14%
10; 21%
5; 10%
9; 19%
9; 18%
9; 18%
No
Annually
Yes, constantly
Yes, annually
Yes, every few years


48. Does your storage or display rooms have an appropriate ventilation system to reduce radon concentration?
No answer
5
Large room with regularly airing of the room
1
Specially designed building and facility for the study of radioactive minerals
1
Built facility with extraction, washable floors and walls, etc
1
Dedicated, registered radioactive storage with a radon extraction hood
1
Extra safe storage room with air filter
1
Cabinets opened 1 hour before accessing the minerals
1
No
10
Yes
27
0
5
10
15
20
25
30