POLITECNICO DI MILANO
DIPARTIMENTO DI ARCHITETTURA E STUDI URBANI (DAStU)
DOCTORAL PROGRAMME IN PRESERVATION OF ARCHITECTURAL HERITAGE

HISTORICAL CLIMATES AND CONSERVATION ENVIRONMENTS
Historical perspectives on climate control strategies within museums and heritage buildings

Doctoral Dissertation of:
Andrea Luciani

Supervisor:
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Year 2009/2013 – Cycle XXIV

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Introduction

0.1 Historic buildings, museum environments and hygrothermal standards: origin of the thesis

The installation of climate control to provide human comfort and good conservation conditions may result in many unwanted drawbacks and the question is particularly significant if we deal with controlling indoor climate within historic buildings, which is a very complicate issue, involving a long series of problems and conflicting needs.
Commenting the beneficial effect that the storage into underground repositories had on British collections in wartime, Ian G. Rawlins wrote that "*some good comes out of evil*" (Rawlins 1943a). That experience, as it will be shown, was indeed very influential on the development of environmental conservation strategies in post-war museums.
Nevertheless, talking about the implementation of climate control in historic buildings, Rawlins' words could also be turned over and we could ask: how much evil came out from the good? How many negative consequences were caused by the positive willing of having a close control of the indoor climate within historic interiors?

First of all, historic buildings were obviously not supposed to be equipped with modern HVAC systems, but they had their own traditional methods to control their indoor environment. Dean Hawkes (2012) has shown in his study on the history of British architecture that the solar orientation, the position and shape of the windows, the heating system layout and the arrangement of the rooms in accordance with their function were all elements traditionally influencing both the building construction and the design. The emergence of modern HVAC systems, from the introduction of central heating and ventilation systems to the spread of modern air conditioning, changed the way the indoor environment was conceived by people and architects, leading to the emergence of the profession of the building services engineer with his specific and well-defined role in the building designing process (Giedion 1955, Banham 1969, Bruegmann 1978, Cooper 1998).
The consequences of this discontinuity are clear, when looking at the problems that the installation of contemporary building services can generate in historic buildings: not only devices may be very invasive in terms of visual impact and the installation of piping, wiring or ducting can cause a loss of original material, but also the hygrothermal conditions of an old building can be dramatically modified by a modern system and result in decay of building components.
Nevertheless thermal comfort is nowadays considered a fundamental requirement for a living or working space and climate control systems are generally needed to provide comfort to building users.
A first contradiction of terms is thus introduced: we know that use is one of the most powerful methods to ensure a long term care and preservation of a historic building but, at the same time, the interventions needed to facilitate it, may introduce a potential source of problems and decay.

This potential incompatibility is put to even more stress when valuable collections are exposed in historic buildings. Due to their historic meaning, to their traditional function or their acknowledged role in cities and societies, buildings originally designed for other purposes can be changed into museums or exhibition spaces and opened to the public. Their main function then becomes the

Fig. 0.1 – Example of a very invasive introduction of modern climate control devices within a historic building (Pictures by C. Manfredi).

preservation and exhibition of collections, whether these are their historically owned ones or artworks otherwise collected and placed into the building in a second time.
A similar but distinct case is represented by churches and places of worship which obviously have their special use but, at the same time, they represent an important part of our cultural heritage, due to the building itself and the artworks kept in the building.
In both cases a safe and suitable environment must be guaranteed, in terms of hygrothermal conditions, light and air quality, not only for human comfort but also for preservation.
And this is the problem: due to the development of strict hygrothermal standards for the preservation of collections, many historic buildings have been forced to control their indoor climate to a level they could hardly support without consequences on the preservation of the building fabric. A second contradiction is thus represented by the potential conflict between the conservation needs of the artworks and those of the building.

A third level of complexity is then introduced by the definition of which are the best hygrothermal conditions for the preservation of collections. The question has been debated for centuries, sometimes giving rise to harsh discussions, and represents a consistent part of the history of conservation. This topic gained growing interest among museum professionals with the spread of preventive conservation theories, which asked for a close control of the hygrothermal conditions to which the objects were exposed as an effective method to prevent damage.

Finally we have to consider also the growing need for sustainable buildings, both in the sense of an higher energy efficiency and in the sense of a reduction of operating costs. The request for a close control of hygrothermal fluctuations, especially in old building structures with envelopes not compatible with modern air conditioning, generally resulted in over-dimensioned and low-efficient climate control systems with a high energy consumption. Not only is this inappropriate from an ethical point of view, but it introduces further risk factors due to the costs involved: a historic building can be abandoned or not used because of the excessive costs needed to reach the environmental standards requested; museums or cultural institutions, in times of limited budget like our days, may be forced to cut funds from other conservation activities or to turn the climate control systems off because they cannot afford operating and maintenance costs.

The paragraphs above summarise the background of my research and present the problems originating it, while the occasion to start my study was the project on Villa Reale in Milan, developed in 2009 by the Laboratorio di Analisi e Diagnostica del Costruito (LADC - Laboratory for analysis and diagnostics on built heritage) of Politecnico di Milano in collaboration with Comune di Milano (the city administration owning the building and the collections) and with the museum staff of the Galleria d'Arte Moderna (GAM - Gallery of Modern Art). Here, a late 18th century dwelling housing the civic collection of modern art, almost all the problems above described had to be faced.

Two different fields of interest could be merged in this research project: on the one hand the staff of the LADC, which is specialised in construction history and indoor climate analysis within historic buildings, was interested in the historical air-heating system installed in the building; on the other hand the conservator of the museum needed an assessment of the conservation conditions in the museum and asked for a monitoring of the indoor climate after a recent refurbishment of the building.

The first step was to study existing Italian standards. The most used Italian museum specifications for indoor climate control were contained in the Italian standard UNI 10829:1999 '*Works of art of historical importance. Ambient conditions for the conservation. Measurement and analysis'* (UNI 1999) and in D.M. 238 law of 2001 (MiBAC 2001).

Both these documents are inspired to the theories of preventive conservation and should be placed in the footsteps of the theoretical and practical contributions by Giovanni Urbani. Spread of preventive conservation in Italy is generally considered quite recent and not yet so acknowledged, but a great contribution to the research on prevention in conservation theories was given by Urbani at the ICR in the 1970s. He changed the concept of "preventive restoration", previously developed by Brandi (1977), into the definition of "planned conservation" (Urbani 1973, ICR 1976): a renewed attention was paid to risk factors related to the environmental context in which cultural heritage objects were placed.

The objective of the UNI 10829:1999 standard was to define monitoring procedures and climate control specifications so that "*historical and artistic heritage will be placed in locations where environmental conditions influencing decay processes are properly controlle,, in order to limit the speed of the processes themselves*"[1] (UNI 1999, p.1). If the methods for environmental monitoring activities here recommended were widely accepted and used for the analysis of the indoor environment in museums and historic buildings, discussion had been raised over the table in the

[1] English translation from the Italian by the author. Original text: *"beni di interesse storico e artistico […] siano collocati in luoghi ove le condizioni ambientali, influenzanti i processi di degrado, siano opportunamente controllate al fine di limitare la velocità dei processi stessi"*

appendix where "*for the design of new air conditioning systems in rooms containing historical or artistic heritage, reference values to be considered in case of absence of alternative specific guidance are reported as an indication. These values regard the environmental parameters for the preservation of 33 categories of materials and objects, in stable climate conditions over time*"[2] (UNI 1999, p.2). These ranges of values were defined by an extensive study of existing scientific literature (see Aghemo, Filippi & Prato 1996)

The D.M. 238 law presented the quality standards for museums defined by the State to be transmitted to the local administrations in charge of their management. It contained as well an appendix in which *"some charts are presented with the purpose of indicating the values of environmental parameters within which it is possible to obtain suitable conservation conditions for artifacts"*[3] (MiBAC 2001, p.126).

In both cases recommended ranges of hygrothermal conditions for different categories of objects and materials were reported but, quite surprisingly, the two standards often do not correspond on the division into categories, on the type of decay described and on the ranges specified. As an example, considering paintings on canvas, the UNI 10829 specifies a RH target range between 40 and 55%, with a maximum daily variation of 6%, while the D.M. 238 specifies the same range to prevent biological decay but a range between 35 and 50% to prevent chemical and physical damage. Even supposing that the building could support these levels of climate control, would it have been a wise (and possible) choice using them as a reference for evaluating the indoor climate in Villa Reale?

A different approach characterised another Italian standard then in use, the UNI 10969:2002 *'Cultural heritage. General principles for the choice and the control of the microclimate to preserve cultural heritage in indoor environment'* (UNI 2002) which stated that *"it is impossible to determine for each object defined thresholds or ranges of optimal values of environmental parameters with conservation purpose"* and thus that "*for each object it is necessary to consider its past history, in which the microclimate has determined an adaptation of the material as a response to external environmental stresses and to its own physical and chemical properties*"[4] (UNI 2002, p.1). The UNI 10969:2002 standard seemed to suggest a shift in the approach to environmental conditions for conservation: target ranges should not be pre-determined and then simply applied to an existing environment but had to be derived for each object by the comparison between the decay already occurred to the object and its climatic history; a careful preliminary analysis of the conservation environment in which the object had been preserved was thus required. This approach was further emphasised by the European Standard EN 15757:2010 (CEN 2010a), which was developed in the meantime and introduced the definition of historical climate.

Even though many articles (Costanzo et al. 2006, Camuffo 2008, La Gennusa et al. 2008) have discussed the feasibility for a compatible use of so different standards (sometimes with paradoxical

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[2] English translation from the Italian by the author. Original text: *"sono riportati ai fini della progettazione di nuovi impianti di climatizzazione per ambienti contenenti beni di interesse storico o artistico, a titolo indicativo, i valori di riferimento da considerarsi in mancanza di indicazioni specifiche diverse, per i parametri ambientali relativi alla conservazione di 33 categorie di materiali e oggetti, in condizioni di clima stabile nel tempo"*

[3] English translation from the Italian by the author. Original text: *"vengono riportate alcune tabelle con lo scopo di indicare i valori dei parametri ambientali entro cui è possibile realizzare condizioni di conservazione dei manufatti idonee"*

[4] English translation from the Italian by the author. Original text: *"è impossibile fissare per ogni oggetto precisi valori di soglia o intervalli di valori ottimali dei parametri ambientali ai fini della conservazione. (…) per ogni oggetto è necessario considerare la sua storia pregressa, in cui il microclima ha determinato un assestamento del materiale, in risposta alle forzanti ambientali esterne e alle proprie caratteristiche fisico-chimiche"*

results), the impression derived was that different opinions and interests had resulted in confused and cacophonic indications, a sort of “standards Babel”.

Hence the first research question arose. How have hygrothermal specifications for conservation been developed? The answer could not be limited to Italy and the field of investigation had to be extended to cover at least the European and North American context.
Furthermore, another extension of the research was implied: a study on conservation standards could not be limited to building conservation but had to move into the field of object conservation and its historical development. The museum environment was thus identified as the context where the influence of hygrothermal conditions on the conservation of artworks started to be observed in the past and has been extensively studied until our days.
In the attempt to lay the ground for an Italian and European state of the art on these topics, an international conference was organised in April 2010 at Villa Reale (Del Curto & Fratelli 2010). The long title, *Historic buildings as museums. Buildings and artworks preservation. Plans for existing systems restoration and integration*, expressed the complexity and wideness of the issues covered. It was the occasion for a first contact with the Swedish research group from Gotland University, which presented the interesting case of Skokloster Castle (Broström & Leijonhufvud 2010). After a 6-months international stage at Gotland University in Visby, the castle was chosen as the second case study presented in my thesis.
A consistent part of the conference was devoted to the historical evolution of climate control systems. If hygiene and comfort were the primary needs leading to the general development of heating and ventilation systems, the importance of conservation requirements cannot be ignored when dealing with museum environments. A well-known paper by Brown and Rose (1996) had described the empirical development of humidity control in museums and historic buildings and had underlined the correlation between the spread and development of more and more sophisticated air conditioning systems and the adoption of stricter and stricter environmental specifications.
This link was then found to be a key topic of the research: how was climate controlled in conservation environments before the spread of air conditioning?
This question not only allowed the research to associate construction history with the field of conservation and museum studies, but also involved an in-depth analysis of the concept of historical climate.

0.2 Historical climate or climate history? A methodological preface to the research

When we talk about the history of climate in general, it is commonly assumed that we refer to the study of atmospheric climate in the past, based on the reconstruction of climatic series from early measurements or on the study of other primary sources (archival sources, historic documents, traces of geological, biological or physical phenomena) which can give us information on meteorological events which occurred before scientific measurement of climatic conditions was possible, even going back to ancient times (paleoclimates). Growing interest on this topic was pushed in recent times by the question of global climate change and by the search for evidence of human impact on it, but this is something beyond the field of research of this thesis.
Downscaling the field of research to the building scale, the above-mentioned studies on the evolution of building services for environmental control could be considered as well as a history of

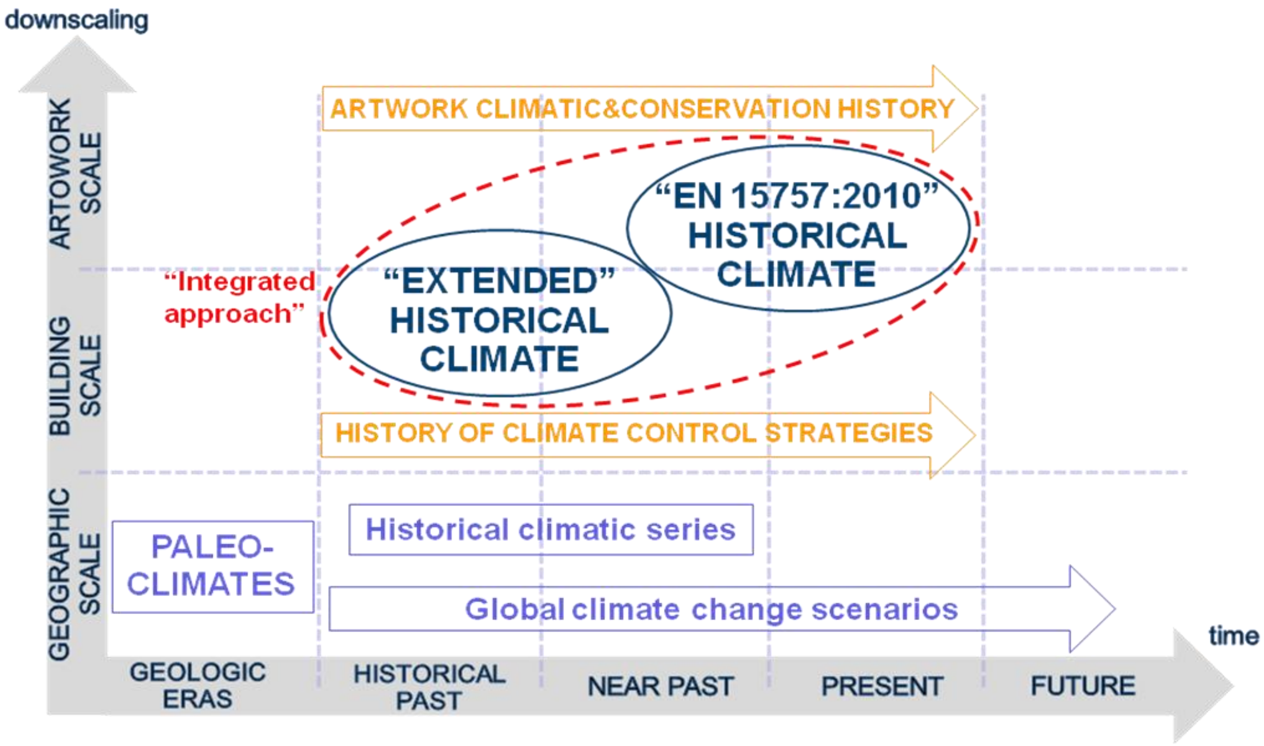

Fig. 0.2 – A classification of different possible meaning and uses of the concept of historical climate.

indoor climates and of the strategies applied to obtain determined environmental conditions within buildings in general.

In the field of conservation a further downscaling may be requested: the conservation history of an artwork, a specimen or a cultural object, is obviously influenced by the climatic conditions to which it has been exposed throughout its history. In other words, knowing the climatic history of a single cultural object can be fundamental for understanding how decaying processes have modified it until our days and for determining correctly its state of conservation.

In this thesis, which focuses on climate control for conservation, it was attempted to take into account both these approaches to the history of climate, at building and artwork scales.

The use of the term "conservation environment" is meant to include in the analysis the local outdoor climates, the indoor climates and the microenvironments which can influence (and be influenced by) buildings and artworks.

In this restricted context, an interesting approach to the concept of historical climate was introduced by the mentioned European standard EN15757:2010 – '*Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials*'. Here it is defined as the "*climatic conditions in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least one year) and to which it has become acclimatized*" (CEN 2010a, p.6).

In case the object is preserved in good conditions, the standard recommends the priority of the historical climate, which should be possibly left unchanged. The standard also suggests a procedure to determine acceptable fluctuations of the indoor climate.

Unlike many previous environmental standards, the priority is not to specify hygrothermal ranges, but to understand whether the existing climatic conditions, to which an object has been exposed for a long period of time, are harmful or not; focus is thus on the climatic history of the object.

This definition of historical climate has obviously to be considered within the particular and limited context of a standard, which has to be clear and concise in explaining its own methods and objectives. Nevertheless that definition can be used as a basis to develop and extend the concept of historical climate: given that many cultural objects have been preserved in the same environment for centuries, what do we know about the conditions to which they have been exposed in the past? Which climate control strategies determined these conditions? Which were their consequences on the conservation of artworks?

An extended conception of historical climate was suggested in a presentation on climate control in churches by Mattias Legnér and Mia Geijer at the conference E*nergy Efficiency in Historic Buildings*, held in Visby in February 2011. The authors stated that "*archival sources not only can supply data on climate history and the condition of a building, but that these sources also can tell us something interesting about how indoor climate and its management have been viewed by engineers, architects, conservators, priests and churchgoers*" (Legnér & Geijer 2012, p.245). Other papers from Legnér (2011, 2012) on the history of climate control in different historic buildings, had confirmed the effectiveness of this methodology when applied to museum environments and historic buildings.

The study on the Alte Pinakotheek of Munich, recently presented by Melanie Eibl and Andreas Burmester at the conference *Climate for Collections. Standards and uncertainties,* follows the same approach: "*It is supposed, that every change which happened to this building in the past, influenced in the one or the other way the indoor climate. Therefore, the primary goal is to reconstruct the building's history in order to reconstruct the indoor climate history*" (Eibl & Burmester 2012, p.2). In this case one interesting step further was the use of information from archival sources as input for a hygrothermal building simulation.

All these studies, based on historical methods and construction history, are very similar to the work that has been carried out about the historic heating systems in Villa Reale (see par. 4.1.2) and match very well with some of the objectives of my thesis.

Most of all, they confirm a growing general interest in the conservation science community in what is here defined as an extended concept of historical climate, i.e. the study of climate history and climate control strategies applied in the past to conservation environments

The double meaning of historical climate above described is partially reflected in the division into two parts of my thesis. The first part will be inspired to the extended concept of historical climate and will deal with the history of conservation environments, intended as the result of the climate control strategies and systems developed in Europe and North America since the introduction of central heating systems in museums in 19th century. The second part will focus on historical climates as defined by the EN 15757:2010 standard: conservation environments will be analysed and assessed in two case studies. The aim will be to merge climate analysis and construction history into a unique integrated approach.

This methodology will be described in detail in the introductive paragraph of the second part of the thesis, while a significant premise is necessary for the first part, focused on historical research: method, type of sources analysed, reference context and objectives of this part of the research, can be more conveniently specified here.

The historical method was chosen for a critical revision of the development of standards and climate control strategies in the field of conservation. The idea behind this choice is that history is the most effective way to describe a process of knowledge construction, even in the case of scientific knowledge.

The analysis will not be based on a limited number of case studies, as in the works mentioned above, since the objective is to reconstruct and understand the general context in which theories

and practices regarding climate control and conservation strategies were promoted and spread at an international level.
Firstly, this implies that focus has to be on museum studies and on the history of museum environments, since in this context the influence of hygrothermal parameters on artworks conservation started to be observed and extensively studied.
Secondly the choice of the sources consulted has been influenced: they are not so much archive documents or primary sources but mainly articles, papers or chapters published in international journals, conference proceedings, manuals and treatises. Many examples of climate control installations extracted from this bibliography will be presented but their discussion will be obviously limited by the completeness of the sources analysed. The risk involved in this approach is clear: in published sources authors generally tend to be interested in describing their way to solve problems and in emphasizing positive results of their work; on the contrary an in-depth research on primary sources generally can show the discrepancy between theory and practice: problems occurred are highlighted and it is easier to find and understand what went wrong in the application of those solutions.
A good example is given once again by the experience of the London National Gallery during the second world war. The storage of artworks in underground repositories placed in the Manod slate quarry was promoted in the following years as the most successful solution for the protection of artworks in wartime in countless publications (see par. 2.2). Nevertheless only in the most recent publication on this topic (Bosman 2008, p.83), based on research on the museum's archives, I found out the episode of a potentially disastrous collapse of one section of the quarry's vault, which just by luck resulted in minor damages to the artworks.
We must be aware that the preference for this type of documents as sources can lead the first part of the thesis to be a sort of historical catalogue of good intentions rather than a complete description of good and internationally acknowledged conservation practices in relation to climate control, since drawbacks tend to be excluded *a priori* by their difficult traceability in the sources surveyed.
A further specification on the use of the sources must be provided: some parts of the text are mainly based on the selection and discussion of publications coeval to the cases described (e.g. paragraph 1.2 and 2.2); on the contrary, in other parts, like paragraph 1.1, it was preferred to collect recent studies on single cases, which had previously analysed and compared different types of sources.

My intention was to trace a sort of comparative history of museum climates and, at the same time, to reconstruct the sources which had informed throughout the time the choices of conservation professionals, such as museum directors, conservators or staff in general, and/or technicians involved in defining climate control strategies, mainly engineers and architects.
Once this international framework is accurately reconstructed, looking in depth at single case studies through archival research will be more effective and meaningful, since it will be possible to evaluate consciously whether the strategies adopted were in compliance or in conflict with the internationally acknowledged theories which were at that time predominant.
The general approach to the research follows in part the study by Brown and Rose (1996) describing the historical development of relative humidity specifications. Nevertheless my attempt was to extend their perspective looking at other fields of investigation, such as the influence that standards and specifications had on museum practice and on the choice of the technical installations. I will try to show that the method chosen is useful and convincing for the purposes of the thesis.

0.3 Research questions

Some of the research questions originating the thesis have been already mentioned, while others are implied or derived. All these questions, which developed from a reflection on the concept of historic climate, on its possible meanings and consequent uses, will be here explicitly presented and discussed.

1) How have hygrothermal standards and specifications for environmental control been developed, spread and applied in the past? And how was climate controlled in museums before the introduction of modern air conditioning?

A large number of publications have dealt with the history of conservation, both of objects and buildings. Some authors have already discussed the development of hygrothermal standards and others have applied historical methodology to museums in single case studies, but there is a lack of knowledge on the technical systems and on the control strategies used in the past to apply climate specifications to conservation environments. The aim of Chapter 1 and 2 is to fill this gap and to highlight interesting climate control installations and strategies in use before the definitive spread of full air conditioning in museums after the Second World War.

2) Can an historical approach bring new knowledge and tools for the assessment of the present indoor climate in historic buildings?

The concept of historical climate, emphasizing the importance of climate conditions to which artworks were exposed in the past, can be extended to the application of historical methodology on the study of conservation environments. When assessing the indoor climate of historic buildings, data gathered by indoor climate monitoring could be integrated with research on construction history. At the same time special attention should be paid in analyzing peculiar features and mechanisms that can be found in conservation environments within historic buildings. The presentation of two case studies in Chapter 4 and the discussion in Chapter 5 will try to demonstrate these points.

3) Which potential consequences does the concept of historical climate have on building conservation practice?

This question somehow summarizes the aim of the whole thesis. It will be discussed the potential of the concept of historical climate, which was mainly developed for the preservation of objects composed of hygroscopic materials, in leading to beneficial effects on the preservation of historic buildings.

The problem of climate control in historic buildings has been extensively discussed in regards to environmental preservation and it is today on the agenda thanks to the growing interest in the questions posed by the application of sustainable and energy efficient strategies to the field of cultural heritage.

The proposed and integrated approach to the study of conservation environments within historic buildings, merging climate analysis with the study of climate history and of climate control strategies applied in the past, could open new perspectives in the so-called process of knowledge of historic structures, allowing a better comprehension of the hygrothermal behaviour of historic buildings.

0.4 Outline

Chapter 1 deals with early conservation environments, from the consequences of the introduction of central heating systems in museums in 19^{th} century to the Second World War. Special attention will be paid to climate control applications in museums in the 1930s.
Chapter 2 describes how the experiences in wartime repositories in United Kingdom influenced the definitive spread of air conditioning and the adoption of strict environmental standards in the postwar period while in Chapter 3 the recent debate on hygrothermal specifications and the push for more relaxed standards is discussed.
In Chapter 4, the monitoring and assessment of two case studies is presented and discussed: an Italian one, Villa Reale in Milan, and a Swedish one, Skokloster Castle. The aim is to show some peculiar features and environmental mechanisms of historic buildings.
Chapter 5 presents some positive results derived by the application of the concept of historic climate to historic buildings.
Each of the two parts is introduced by some paragraphs summarising the topics discussed and methodological issues. The thesis ends with the conclusions.

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Part 1

Towards a history of conservation environments: the development of environmental standards and climate control strategies for preservation

Research on the development of conservation strategies and standards for climate control between the 19th and 20th centuries must necessarily involve the topic of the museum in its complexity and amplitude. It was in this context that issues like the conservation of art collections, archaeological materials and archives were specifically studied.
The period between the two wars is generally considered as the moment in which different museums and institutions systematically started to face the problems caused to the collections by environmental conditions and thus a correlation between hygrothermal parameters and some decaying processes were identified.

Chapter 1 will deal with the beginning phase of this sort of history of museums climate which is the main topic of the first part of the thesis.
A fundamental role was played by the installation in museums of central heating systems, which took place in the 19th century. During the same period, two other trends had a great influence on the development of the museum practice, leading to a new conception of the museum environment.
Firstly there was an effort towards an International definition and codification of scientific practices in the field of conservation. This meant, through the establishment of the first scientific conservation laboratories, that new professions and expertise, especially related to chemistry and physics, entered museums and influenced not only the traditional procedures of restoration, but also the methodology of analysing artworks and their materials and, finally, the conservation practices in general, also involving the environmental conditions.
Secondly during the same period we assist in the development of the first codification of museography, which had a strong impact in the way artworks were arranged, exhibited and presented to the public, in the way museums and their functions were met and valued and on the development of innovative technical solutions to offer the best conditions for the comfort of visitors and the conservation of artworks.
Both these tendencies have to be related to the crucial work of the Office International des Musées (OIM). Founded after the First World War as a part of Institute de Coopération Intellectuelle of the League of Nations and later merged into the ICOM, it contributed in leading, coordinating and spreading an international cooperative research on these topics.
Special attention will be paid to climate control installations in 1930s because, after the conference *Muséographie* in 1934, the control of climate became a key point of museum practice and interesting solutions were proposed.

The protection of museum collections during World War II was at the same time a tragic need and an opportunity for conservators and heritage professionals. Looking in retrospect we can claim that it was a crucial event for the following development of climate-related conservation strategies.
Chapter 2 will therefore analyse the war period, including some pre-war publications. Focus will be on the war experiences of English museums, mainly the National Gallery of London, since they are extensively documented and they were very influential in the post-war period for the spread in museums of strict environmental standards and, as a consequence, of air conditioning.

The debate on standards and specifications is described in chapter 3: here the most recent research on the response of hygroscopic materials to hygrothermal conditions will be summarised and problems related with the installation of modern air conditioning in historic buildings discussed.

Fundamental sources for the research presented in this part were the contributions and the proceedings of two of the international conferences organised by the Office International des

Musées (the *Conférence Internationale pour l'Étude des méthodes scientifiques appliquées a l'examen et la conservation des oeuvres d'art* took place in Rome in 1930, *Muséographie. Architecture et Aménagement des Musées d'Art* in Madrid in 1934) and the articles collected in its various publications, especially its official review *Mouseion*, until the Second World War.
Regarding the post-war period, sources related with the activities of institutions like ICOM, IIC and ICCROM were used.
Given the complexity and the extension of the topics treated, the author wants to stress the point that a complete and exhaustive presentation of all of them would be impossible. If the materials produced by the OIM and the other institutions offer a rather comprehensive basis for the analysis starting from the 1920s, there is still a lack of studies on the 19th century museums, which is reflected in Paragraph 1.1.
Nevertheless Part1 will attempt an overview on the general context and, through the description of some significant experiences, to understand how climate control was introduced in museums and what consequences this had on the study and development of hygrothermal parameters and specifications for conservation.

Chapter 1
Early conservation environments between scientific research, technological innovation and museography

1.1 Central heating systems in the 19th century museums

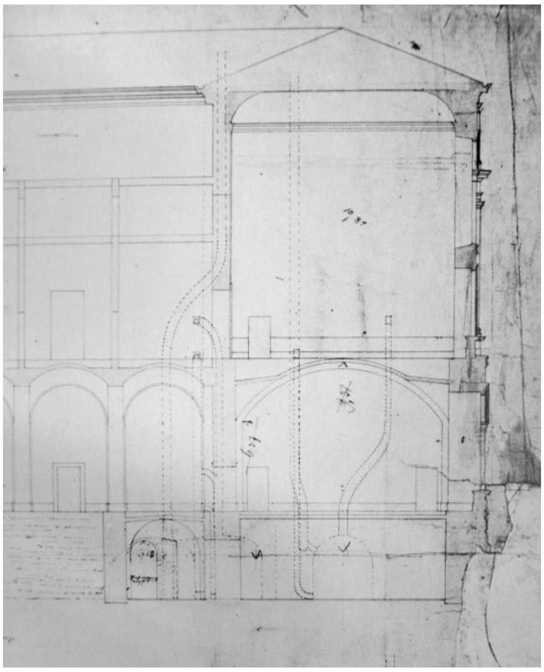

Fig. 1.1 - Dulwich Picture Gallery, drawing of a construction phase with heating pipe channels.
Fig. 1.2 - Alte Pinakhotek, cross section with the scheme of the air ducts.

Central heating systems were introduced in museums during the first half of the 19th century.
Their extensive installation took place in public buildings such as hospitals, institutions, theatres and, as a consequence, even in museums. Only the development and spread of the various typologies of air, water or steam heating made possible to control the indoor climate in large buildings to an extent never known before. Central heating could provide comfortable and hygienic conditions and, at the same time, helped to minimize some fundamental problems as management and adjustment (a limited number of boilers could serve different rooms) or fire risk (there was no need to have open flames in rooms any more). All these advantages were of the highest interest to museum keepers.
Nevertheless conservation problems caused by their operation were soon noticed. Conservators and scholars almost immediately paid attention to the mechanical decay of hygroscopic materials and the research began to focus on these mechanisms, which were soon noticed to be caused by new heating systems. Anyway, though representing one of the main cause of conservation problems, these systems were at the same time considered a possible (when not the preferable) way of solving those problems.
It is reasonable to suppose that these installations were mainly installed to obtain a comfortable and hygienic environment for humans rather than a suitable one for artworks conservation. Nevertheless a survey of some of these experiences should provide useful suggestions on the process by which decay and hygrothermal conditions started to be related and studied.

A rather well-known case is the Dulwich Picture Gallery, designed by Sir John Soane, which is considered the first independent gallery built with the purpose of exhibiting a public art collection in the United Kingdom. It is not surprising that an architect so interested in experimenting with central heating systems, tried to install one of them even in a building intended for hosting and preserving artworks. Tod Willmert (1993) has highlighted Soane’s inclination for using at the same time

different solutions, both traditional and innovative, responding to the needs and functions characterizing the environments which had to be served.
In this perspective his famous house/museum in Lincoln’s Inn Fields was a model, since private rooms were characterized by traditional fireplaces while central heating systems were installed in the office and, in a later construction phase, in the museum rooms.
The impressive series of attempts to obtain a comfortable environment by means of different heating systems, up to the choice of a Perkins one in 1832 (just one year after its patent), was documented by Willmert (1993). From this research it was possible to obtain interesting data on which hygrothermal values were supposed to be comfortable for this rooms. Temperatures between 52 an 55°F (about 11,1 and 12,7°C) were considered satisfying (Willmert 1993, p.45), while the Perkins system was capable to provide temperatures up to 60°F (15,5°C) (Richardson, p. 52).
In the Dulwich Picture Gallery, built between 1811 and 1815, Soane decided to install a steam heating system designed by Matthew Boulton and James Watt Jr: steam pipes were running under the floor and warmed the air through grilles. Soon troubles appeared: leaks from the pipes’ sliding expansion joints were supposed to cause a dry rot attack on timber floors (Willmert 1993, p.54). Soane was probably aware of these problems and discussed them in his lectures at the Royal Academy but it seemed to him as if the causes were related to poor quality of building materials.
Even if expectable, it must be stressed that Soane’s aims in the use of heating system were addressed to human comfort, even in a building hosting an art collection. In the case of the Dulwich Picture Gallery, his worries regarded building maintenance problems and were not in any case referable to the conservation of the exhibits.

A further significant example is the Alte Pinakhotek in Munich, inaugurated in 1836 and designed by another famous architect: Leo von Klenze. Here an air heating system was installed, having air warmed in big ovens in the basement and then drawn into the rooms by ducts cut into the masonry (Böttger, 1972). Again, problems soon occurred. Immediately a damaging effect of the heating system on the artworks was noticed, so it was decided it should be turned off after only five years of operation to preserve the collections (Eibl & Burmester 2012, p.3).

A few years later, evidence on relations between conservation practices and artworks restoration is represented by the 1850 and 1853 reports of the commissions created by the House of Commons to enquire on the situation of the National Gallery of London (Brommelle 1956, Boothroyd Brooks 1999).
Worries were about the awful conservation state of the exhibits and about the quick decay of artworks. The main cause was supposed to be the combined effect of the overcrowding of the galleries and of London air pollution. With huge amounts of visitors inside, air soon became vitiated due to the dirt they carried inside; windows were then opened and the heavy polluted and dusty outside air entered the galleries.
It is very interesting to notice that, among all the possible solutions, Sir Charles Eastlake, Keeper of the collections from 1843 to 1847 and first Director of the National Gallery since 1855, considered the idea of installing a new system to solve the problem and, on suggestion of architect Charles Barry, consulted David Boswell Reid: “*the abatement of the smoke from the neighbourhood was not feasible, but (…) Mr. Barry believed that an architectural arrangement could be made, to neutralize the effect, and that Dr. Reid had a scheme for determining by draughts the exclusion of all such dust so as not to approach the pictures”* (Bromelle 1956, p.177).
Barry and Reid at the time were collaborating for the new building of the Houses of Parliament and Reid in particular was well-known for his installations of heating and ventilation systems such as

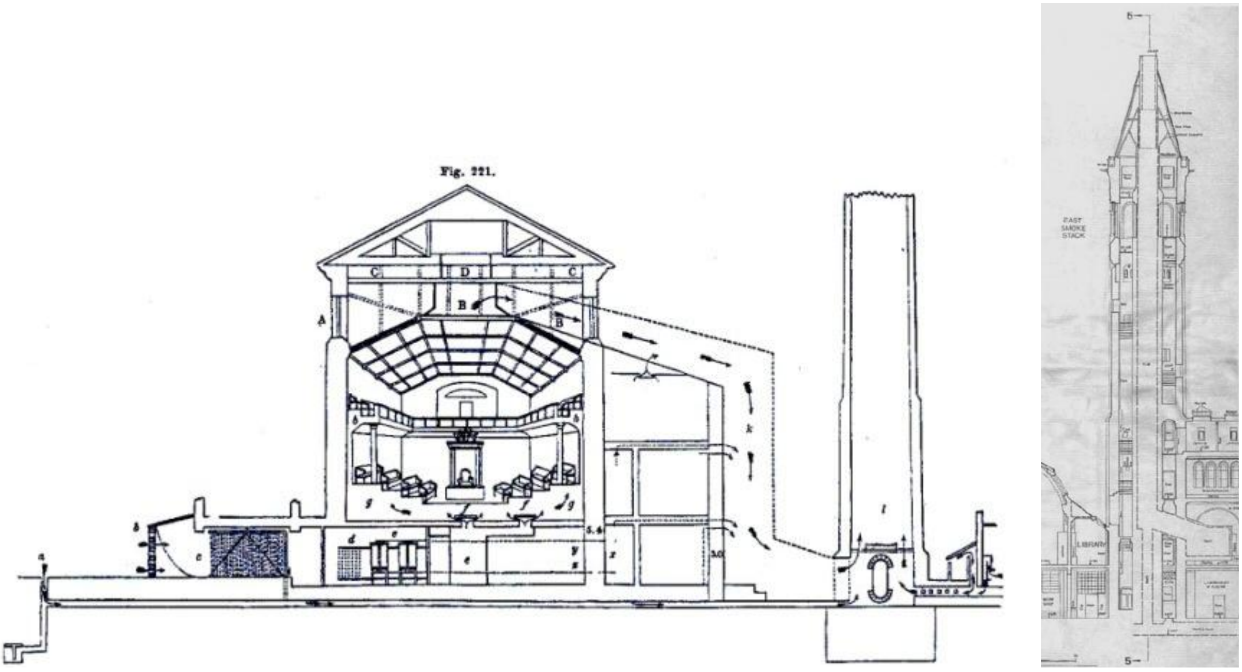

Fig. 1.3 – A comparison between Reid's scheme for the House of Parliament and a chimney of the Natural History Museum designed to provide both combustion smoke expulsion and vitiated air extraction

the one he installed in the temporary seat of the Houses of Parliament. Here vitiated air was extracted through a built-on-purpose ventilation tower which had a fireplace at the bottom to promote the stack effect. To guarantee air quality the system was equipped with a gauze filter and an air-washing apparatus, which could also add moisture to the air. An illustrated description of this system appeared in his widespread 1844 treatise (fig.1.3).
A similar installation was probably intended for the National Gallery to improve air quality, but the scheme was never realised and it was preferred to protect the paintings with more common passive methods, such as glazing the front and covering the back of the paintings.

A system that could be considered an evolution of Reid's apparatus was applied to a London museum a couple of decades later: the Natural History Museum, designed and built from 1873 to 1881 by architect Alfred Waterhouse to host the natural history collections of the British Museum, was equipped with a heating and ventilation system by Wilson W. Phipson.
A huge steam boiler supplied heat both to the radiators, placed in correspondence with the windows, both to underground batteries warming the air that was then ducted into the rooms, while the extraction system was again based on convection.
The various extraction towers had a strong impact on the building's exterior and represented a deep and studied integration between architecture and technological equipment (Cook and Hinchcliffe 1995 and 1996).
On his proposal for the building service Phipson guaranteed operation air temperatures of 13.9, 12.8 and 11.7°C in winter, depending on the rooms, an air change rate of at least 3 volumes per hour and "*a proper Hygrotermical state of the air in all seasons*" (Cook and Hinchcliffe 1995, p.70).
Once again installations seem to be aimed for the visitors rather than for collections and as a consequence in an 1883 letter "*"the great inconvenience and the injury to the collection caused by frequent variations of temperature and odd draughts in the Galleries"* were noticed (Cook and Hinchcliffe 1996, p.71).

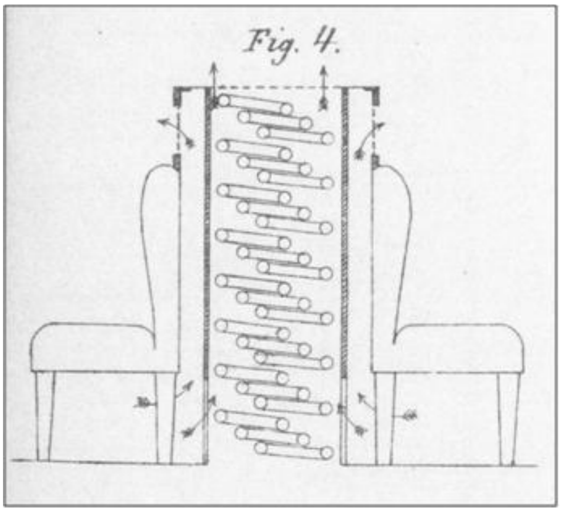

Fig. 1.4 – Alte Pinakothek, an 'enfilade' of radiators hidden by seats in a 1926 picture
Fig. 1.5 – A drawing representing the solution in detail

A typical alternative to air systems for museums at this time consisted of having water or steam radiators in the middle of the room, surrounded and hidden by benches or seats. This was the solution chosen at the end of the 19th century for the galleries of paintings of the Kunsthistorisches Museum in Wien, designed by Gottfried Semper and Karl Freiherr von Hasenauer and opened in 1891. Looking at the occurrences of the Alte Pinakhotek, one could expect that such installations were considered less harmful to collections compared to air systems, but this proved not always to be true. Air dryness, rather than its temperature, was beginning to be recognized as the leading factor in causing decay to artworks and, in the attempt to add moisture to the air, evaporating pans full of water were often placed over the radiators.
That was the case of the new system installed at the Alte Pinakhotek in 1891, after 50 years without any system running and only passive climate control in the gallery: "*A low-pressure steam heating system allowed not only to heat the galleries but also to humidify to some extent. (…) About 20 years before the new heating system was put into operation, a commission of experts evaluated existing climate control systems in the most prominent museums in Europe to come up with a concept for the Alte Pinakothek. Their report included a description of advantages and disadvantages of the inspected systems and one of the first proven remarks on set point values for museums.* " (Eibl & Burmester 2012, p.4). The suggested specification was to keep relative humidity as close as possible to 50%.

Nevertheless the use of evaporating pans proved to be rather unpractical and water spraying was generally preferred and considered more efficient to control the moisture content of the air.
We know that this type of installation was already applied by engineers in the second half of the 19th century, but other problems were involved: "*The spraying plant and controls in themselves, even for a large building, would not be costly, but the fans and duct work necessary to ensure reasonable distribution are necessarily elaborate. For instance, a scheme of this kind was designed for the whole of the National Gallery, Trafalgar Square, and the overall cost was estimated at £5000, most of which was for fans and ducts. The plant has not been installed meantime.*" (CiOA 1934?, p.10). The source does not provide a date or a designer of this scheme, so that it is impossible to say if it is the same one proposed by Reid and above mentioned. However, at the turn of the century designers could exploit electric energy to have more efficient fans and different interesting industrial application were installed on both sides of the Atlantic

Ocean. The use of spraying systems for humidity control was clearly understood by engineers (ASHVE 1910) and underlay the development of air conditioning systems in USA.
Some decades later Cellerier, Director of the *Conservatoire National des Arts et Metiers*, recommended this kind of systems to maintain constant humidity and temperature and to avoid the introduction of dusty and dirty air: "*A very good result could be obtained with central air conditioning systems, like those used in America. In these systems, automatic thermostats and humidistads provide air temperature and moisture level determined in advance, independently from outdoor temperature. Furthermore the air is filtered and washed. This system should be recommended in any case inside new buildings*"[1] (Cellerier 1931, pp.66-67). He also considered radiators and, even more, the old air heating systems dangerous since causing hot air draughts and dust movements: *"If air conditioning is not possible it is better not to use air heating with air vents in the rooms, to avoid the introduction of dust from the outside. Even if the batteries are equipped with air filters, their efficiency is often not so perfect due to a lack of maintenance"*[2] (Cellerier 1931, p. 67).

Engineers Hollis French and Allen Hubbard installed water spraying in the new building for the Museum of Fine Arts of Boston, opened in 1909 and designed by Guy Lovell (MoFAB 1916, pp 407-422 and Gilman 1920, pp 19-21). Interesting studies were carried out by James F. McCabe in collaboration with engineer Gosline and W.W. Mac Lean to identify proper humidity levels in the galleries, as reported some years later by John McCabe (1931a and 1931b): "*The first attempt to introduce humidity and air washing into an art museum building, was made by the Museum of Fine Arts, Boston, just after the new building on Huntington Avenue was erected in 1908. [...] This experiment continued for about two years, during which time records were kept and varied conditions noted with reference to the relative humidity. It was found that the humidity best adapted for paintings and other works of art ranged from 55 to 60 percent regardless of the temperature or the time of the year*."(McCabe 1931a, p.7).
A similar system was installed in 1913 by the same engineers in the Cleveland Museum of Art, designed by the local architects Benjamin Hubbell e W. Dominick Benes: "*The heat will be derived from both the direct and the plenum systems, using steam from a source outside the building. For ventilating, large motor-driven fans in connection with air washing and humidifying systems will be used. […] The ventilating fans, air washing machinery, pump and elevators will be driven by electric motors.*" (CMoA 1912).
Once again studies were carried out to determine the most suitable humidity levels for artworks conservation, with slightly different results: *"At Cleveland between 50 and 55, rather than between 55 and 60, is the proper percentage of humidity for the protection of works of art."* (McCabe 1931a, p.7).
It is not possible to be absolutely sure if the Boston Museum of Fine Arts was the first art gallery equipped with air spraying systems. Brown and Rose (1996) report in their well documented article that McCabe's specifications of relative humidity are the oldest they could find for the conservation

[1] English translation from the French by the author. Original text: *"Un très bon résultat pourrait être obtenu par les appareils de conditionnement d'air centralisés tel qu'ils sont employés en Amérique. Dans ces appareils, les thermostats et hygrostats automatiques assurent une température d'air et un état hygrothermique déterminés à l'avance, quelle que soit la température extérieure. De plus, l'air y est filtré et lavé. Ce système est en tous cas à recommander dans les bâtiments neufs"*
[2] English translation from the French by the author. Original text: "*Si les conditionnement de l'air n'est pas possible, il ne faut pas songer à employer le chauffage soufflé, avec bouches de chaleur dans les pièces, afin d'éviter tout apport de poussières de l'extérieur, même si les batteries sont munies de filtres d'air, dont l'efficacité est rendue souvent imparfaite par suite du manque d'entretien."*

of artworks, but the above-mentioned experience at Munich Alte Pinakothek would give an earlier date.
On the other hand, in his 1931 articles John McCabe proved to be aware of the limits and potentialities for conservation of air spraying systems, even though dehumidification in summer was still considered too expensive and unfeasible. Interesting considerations were made on the possibility of having different humidity levels in various parts of the building in relation to conservation needs of the artworks.
The experiences described by McCabe also demonstrate that in the beginning of the 20th century relative humidity control was identified as the key factor to give artworks a suitable museum environment. From now on, the task for conservators and engineers were to determine how and to which extent this value had to be controlled.

1.2 Introduction of scientific laboratories in museums and first experimental studies on climate induced decay

What has been discussed until now suggests that the introduction of central heating in museums runs parallel with the gathering of experience and knowledge by conservators and museum professionals on their effects on artworks. It is then from the 1920s that the introduction of scientific methodologies began to speed and, as a consequence, different museums and institutions established their own scientific laboratories addressed to the conservation of the collections and thus also to their environmental conditions.

This innovative trend was probably influenced by the development of analytical and diagnostic techniques and by the difficulties that many conservators were facing due to the inadequacy of conservation and restoration procedures. That is why many of them started to set as targets the establishment and the spread of new documented and shared procedures and, at the same time, the professional education of restorers and conservators. The growing importance acquired by the research and analysis on artworks materials involved a greater attention on their reactions not only with the various elements used in cleaning and restoration works, but also with the environmental conditions which they were exposed to. The influence of hygrothermal values on the conservation of the collections started to be identified and, with particular regard to relative humidity, interesting experimental studies were performed.

Early experiences concerned the field of conserving archaeological specimens, results of which date back to the end of 19th century. Consulting scientists was not infrequent for museums from the beginning of their history, as testified by the relations between the English chemist Faraday and the British Museum and the National Gallery (Bromelle 1956, Boothroyd Brooks 1999 and Oddy 2002). Nevertheless it was only in April 1888 that the German chemist Friedrich Rathgen was hired by Berlin Königlichen Museen and he is considered being the first scientist officially employed on the staff of a museum to take care of its collections: *"The formation of the Chemical Laboratory of the Royal Museums of Berlin and the appointment of Rathgen as its first Director were due largely to the efforts of the eminent German chemist Otto Olshausen. In 1887 Olshausen was approached by his close friend and colleague Adolf Erman, the Director of the Egyptian Collection at the Royal Museums of Berlin, for advice with regard to what he described as the unusually rapid decay of many of the bronze and stone antiquities in the collection. [...] Olshausen, who had previously demonstrated a keen interest in the scientific study of antiquities, recommended the establishment of a permanent position for a trained chemist who would be responsible for their care and preservation. For this position Olshausen sought the appointment of the young chemist Friedrich Rathgen [...]. With the approval of the museum authorities, on April 1, 1888, Rathgen was appointed 'chemist-in- charge' a position he held for some forty years"* (Gilberg 1987, p.107).

He collected many of his studies in the manual entitled *Die Konservierung von Altertumsfunden* (Rathgen 1898), which was translated into English in 1905 (Rathgen 1905) and for many years it was the main source of scientific research on these topics.

It is not until 1919 that we find a similar episode: the British Museum commissioned the chemist Alexander Scott to make an investigation on the sudden decay of its collections caused by damp and moisture after they were kept in underground tunnels during the First World War (Caygill 1992). He organized an emergency laboratory in 1920 which in 1931 officially entered the institution as Research Laboratory (Plenderleith 1998).

Harold J. Plenderleith, who succeeded Scott as the director of the laboratory and was one of the most influential conservation scholar of the 20th century, wrote: "*Many of the objects had suffered very badly from their sojourn in the strange, rather damp and over-heated environment. Staining,* *mildew and efflorescent crystals were to be seen everywhere, and many metal artifacts were in a state of serious corrosion. Objects from desert countries (notably stone and pottery) were usually found to be full of soluble salts. The salts had crystallized and recrystallized, damaging especially the surfaces. There was loss of ornament, inscriptions and color and even glazes, to the extent that the very significance of the material was often in jeopardy. Whilst it was certainly true that a long tradition of able restorers existed in most Departments of the Museum, and although the restorers through the ages had been successful in maintaining the collections in fair shape under normal conditions, the Trustees now found themselves confronted by an emergency of vast proportions, far beyond their powers and experience"* (Plenderleith 1998, pp. 129-130, see also Anon 1921-1923-1926).

Considering the scientific approach to art collections, it was of great importance the establishment in 1925 of the Research Deparment of the Fogg Art Museum at Harvard University, headed by George L. Stout and Rutherford John Gettens (Bewer 2010): here not only did research especially focus on artworks materials and on scientific methodologies for conservation, but the review *Technical Studies in the Field of Fine Arts* also was edited. Collecting and publishing articles on these topics, it soon became a well-known international reference for scholars from all over the world. The review was published regularly from 1932 to 1942 and, apart from the original studies and articles, had a rigorous and comprehensive section of abstracting.
From the 1930s the establishment of laboratories interested a large number of museums and institutions (see Cardinali, De Ruggeri & Falcucci 2007): among other institutions, the Louvre Laboratory was founded in 1932 (Billiet 1932) and a few years later those of the National Gallery, headed by F. I. G. Rawlins (Rawlins 1935), and of the Courtauld Institute of Art, headed by P. D. Ritchie (Ritchie 1935), followed, respectively in 1934 and 1935. In 1934 the Laboratoire Central des Musèe de Belgique, headed by Coremans, was also established in Bruxelles, and in 1937 the Betreuung der Bestände der Bayerischen Staatsgemäldesammlungenthe, today Doerner Institut, was established in Munich. In Italy the Gabinetto di restauro dei dipinti, founded in 1932 by Ugo Procacci and the Regio Istituto Centrale del Restauro, founded in 1939 in Rome by Brandi and Argan, could be related to this tendency.

A strong influence on the spread at international level of these experiences was exercised by the Office International des Musées. A *Conférence Internationale pour l'Étude des méthodes scientifiques appliquées a l'examen et la conservation des oeuvres d'art* was organized in Rome in October 1930.
The conference conclusions were published in the review *Mouseion* in the main languages (OIM 1931) and some extracts clearly show how, though in a general research frame, the influence of hygrothermal parameters on artworks conservation had been understood and the effect on particular types of supports and materials highlighted: "*The reports and discussions had convinced the Conference of the utility of laboratory research as an aid to the study of the history of art and of museography (…). Their [of the experts] investigations in regard to oil painting were concerned with the constituent elements (…), with <u>the problems raised in combating destructive agents</u> (micro-organisms, <u>atmospheric conditions</u>, etc…) and with the technique of safeguarding and protection. (…) For the preservation of sculpture, the experts studied the best methods of combating the action of worms in wood and <u>the menace to various materials from atmospheric influences</u>. They examined on the spot a remarkable example of the protection of antique stucco situated at a great depth (…) [which] <u>had justified the principle of adapting works of art to the milieu in which they had long remained.</u> (…) The experts paid special attention to the subject of general museography: material conditions for installation, museum architecture, <u>heating, ventilation,</u>*

lighting *and, in particular, the introduction of a certain percentage of humidity in the atmosphere*" (OIM 1931, pp.162-163, underlining by the author). Again, the first conclusion of the *Committee on Restoration of Paintings and the use of Varnish* was *"That is important that in every museum such conditions of heating, conditions of atmosphere (dryness, humidity, and purity) and lighting should be established as are most favourable to the conservation of the work of art therein"* (OIM 1931, pp.164-165, underlining by the author).

In the following issues of *Mouseion* many of the relations presented at the conference are published. Among others, McCabe's and Cellerier's contributions on the advantages of air conditioning systems were particularly interesting and were already described in paragraph 1.1.
Corrado Ricci on the other hand, in telling some anecdotes from his experience as director of different important Italian art galleries (Ricci, 1931), gives us a different perspective on the matter in question: the point of view of an art historian and museum keeper. Apart from his introductive appreciation for the Rome conference "*which has the merit for moving the delicate question of preserving the artistic masterpieces from the realm of empiricism to the realm of science*"[3] (Ricci, 1931, p.8), two other points of his article must be underlined: firstly his declaration on the importance of understanding decaying causes before proceeding with restoration works and his preference for passive protective methods, *"(...) since ancient paintings, like aged people, suffer the medicines, and it is preferable to consider carefully at first if there are contingent accidental reasons related to the position or the environment and if it is possible to modify them rather than calling a surgeon. At first sight this could seem obvious to many people, nevertheless my long experience has proved me that we almost never think like that and, as long as a painting presents signs of decay, we only think about having it restored*"[4] (Ricci 1931, p.9); secondly, regarding wall paintings and frescoes, his considerations – reported in the conference conclusions – on the importance of having them preserved in the same conditions they have adapted to, a sort of anticipation of the concept of historical climate. Furthermore, he observed that "*in some countries, the temperature can range from a very cold to a very warm level but the transition occurs gradually and if, by chance, there is a sudden change, this temperature difference is highly buffered inside buildings, if they are properly maintained*"[5] (Ricci 1931, p.10). That said, his description of the supposed environmental causes of the decay of paintings still seems to be to a great extent focused on the effect of sudden changes in air temperature caused by air draughts and heating systems, rather than on air humidity levels and fluctuations.
Apart from articles in Mouseion, no conference proceedings were published, but a manual on the conservation of paintings was extracted years later from the conference materials: the French version appeared as a monographic number of Mouseion in 1938 (OIM 1938) and as a book in 1939, while the English version was published in 1940 (OIM 1940b).

[3] English translation from the French by the author. Original text: "*qui ont le mérite de faire passer du domaine de l'empirisme à celui de la science la question délicate de la conservation des chefs-d'œuvre artistiques*"
[4] English translation from the French by the author. Original text: *"que les peintures anciennes, come les personnes âgées, supportent mal les remèdes et qu'il est préférable d'abord d'examiner avec attention s'il existe des causes en quelque sorte accidentelles dépendant du lieu ou de l'atmosphère, qu'il soit possible de modifier, sans recourir pour cela au chirurgien. De prime abord, cela peut paraitre évident à beaucoup de personnes, et cependant une longe expérience m'a prouvé qu'on n'y pense presque jamais et que, lorsqu'un tableau présente des traces de détérioration, on ne songe qu'à le faire restaurer"*
[5] English translation from the French by the author. Original text: "*dans certains pays, la température peut passer d'un grand froid à une grande chaleur, mais le passage ne se fait alors que graduellement et si, par hasard, il se produit quelque changement brusque, cette différence de température se trouve fort atténuée à l'intérieur des édifices, s'ils sont bien tenus*"

In the meantime further research was carried out. Once again, in London we find one of the most influential experiences, described in a publication of the Courtauld Institut of Art (CIoA, 1934?).
In 1929, after a very dry year that worsened the effects of the heating system on the collections, causing serious damage, the National Gallery asked for consultancy and a conference was called with representatives of the main British public museums, the Meteorological Office, the Department of Scientific and Industrial Research and the Office of Works. The aim of the conference was to investigate on the influence of humidity variations on art collections. The introducing article of the publication was written by John Andrew MacIntyre, Senior Engineer of H. M. Office of Works. Some considerations on problems related to humidity control in indoor environments were presented, as well as clarifications on which physical quantities and values consider and on the instruments and methodologies to measure them. In relation to artworks conservation, he wrote: *"The problem of air conditioning as affecting picture galleries and certain rooms in museums is to avoid excessive dryness and, on the other hand, to prevent not only the deposition of moisture from the atmosphere, but also to ensure that the relative humidity does not rise to the high levels which are favourable to the growth of moulds. Also, that variations in humidity are not such as to set up undue stress in the materials of the exhibits"* (CIoA 1934?, p. 8).
The necessity of equipping the British museums and galleries with humidity control was also discussed and water spraying systems were suggested as the better way to obtain a good winter humidification, specifying that excessive humidity levels had to be avoided to prevent the risk of condensation on colder surfaces. For existing buildings, where humidity could not be controlled by a central system, it was suggested to use portable humidifiers in single rooms. The main problems were individuated for dehumidifying in summer which would have requested a cooling equipment and, therefore, would have been too expensive. Analogies with McCabe's considerations are evident.
Finally MacIntyre suggested values that, at least in a good storage room, would have been possible to keep quite constant: *"The temperature of this store should be 60°F [15,5°C], as this is the temperature at which galleries are maintained in this country during the winter months. Decision to the correct relative humidity is more difficult, but in a gallery where spraying plant is provided and where the range of variation therefore will be of the order of 50 per cent. to 95 per cent. the value for the store should be about 60 per cent. Where there is no spraying plant to control the gallery air 55 per cent. is recommended meantime"* (CIoA 1934?, p.15).

The book contained four appendixes describing in detail different experimental studies. The first one, dated 1931, discussed the tests performed by the Forrest Products Research Laboratory on paintings on wood. Different treatments were applied to sections of panel paintings which were then exposed to temperature and humidity variations and mechanical tests: *"The scheme of the experimental work was drawn up by Sir Ralph Pearson, then Director of Forest Products Research, in collaboration with Dr. Alexander Scott."* (CIoA 1934?, p.18). Scott, as we saw, headed the Research Laboratory of the British Museum.
"Among other factors the question of humidity variation was considered and from the known effects of humidity variations on wooden panels, particularly those which had greater protection on the one face than the other, it was suggested that the movement from this might well be contributory to deterioration. [...] The experiments were made on a series of old panels of small intrinsic value with the object of giving some indications of how far the movement of a painted panel in sudden or repeated variation of humidity might be responsible for the flaking and blistering of the paint" (CIoA 1934?, p.18).
The experiments were therefore focused on understanding the influence of bending on flaking and blistering, but the conclusion was that the main decaying mechanism probably had to be

individuated in the differential stresses caused on different layers by relative humidity variations, rather than in a differential mechanical compression in the panel section between the front, protected by the painted film, and the back exposed to humidity.
A second series of experiments was only announced here and was focused on exposing wood samples throughout a year in the heated environment of the National Gallery of London. It is described in a later publication: "*The second investigation was to determine the moisture-content of wood. For the purpose, small samples of fir, oak, elm, beech were placed in various key positions, and their weight recorded every month. Thus, it was seen how the intake and output of moisture (compared with dry weight) varied with the seasons. The peaks and troughs were normal for London, but the variations were judged to be severe enough to impose considerable strains on panels, especially those known to be of delicate construction. From all the relevant data, it was deduced that the average moisture-content throughout the year was about 11 per cent (compared with dry weight). On inserting this figure in the equilibrium curve for wood as a function of the relative humidity of the atmosphere in which the sample is placed, it follows that the optimum value for the latter (R. H.) is between 55 and 60 per cent."* (Keeley and Rawlins 1951, p.195).
These values, as we will see, were to be extremely influential in the after-war period.

1.3 Towards a new conception of the museum environment: technical installations for climate control in the 1930s

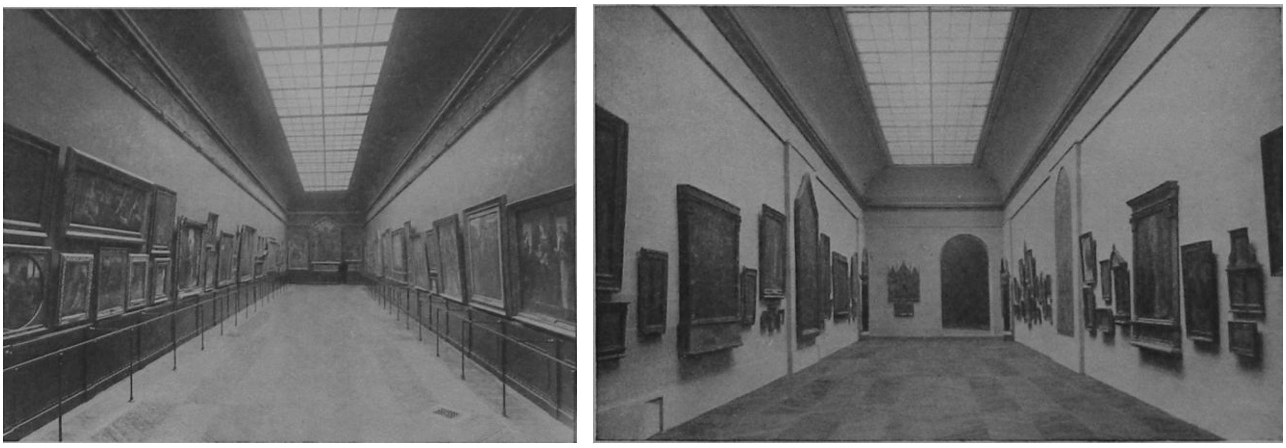

Fig. 1.6 – The gallery of the Italian primitives at Louvres before and after the rearrangements

"Organizing an international conference of experts to study the problems related to general museography is the logic and necessary conclusion of the studies carried out in this field by the International Museum Office since its foundation. Until now, these studies have been necessarily rather theoretical; it seems essential to find an occasion to compare the ideas proposed in these studies to obtain some general principles of application"[6] (OIM 1935b, p.237).

In 1934 the Office International de Musées organized in Madrid a third important international conference, after the ones in Rome in 1930 on the conservation of painting and in Athens in 1931 on the restoration of historic monuments.

The proceedings of the conference were soon published as *Muséographie: Architecture et aménagement des musées d'art: conférence internationales d'études, Madrid 1934* (OIM 1935a), responding to the need for a text summarising for stakeholders all the innovative experiences emerged: "*a synthesis was required, not much as a code of doctrinal principles, but as a collection of all the different methods currently applicable to the enhancement - in the broadest sense of the term - of objects under the care of conservators."*[7] (OIM 1935a, p.9).

Following the method used for the presentations of the conference, every chapter of the book reported the relation of a chosen expert, based on the documentation collected by the Office International des Musées. In this way a general outlook on the question was combined with a critical, though subjective and partial, comment.

The fourth chapter of the conference proceedings, entitled *Chauffage, ventilation et aeration* was dedicated to climate control and was written by John Andrew MacIntyre, the same author we found in the Courtauld Institute of Art publication on the effect of humidity on artworks. An effective collaboration on these topics between MacIntyre's Office of Works and the Office International des

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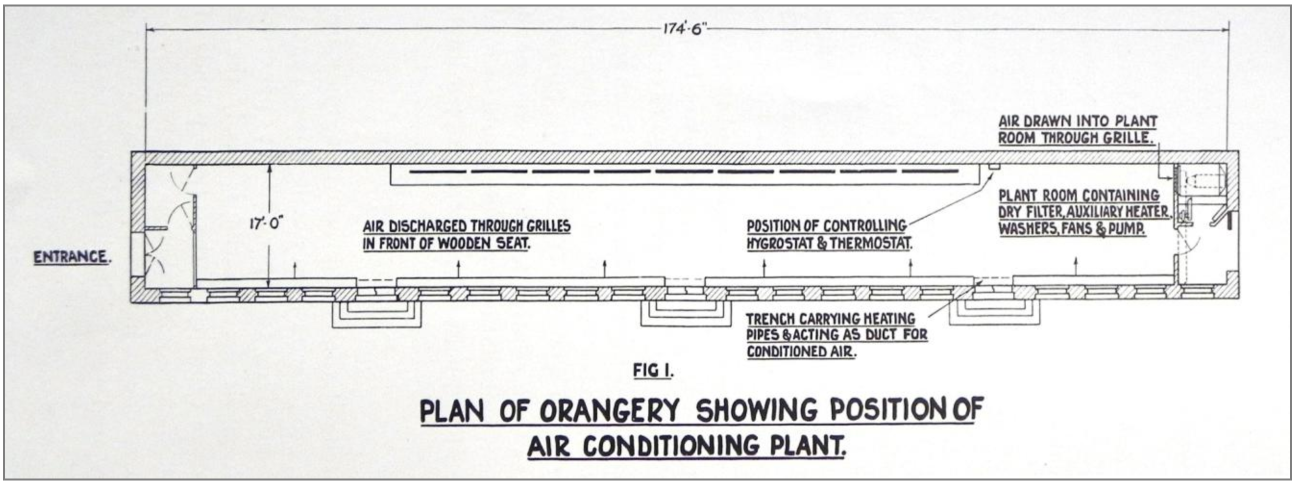
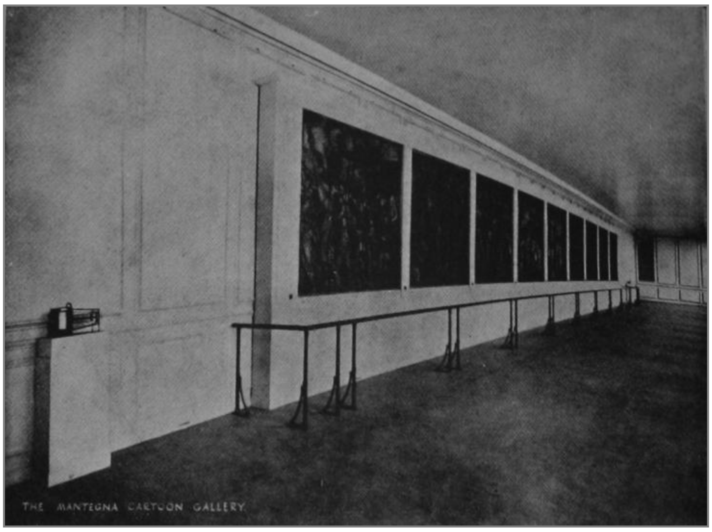
[6] English translation from the French by the author. Original text: "*L'organisation d'une conférence international d'experts pour l'étude des problèmes de muséographie générale est la conclusion logique et nécessaire des études entreprises dans ce domaine par l'Office International des Musées dès sa création. Ces études avaient forcément jusqu'ici un caractère plutôt théorique, il était donc indispensable de trouver l'occasion de confronter les idées émises dans ces études pour en dégager certains principes d'application générale."*

[7] English translation from the French by the author. Original text: "*une synthèse s'imposait, non point sous le forme d'un code de principes doctrinaires, mais sous celle d'un recueil d'ensemble des différents moyens actuellement applicables à la mise en valeur, - dans le sens le plus large du terme, - des objets confiés à la garde des conservateurs.*"





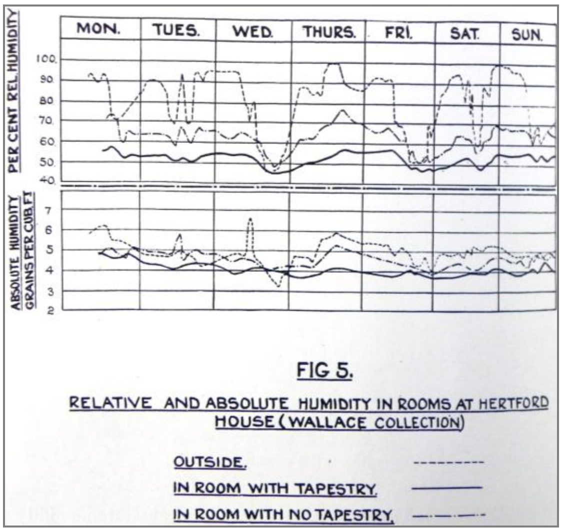


Fig.1.7 – Plan of the climate control system designed by J. A. MacIntyre for the Orangery of Hampton Court.
Fig.1.8 – Picture of the exhibition, in the foreground a hygrometer.
Fig.1.9 – Comparison between measurements performed in exhibition rooms with or without tapestry.

Musées was already well established as testified by the 1934/35 annual report of the OIM: *"the Office could assure – in addition to its own documents – a continuous collaboration with different institutes studying different heating, ventilation and air conditioning systems. The experts from the Office of Works, in London, have confirmed their availability to the Museum Office not only for gathering information on this field, but also for studying the different methods of environmental control in relation to the particular issues that will be proposed by the International Museum Office, regarding different types of objects"*[8] (OIM 1935b, p. 238).

On the other hand McIntyre had developed good expertise on these topics: his research in the field was applied in the installation of a small air conditioning system in the Orangery of Hampton Court

[8] English translation from the French by the author. Original text: *"l'Office a pu s'assurer, à côté de sa propre documentation, une collaboration suivie avec divers institutes préposé à l'étude des différents systèmes de chauffage, de ventilation et d'humidification; les techniciens de l'Office of Works de Londres se sont obligeamment mis à la disposition de l'Office des Musées, non seulement pour le documenter en ces matières, mais pour mettre à l'étude les modes de conditionnement de l'atmosphère dans leurs rapports avec tel ou tel point particulier qui leur serait soumis par l'intermédiaire de l'Office International des Musées, touchant la conservation de certaines catégories d'objets"*

Palace in October 1933, where the famous Mantegna's series *Triumph of Julius Caesar* were exhibited. The results he obtained as well as his considerations were published (Waterhouse, Collins Baker and MacIntyre 1934 and MacIntyre 1934c).
Mantegna's paintings had quite a troubled conservation history, continuously suffering of serious environmental decay, and, due to the recent worsening of their condition, it was decided having them restored by S. Kennedy North. The Cartoons were then encased in a double film of paraffin wax, as they thought this protection would be enough to protect them from hygrothermal variations. However the decision of moving them inside a largely windowed south-facing orangery to have them better protected from fire risk, would have exposed them to dangerous fluctuations: measurements recorded while the Cartoons were under restoration in another room, showed a relative humidity fluctuating between 35% and 90% yearly and a range of temperature between 80°F (26,7°C) in summer and 55°F (less than 13°C) in winter, with an underfloor heating system running. MacIntyre clearly states that his primary aim was to limit RH fluctuations, which he knew to be more dangerous than temperature levels for the conservation of paintings on canvas, to a 20% range.
Since a full air conditioning scheme equipped with an air cooler was believed too expensive and not strictly necessary, MacIntyre decided to exploit the buffering properties of hygroscopic materials. Experiments performed by the Office of Works introducing hygroscopic materials in glazed boxes and picture frames had showed the efficiency of this approach and this was also demonstrated by the comparative environmental monitoring of rooms with and without tapestries (fig. 1.9). The equipment designed for the Orangery of Hampton Court had an air spraying system to compensate the drying effect of the existing heating system during winter and – what it was quite peculiar – used 850 kg of old fire-hose canvas to limit RH levels rising during summer and limit daily fluctuations, by means of a fan recirculating air through the canvas hoses. Furthermore, the system was automatically regulated by a thermostat and an hygrostat placed near the paintings. It can be considered a clever and cost-efficient solution that found some favour in those days (Collins Baker wrote that *"the Cartoons now enter an Orangery in which atmosphere is controlled more efficiently than, I think, in any other picture gallery",* Waterhouse, Collins Baker and MacIntyre 1934, p. 108) and have been revaluated by some present-day scholars ("*The first recorded attempt to buffer the relative humidity in a museum gallery was published by MacIntyre in 1934. After seventy years of inactivity in this branch of preventive conservation, we see an increasing interest in the use of absorbent materials and clever design, rather than machinery, to control the indoor climate"* Padfield & Larsen 2004, p.137).
MacIntyre claimed that his system was designed to limit the RH variations inside the Orangery in a range of 55-75% (the range recorded during the year 1934 was 55-67%, as reported in OIM 1935a, p.173) but no traces of it or records of its performance were found, except for the weekly graph published by McIntyre himself in his article (fig. 1.10).

The case of Hampton Court exemplifies quite well which were the priorities in climate control in those years. Relative humidity was widely recognized in literature as the main factor influencing the exchanges of water vapour between the air and the artworks, in particular those made of hygroscopic organic materials such as wood, paper and textiles (e.g. books, paintings and furniture); as a consequence it was individuated as the most important parameter to be controlled for the conservation of museum exhibits. Temperature values were only considered in relation to their influence on relative humidity and to the local or general "drying effect" caused by the heating systems or other factors like air draughts and direct solar radiation.

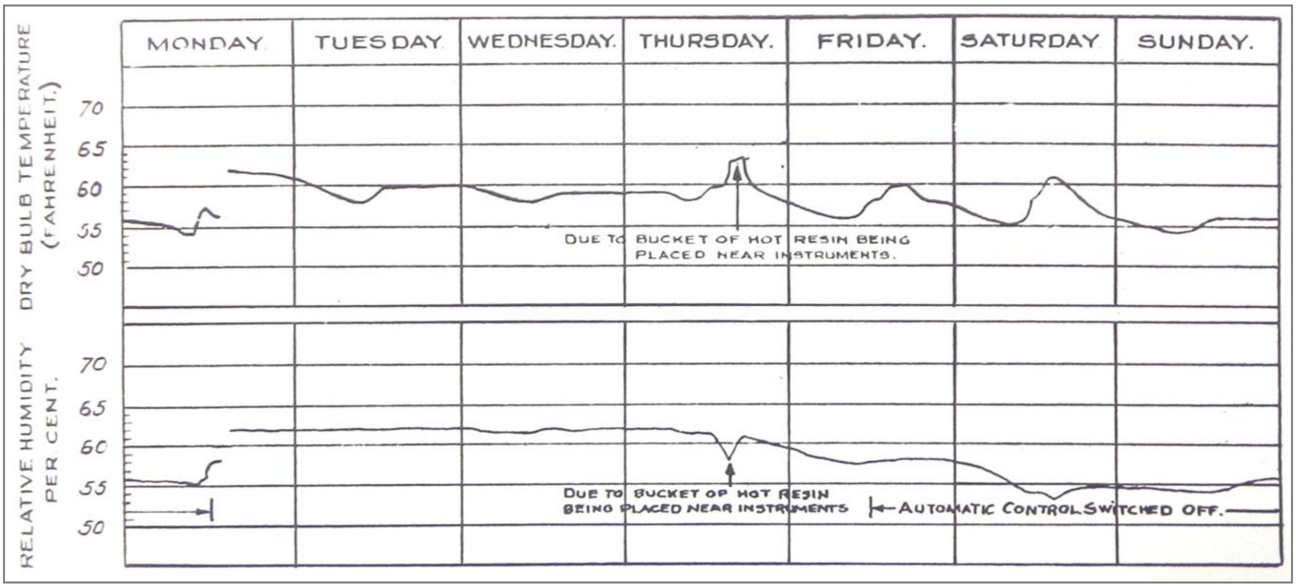


Fig.1.10 – Records of temperature and relative humidity inside the Orangery at Hampton Court Palace during the week from 20th to 27th November 1933.

On the other hand scientists and conservators, using both experimental research and empiric knowledge, were studying the decay mechanisms specifically influenced by hygrothermal factors and trying to individuate dangerous levels and harmful variations of the parameters.

The experiments performed by the English Forest Products Research Laboratory were reported by MacIntyre in *Muséographie* as state of the art on the effects of relative humidity on panel paintings, provided that *“it was impossible – on a limited base of experience – to formulate accurate conclusions due to a great number of variables, but we could anyway establish that the humidity variations are at least one of the causes of the flaking and the blistering”*[9] (OIM 1935a, p.162).

Different other case studies were quoted, such as experiments on the fading of watercolors or on the application of wax-based coatings on canvas paintings to prevent hygrothermal decay (he probably referred to Plenderleith & Cursiter 1934).

Among other things, the indications reported from “*the experiences made by Rosenberg at the National Museum of Copenhagen*”[10] (OIM 1935a, p.160) are of some interest: in his article published in *The Museums Journal* in 1933 (Rosenberg 1933), studies on the decay of archaeological metals were presented and the interactions between vapour pressure and salts generally contained in them observed to determine RH levels causing decay. An upper threshold of 65% was suggested for the conservation of inorganic materials and a reasonable RH range of 45-65% was in the end recommended to preserve most of the museum exhibits, either organic or inorganic.

Rosenberg suggested the use of small electric radiators in summer to reduce RH levels in rainy and wet days, a sort of conservation heating, but this was not considered possible or advisable by MacIntyre in British museum, due to the discomfort for visitors. The two had a mail exchange in The Museums Journal about these issues (MacIntyre 1934a, Rosenberg 1934, MacIntyre 1934b),

[9] English translation from the French by the author. Original text: “*il fut impossible, sur la base d’un matériel d’expérience limité, de formuler des conclusion précises, en raison du très grand nombre de variantes, mais on a pu toutefois établir que les variations d’humidité constituent tout au moins une de causes de l’écaillement et des boursouflures”*

[10] English translation from the French by the author. Original text: “*les expériences faites par Rosenberg au Musée National de Copenhague”*

which introduces a crucial question about climate control in museums, i.e. the methods and technical solutions to adopt for protecting artworks and museum exhibits from RH variations inside museums and galleries. The chapter from *Muséographie* can be used to have a significant overview on this topic.

First of all, protective interventions were described, such as the already mentioned application of wax-based coatings on painted canvases and panels, or the different techniques of glazing and encasement. Different examples were presented: the encasement of a Turner on a vacuum and hermetically sealed display case at the Victoria and Albert Museum, the use of silica gel or other hydrated salts inside cases at the National Gallery of Edinburgh or, finally, the conditioning of display cases or single small rooms to protect particularly delicate objects.
On this last method, MacIntyre stated that: *"The device needed to control humidity inside most of the encasements and of the large display cases – but also to control temperature and humidity inside small rooms with insulated envelope – won't be more bulky than a common model of refrigeration apparatus for domestic use. If all the important museums in Europe and America could be equipped with such an installation and if they could coordinate their research on these issues, the technical knowledge on this field could will develop very quickly.*"[11] (OIM 1935a, p.169). The advantages were clear: the volume of air to be conditioned was considerably smaller, making the use of refrigerators economically affordable, and the dimension of the ducts could be reduced. MacIntyre seemed to be quite optimistic about this technique, since in this way an almost complete control of hygrothermal parameters would have been possible and constant levels of temperature and relative humidity obtainable within small and well insulated environments. Despite of MacIntyre's thoughts, documented and realised examples of this solution could not be found in the following years. It is anyway interesting to quote his statements about the consequences that such a strict control of hygrothermal conditions could have had and, most of all, about the decision of which conditions had to be chosen and why: *"We could quote other examples where a good work could be obtained thanks to the use of a little amount of air completely controlled. Until at least a part of these researches will not be developed, the specifications that a museum conservator should give to the engineer in charge of designing the heating and ventilation system can only be empiric. (…) a temperature of 15° C and a relative humidity of about 55% will not require, in a temperate climate, an excessive cooling load and, as a consequence, the operating costs will not be so high."*[12] (OIM 1935a, pp. 169-170).

When operating in larger environments, such as museums and galleries, things became obviously much more complicate: strict and constant values could not be guaranteed and the influence of the local climate became a leading factor. The question was not so much determining ideal values but

[11] English translation from the French by the author. Original text: *"L'installation nécessaire pour le réglage de l'humidité à l'intérieur de la plupart des cadres et même des grandes vitrines, ainsi que pour le réglage de la température et de l'humidité dans quelques petites salles à parois isolantes, ne sera guère plus encombrant qu'un appareil ménager de réfrigération, d'un model courant. Si tous les grands musées de l'Europe e de l'Amérique pouvaient être dotes d'une installations de ce genre et si l'on pouvait coordonner les recherches portant sur ces problèmes, le connaissances techniques marqueraient dans ce domaine un progrès très rapide*"

[12] English translation from the French by the author. Original text: *"Nous pourrions citer d'autres exemples où il serait possible de faire du bon travail si l'on disposait d'une petite provision d'air rigoureusement contrôlé. Avant qu'une partie tout au moins de ces recherches aient été mise au point, le normes qu'un conservateur de musée doit donner à l'ingénieur chargé de dresser les plans d'une installation de chauffage et de ventilation, ne peuvent être que d'un caractère empirique.(…) une température de 15° C et une humidité relative d'environ 55% n'entraineraient pas, dans un climat tempéré, une charge réfrigérante excessive et, par suite, les frais de fonctionnement ne seraient pas très élevés"*

understanding to which extent outdoor hygrothermal variations could be limited inside a building and how. Engineers and architects therefore got involved to give technical and practical solutions to the problem of providing an affordable conservation environment, which at the same time had to be suitable for conservation and comfortable for visitors.
On this point MacIntyre drew on the considerations he published in the Courtauld Institute book: in a temperate climate with outdoor temperatures ranging from -6°C to 32°C a heating system was absolutely necessary for visitors comfort in winter, while a cooling system for the summer still presented some problems and its running costs were considered too high.
A maximum indoor temperature of 29.5°C is therefore indicated as admissible on the warmest summer days, while 18°C are recommended in winter. Regarding relative humidity control, humidification is recommended for winter months to avoid low RH levels caused by central heating (20-30%): *"Luckily it is quite easy to increase the atmospheric humidity and the required apparatus can be installed with low costs. In case of an existing building, we can place some humidifiers in the different rooms, following the solution adopted by the Vienna museum, or, if the rooms are ventilated by a Plenum system, water-spraying can be installed inside the air ducts."*[13] (OIM 1935a, p.172).
Once again, the RH levels that MacIntyre considered achievable through current technologies of heating, humidification and air conditioning are the ones he already indicated in his previous work with the Courtauld Institute and his words are almost the same, just translated into French: *"since all the systems to dry the air on a large scale, such as it will be required in an important museum, will be in general too expensive, the only solution will be to accept a relative humidity ranging fom 80% to 25% without water-spraying and between 80% and 50% with water-spraying within the most important galleries open to the public"*[14] (OIM 1935a, p.172-173).
As we already saw, the real problem was to reduce the RH peaks during the hot and wet summer months. The technology to eliminate the excessive moisture content from the air by means of refrigeration and condensation was already available and employable in air conditioning systems, but it was still very expensive. MacIntyre, although being aware of the risk of mould growth caused by high RH levels, thought that good ventilation would have been enough to limit the period during which these dangerous conditions would have been critical and that the costs involved for a refrigeration system would not have been justifiable for such a short period of operation.

Anyway, some alternative techniques to limit high RH levels were indicated. Besides the strategies used by Rosenberg in Copenhagen and by MacIntyre himself at Hampton Court, a method used in Berlin museums, having air drawn in from fresh and dry underground cellars before introducing it in exhibition rooms, is cited.
This technique was described in *Mouseion* by Ahrens (1934) and it might have been misunderstood by MacIntyre, since Ahrens said, on the contrary, that it was adopted to humidify and refresh the air in the dry days of summer in Berlin. Both authors reported that the method was not so efficient for prolonged periods of time; Ahrens specified that, after three years of use, the cellars were almost dry and that a scheme for air conditioning equipped with humidification was

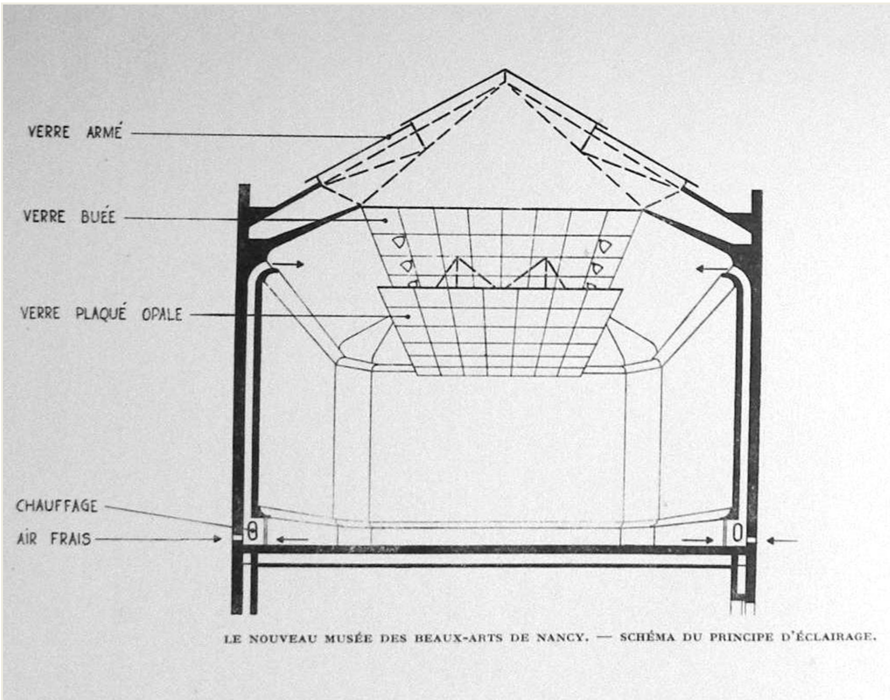
[13] English translation from the French by the author. Original text: *"Il est heureusement assez facile d'augmenter l'humidité atmosphérique et l'appareil nécessaire peut être installé sans grands frais. Lorsqu'il s'agit un édifice déjà construit on peut poser des humidificateurs dans les différentes salles, selon le system adopté au Musée de Vienne, ou, si les salles sont aérées par le système Plenum, des vaporisateurs peuvent être aménagés dans les conduites d'air."*
[14] English translation from the French by the author. Original text: *"puisque toute installation destinée à dessécher l'air sur une grande échelle, telle qu'elle s'imposerait dans un muse important, serait en général par trop coûteuse, la seule solution consistera à admettre un écart d'humidité de 80 à 25% sans vaporisateurs, et de 80 à environ 50% avec vaporisateurs, dans les principales galeries ouvertes au public"*

planned. Even if a constant RH value of 65% was indicated as preferable (Ahrens 1934, p.125), his article in general was not so much discordant from MacIntyre's words in describing hygrothermal decaying mechanisms of organic and inorganic materials, in recommending an automatic regulation of the system or in underlining the high costs involved with dehumidification through condensation.
Ahrens was probably even more incisive than MacIntyre in specifying that different climates required different control strategies, the latter generically talking of temperate climates which seem to be limited to United Kingdom. He stated that heating could be efficiently used for RH control in climates with cold and humid winters (e.g. Kiel, on the Baltic Sea), specifying that further problems could arise during the coldest days of the mid-seasons, with the heating turned off, or from the moisture loads caused by visitors; other situations were then discussed and compared, such as Cairo or Rome, where he claimed that in dry and warm winters only humidification without heating was required and he cited the Vatican Library which installed humidifiers with preservation purposes. Finally he described the problems of tropical climates, with hot and humid summers, where conservation heating could not be used in rooms open to the public and only an expensive refrigeration system would have been satisfactory.
Examples of installations in various countries were quoted by MacIntyre too in the last part of his contribution in *Muséographie*, once he had discussed the values suitable for human-beings: a temperature of 15°C was considered comfortable in Europe, while in America 21°C were supposed to be the standard (OIM 1935a, pp.174-175). Stating that only RH values over 80% are perceived as uncomfortable, MacIntyre concluded that *"inside a museum heated during the winter months, the atmospheric conditions considered suitable for the most part of the objects will be acceptable for the visitors"*[15] (OIM 1935a, p.175). Problems could occur in winter in galleries exposing valuable furniture, where a temperature of 12.7°C, uncomfortable for people, anyway was considered preferable to avoid the drying effect of heated air. On the other hand, during the warmest days of summer, galleries with sky-lighting could choose to increase the ventilation rate to have overheated air extracted, causing negative effects on the collections.

Pros and cons of different types of installations and systems were finally discussed, giving some examples of valuable realized schemes. All the museums cited by MacIntyre were also presented in articles in *Mouseion* and a survey of the various numbers of the review edited in the 1930s allowed to collect further information not only about these cases, but also about some other interesting experiences.

In MacIntyre's pragmatic perspective, funds availability was the first factor to be considered in the choice of the most suitable central heating system for a museum. From this point of view radiators offered the great advantage of not being expensive to install and of having low running and maintenance costs. Systems working with low pressure water enhanced all these features and had the further advantage of being easily and independently manageable and adjustable following the outdoor conditions. For these reasons they were quite common and widespread.
High pressure and Perkins systems were also quite popular but they were thought to be more subjected to failures and dangerous leakages and, since they operated at higher temperatures, they could more easily cause overheating.

[15] English translation from the French by the author. Original text: *"dans un musée qui est chauffé au cours des mois d'hiver, les conditions atmosphériques considérées come favorables pour la majorité des objets, seront acceptables pour les visiteurs"*



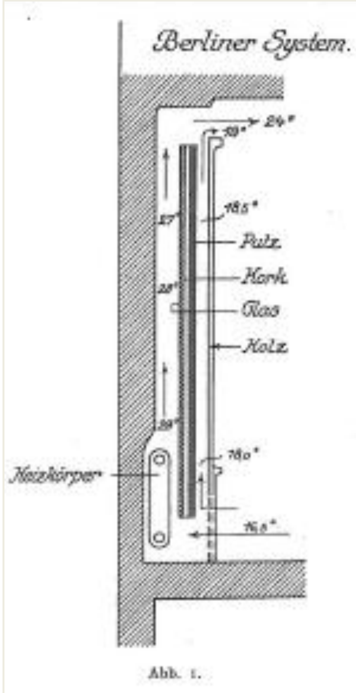


Fig.1.11 – Comparison of the schemes for installing radiators adopted in the Musée de Beaux Arts de Nancy and in Berlin museums

As we have seen, since the end of 19th century radiators in sky-lighted art galleries were usually disposed in the centre of the room, generally surrounded and hidden by seats; this, though considered a cumbersome solution, was preferred by conservators to avoid direct radiation on the paintings and to move dust away from the walls. On the other hand, if rooms had lateral light, radiators were usually placed under the windows, to compensate the uncomfortable heat loss through openings and to avoid condensation on the inner surface of the glasses by warming it.

An alternative way of positioning radiators was the scheme designed for the Musée de Beaux Arts de Nancy (fig. 1.11), where radiators were placed at the bottom of a cavity wall in an attempt to avoid the deposition of dust on the paintings: *"The air is drawn in at the height of the skirting board, it passes through an oil filter (…) it is warmed by the batteries and goes out in the upper part of the rooms (…), where the air extraction vents are hidden. In this way neither draughts nor dust depositions can affect the exhibited paintings. The warmed air goes down very slowly in horizontal layers"*[16] *(*André & André 1937, p.114). Adjustable air vents were used in summer to introduce fresh air and in winter to regulate ambient humidity by mixing heated and non-heated air. Vitiated air was expelled by grilles in the lower part of the room in winter and in the upper part in summer.

A similar scheme adopted in Berlin museums was already called into question and criticized years before in an article by Stegemann (1914).

Electric radiators were also available: they had a quicker response time and could be more easily connected to a system of automatic adjustment of the temperature, but their operation costs could only be competitive in countries with a low electricity cost. An interesting case in which they were used is Gripsholm Castle in Sweden, as described by Mattias Legnér (2011). A collaboration between the curator Sixten Strömbom and the electrical engineer Frits Jacobsson lead to the

[16] English translation from the French by the author. Original text: "*L'air entre à hauteur de plinthes, passe par un filtre a huile (...) est réchauffé par la batterie et sort à la partie supérieure des salles (…) qui cache les sorties d'air. Ainsi aucun courant d'air ni dépôt poussière ne peut produire sur les toiles accrochées. L'air chauffé descend très lentement par couches horizontales."*

installation of electric heaters inside the old tile stoves of the castle in 1923 to limit the risk of condensation and the high humidity levels inside the castle, which were considered a threat for the conservation both of the building and of its valuable portrait collections. The first time the system was turned on, rising an indoor temperature of 18.5°C in the Swedish winter, it had a dramatic drying and shrinking effect on the wooden objects, but a progressive and controlled adjustment of the temperatures brought about reasonable conditions: *"The investigation of Jacobsson and Strömbom were primarily focused on attempting to keep the temperature stable. Humidity was not considered to be of critical importance for the conservation of paintings or the building. However, over the space of a few years things were about to change. Even though curators had only a dim notion of the effects of humidity, the RH levels that were recorded at Gripsholm Castle in May 1923 were surprisingly close to those that would form the basis for future international norms over the following decades."* (Legnér 2011, p.132).
Similar decaying processes due to winter heating have already been noticed and after the dry winter of 1929 they had lead to experimental studies in England, as we saw, and also to the installation of humidifiers in the Kunsthistorisches Museum in Wien to integrate the radiators of the hot-water heating system. The conservator Ernst Buschbeck seemed to be well aware of the problem when he wrote about this episode: *"The biggest problem, in our continental climate, is the regulation of the air humidity, a point not enough considered by the conservators from West Europe. This problem is more frequent in winter than in summer, and most of all during the prolonged periods with very cold temperatures, causing a very dried atmosphere. The hygrothermal level – already very low – is further decreased by the heating. That dryness leads to wood shrinking which is particularly dangerous for panel paintings, in which many cracks occur under these conditions. Due to the very cold climate in 1929 we observed a shrinking of 4 cm on a panel 114 cm wide."*[17] (Buschbek 1935, pp.55-56). The description of the humidification system and the observation on the role of hygroscopic materials in the rooms are of some interest as well: *"water-spraying systems are placed above the radiators inside the largest rooms and in the corners above the windows, inside the cabinets. These spraying systems are controlled by two piping systems – one of them is fed by water and the other by compressed air. A special layout allows a close control of the amount of evaporating water supplied and it also prevents flooding in case of a lack of pressure. In normal winter conditions it is enough to have the system running from 8 a.m. to 2 p.m. – i.e. the operating time of the heating system – to have an average humidity of 60%. If the climate is colder the humidification system needs to run also in the afternoon. We have noticed that the tapestry of the rooms (…) tends to buffer – to a certain extent – the most sudden hygrothermal fluctuations."*[18] (Buschbek 1935, p.56).

[17] English translation from the French by the author. Original text: *"Le problème le plus grave, dans notre climat continental, est celui du réglage de l'humidité de l'air, qui n'entre guère en ligne de compte pour les conservateurs de l'Europe occidentale. Il se pose, en pratique, moins en été qu'en hiver, surtout par les périodes prolongées de grand froid, qui provoquent un desséchement de l'atmosphère ; le degré hygrothermique, déjà très bas, est encor diminué sous l'action du chauffage. Ce desséchement entraîne des rétrécissements du bois, particulièrement funestes pour les tableaux peints sur bois, où il se forme, dans ces conditions, des milliers de cloques. Par le grand froid de 1929, nous avons observé un rétrécissement de quatre centimètres sur des panneaux de 114 cm. de largeur."*
[18] English translation from the French by the author. Original text: *"vaporisateurs [sont] disposés au-dessus des radiateurs dans les grandes salles et dans les angles au-dessus des fenêtre, dans les cabinets. Ces vaporisateurs sont commandés par deux systèmes de tubes dont l'un contient l'eau et l'autre de l'air comprimé. Un agencement spécial permet de régler très exactement le dosage de l'eau ainsi évaporée et empêche tout risque d'inondation au cas où la pression d'air viendrait a manquer. Par un temps normal en hiver, il suffit de faire fonctionner l'appareil de 8 heures jusqu'à 2 heures, c'est-a-dire pendant le temps où le chauffage est en action, pour assurer une humidité moyenne d'environ 60%. Par le grands froids, on*

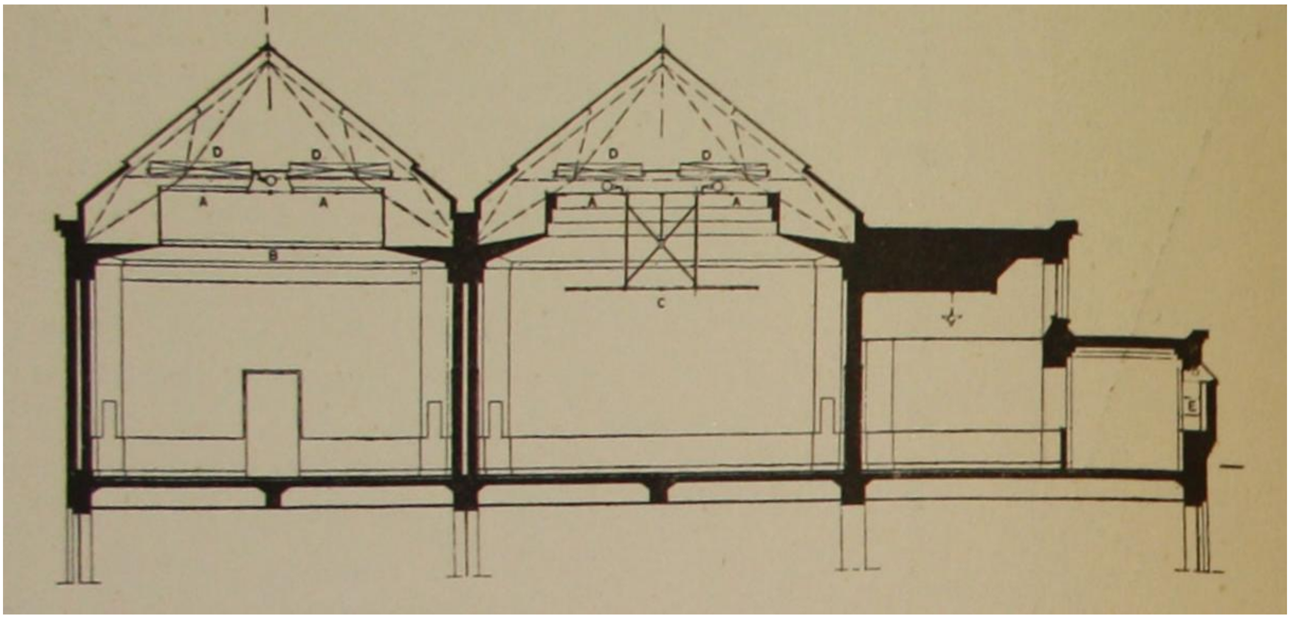


Fig. 1.12 – Cross section of the Gemeentemuseum

To avoid problems with dust deposition, air movements and local overheating, panel heating schemes were also installed. The system was invented by the English professor Arthur H. Barker in 1907 (Bean, Olesen and Kim 2010) and was soon adopted also in museums and galleries, especially in England and in the Netherlands. It was based on warming structure surfaces with a large piping network circulating water at lower temperature than radiators and thus originating a comfortable direct heat radiation. Panel heating presented other supposed advantages compared with radiators: temperature was even and uniform, air stratification thus limited and all the surfaces, both on walls and floors, were available for the exhibition. Furthermore, since visible devices were considered regrettable, the heating system was invisible, to the great joy of museum curators and directors: *"The fact that this central heating system is invisible, represents a further advantage and of the most appreciable"*[19] (Van Gelder 1936, p.151). Nevertheless, some generic problems for artworks due to heat radiation were pointed out by Markham (1935, p.11) but they were not well specified.

A significant example of the use of this system in a museum is the Gemeentemuseum in The Hague, considered one of the masterpieces of the Dutch architect Hendirk Petrus Berlage. Not only was the architectural design of the highest quality, but also a great attention was paid to the technical equipment of the building, such as the natural and artificial lighting of the rooms. Regarding indoor climate, it seems as it Van Gelder, the museum director, believed that central heating was "an enemy of museums" (Singelenberg 1975, p.50). His worries could probably have led to the choice of three different heating methods, corresponding to the different functions of the rooms.

Panel heating was chosen for the galleries of paintings. In his description of the building in *Mouseion* (Van Gelder 1936), the museum director stated that the radiating panels were placed on the ceilings but, at least in the sky-lighted rooms, panels should be installed into the floors or into the walls, even if this was not a usual application at the time.

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maintient l'humidification pendant l'après-midi. Il y a lieu d'observer que la tenture des salles (…) tend à niveler, dans une certain mesure, les oscillations trop rapides du degré hygrométrique."

[19] English translation from the French by the author. Original text: "*Le fait que ce système de chauffage central est invisible, constitue un autre avantage encore, et de plus appréciable"*

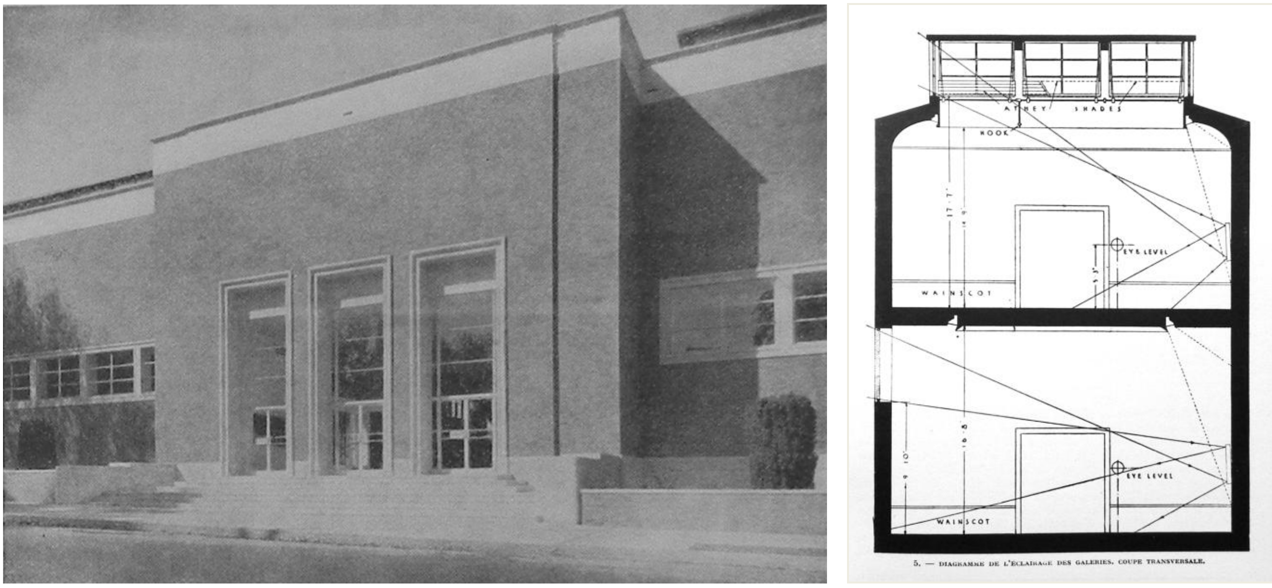

Fig. 1.13 – Portland Art Museum: façade and cross section showing the lighting system

Steam radiators were installed in service and staff rooms, in the library, in the cabinets and in the rooms where ancient furniture and wooden objects were exhibited. Radiators were turned off during the night: “*this interruption allows to obtain the cooling that is fundamental to prevent the drying of the woodworks*”[20] (Van Gelder 1936, p.150). MacIntyre considered this practice as an alternative only when it was not possible to adopt the preferred solution of having hot water convective radiators in association with humidifiers (OIM 1935, p.177), but in this case humidifiers were in use in all the heated rooms and RH levels were measured by hygrometers to prevent damage.
Finally in the conference room and in the entrance hall an air system was installed.

Ventilation and air conditioning system were already considered by many authors as the best for museums, since they allow engineers to have a closer control of hygrothermal parameters: among all, MacIntyre specifications on the best obtainable conditions in galleries and museums clearly required such a scheme. Even though a complete humidity control through refrigeration was still not affordable, at this time we can already find installations of a considerable complexity, such as the air conditioning system of the Portland Art Museum. MacIntyre explains how a clever control of air mixing and ventilation rate was used to compensate the lack of refrigeration: *“the installation that was made at the new Portland Art Museum, Oregon, described by Kemery and Doyle, is excellent: all the air in the museum circulate freely, independently from the amount of fresh air introduced; when outdoor conditions are extreme, the volume of fresh air is lowered to the limit avoiding a vitiated environment*.”[21] (OIM 1935, p.175). And again: *“Thanks to the ventilation system installed all the air in the museum can be conditioned and distributed from a central point; since it was not possible to install a refrigeration system, due to the costs involved, we think that the humidity range between summer and winter will not be over 15%. The amount of air drawn in from*

[20] English translation from the French by the author. Original text: “*cette interruption permet d’obtenir le refroidissement indispensable pour prévenir le desséchement des boiseries*”
[21] English translation from the French by the author. Original text: “*l’installation qui a été fait au nouveau Museum of Art de Portland, Oregon, décrite par Kemery et Doyle, est excellent: tout l’air du musée circule librement indépendamment de la quantité d’air frais admise: lorsque les conditions à l’extérieur son extrêmes, le volume d’air frais est abaissé à la limite évitant la viciation de l’atmosphère”*

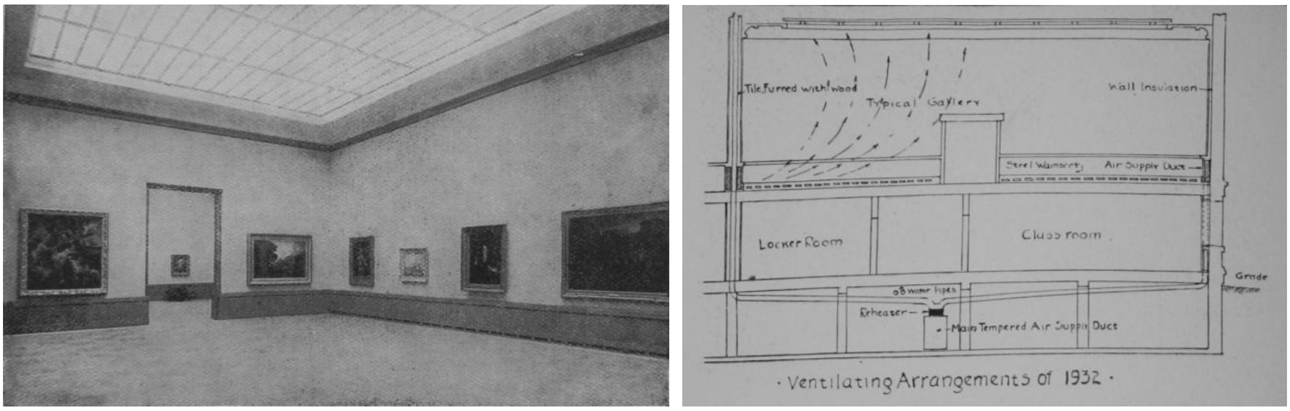

Fig. 1.14 – Toledo Museum of Art, interiors and cross section with the scheme of the third climate control system installed

the outside is controlled by a perfect regulation."[22] (OIM 1935, p.177). The designing of the museum was carried out by the local architecture office "A. E. Doyle & Associate" but, due to the death of the founder, a young Pietro Belluschi, architect, was in charge of the architectural plan (Clausen 1999, p.56) while the engineer W. E. Kemery designed the plenum air conditioning scheme. Belluschi personally presented the building at the Madrid conference and signed the article describing the museum in *Mouseion* (Belluschi, 1936) and containing a specific section by Kemery on "*Chauffage et Aération*". Many interesting technical features are described in detail, such as the reuse of water condensed inside the mixing room to feed the air spraying system or the use of fresh water from the town water system at 14,5°C to lower the temperature of the air in summer.

Another case, demonstrating the increasing success of air systems responding to the needs of museums, is the Toledo Museum of Art in Ohio. Here three different climate control systems were tried throughout the years, following the building expansion from the first emplacement in 1912 to the refurbishments in 1932. The evolution of the systems is described by the engineer Samuel L. Lewis as an annex of a long article by the director Blake-More Godwin on *Mouseion* (Godwin 1935). As a matter of interest, this article was also published in the same year as the first (and only) volume of the series *Les grands musées et les problèmes muséographiques* (Godwin, Berger and Lewis 1935).

An usual solution comprised by coupled radiators in the middle of the rooms surrounded by seats was the first system to be installed. No humidity control was provided. Lewis underlined the typical problems caused by this type of installation to visitors, artworks and to the esthetical quality of the interiors.

The first attempt to solve the problem came with the second solution: radiators were moved in insulated recesses into the walls and hidden under the wainscot. The air was introduced through grilles opened at the bottom of external walls in correspondence to radiators and was extracted by floor grilles on the opposite side of the room. Anyway, new problems occurred, since the system created an hot air flow with a damaging drying effect on the pictures and on wooden furniture. Furthermore, despite being insulated, the radiators warmed the walls surface, which was observed to be dangerous for panel paintings. Finally, the system was inefficient in summer, when fresh air

[22] English translation from the French by the author. Original text: *"Grace au système de ventilateur installé (...) tout l'air du musée peut être conditionné et distribué à partir d'un point central ; bien qu'il n'ait pas été possible d'installer un appareil de réfrigération, en raison des dépenses qu'il eût entrainées, on estime que l'écart d'humidité entre été et hiver ne dépassera pas 15%. La quantité d'air aspiré du dehors est soumise à un réglage parfait."*

was introduced and expulsed in the same way and overheating in the upper part of the sky-lighted rooms was noticed.
Humidification was added and results were discussed: "*We do not have precise data on the effects of regulated humidification, based on the reactions verified by examining the exhibits. On the contrary, we have accurate information on the drying of wooden objects imported from abroad. It was observed a very noticeable difference between the relative humidity in August without heating and the one registered in January with heating. It will be possible to adjust the humidification during the heating months, so that the difference between the humidity level in this season and the level set for a fresh summer day will be reduced*"[23] (Godwin 1935, p. 202). Lewis then specified, as usual, the difficulty of having a cooling system and thus set 50% as RH level for summer and 30% in winter, since higher values would have caused condensation on walls and glazed parts. To help artworks adaptation to different humidity levels, humidification was let on during the first period after switching off the heating system.
With the third expansion of the museum, a new system was designed. Air was now treated and filtered in the basement and then pumped into the galleries on the upper level. Horizontal air ducts were once again placed at the bottom part of the walls under the wainscot but the air vents height was reduced from 45 to 5cm, so that a long continuous inlet sequence was obtained (fig.1.14). Air extraction was moved to the top of the galleries, under the glasses, where fans controlled air extraction and recirculation. In this way air could be directly extracted in summer or recirculated in colder periods and the warm ducts could even help to prevent condensation in skylight glazing.
Results were now satisfying, as reported in the quoted words of the museum conservator MacLean: *"Since I begun to get interested in museums, I tried to obtain a scheme in which the walls of the galleries would be completely cleared of ducts, grilles, vents, radiators, etc. In the history of museums – as far as I know, at least – the Toledo Museum was the first one to design galleries with walls completely unfettered, galleries where the air is not overheated and where dust does not settle in fixed places."*[24] (Godwin 1935, p.205).
What we could probably be even more interested in, is not so much the final results, but the approach used in the whole process to obtain them, "*Proceeding by empirical methods and basing the researches on the heating and ventilation installations of the two previous parts of the museum already built*"[25] (Godwin 1935, p.203). As illustrated by Lewis: "As the Toledo Museum was built in three phases, the experience gathered during the two previous ones could be exploited when the third part of the structure was built"[26] (Godwin 1935, p.201). Such an approach exemplifies very well how climate control methods for museums evolved throughout these years, by means of a learning-from-errors approach and trying to solve different problems that appeared time after time.

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[23] English translation from the French by the author. Original text: *"On ne dispose pas de données précises sur les effets de l'humidification réglée, sur la base de réactions vérifiées par l'examen des objets exposés. Par contre des renseignements précis ne manquent pas quant à la dessiccation des constructions en bois importées de l'étranger. On a constaté une différence très sensible entre le degré d'humidité relative au mois d'août sans chauffage et celui enregistré en janvier avec chauffage. Il serait possible de régler l'humidification pendant les mois de chauffage, de manière à réduire l'écart entre le degré d'humidité à cette saison et le degré a fixer pour une fraîche journée d'été."* Regarding the reference to the information on the environmental decay of wooden objects, a study on the environmental damage caused by heating to European antique furniture imported in the USA was published in 1931 by Brewster (quoted in Brown and Rose 1996, p.15)
[24] English translation from the French by the author. Original text: "*Depuis que j'ai commencé à m'intéresser aux musées, j'ai cherché à obtenir un plan où les murs des galléries seraient entièrement libres de conduits, de grilles, diffuseurs, radiateurs, etc. Dans les annales des musées – pour autant que je le sache, du moins – le Musée de Toledo a été le premier à concevoir des galeries dont les murs sont libres de toute entrave, des galeries où l'air n'est pas surchauffé et où la poussière ne se dépose pas à des endroits fixes*"
[25] English translation from the French by the author. Original text: "*Procédant par des méthodes empiriques et en prenant comme base de recherches, les installations de chauffage et d'aération des deux premières parties du musée déjà construites*"
[26] English translation from the French by the author. Original text: *"Comme le Musée de Toledo a été construit en trois étapes, l'expérience acquise au cours des deux premières a pu être mise à profit lors de la construction de la troisième partie de l'édifice"*

Fig. 1.15 – Nationalmuseum, Stockholm: entrance hall with air inlets (arrows) and hidden radiators (R); exhibition room with air intake and extraction.

Something similar happened in the Nationalmuseum of Stockholm. Designed by the German Architect Friedrich August Stüler and opened in 1866, the building was created to host the Swedish royal collections. It was originally equipped with a Perkins heating system by the German engineer Johannes Haag, with pipes passing through six brick ovens placed into the basement and then running into the rooms through grates in the floors.

Problems with heating arose from the beginning and have been carefully described by Legnér (2011): high fuel consumption, damage caused to the timber floors, walls blackening and dust movements, discomfort for visitors and museum staff, difficulties in maintaining, repairing and upgrading the system, no possibility of obtaining steady temperatures indoors. Since the Perkins system heated just the galleries, further heating devices had to be installed over the years in the museum offices and working places and a steam boiler had to be added to keep snow off the skylights. Consequences for the collections were also noticed, such as a high fire hazard and the risk of leakages from the pipes. Moreover, in 1919 the Director of Antiquities also complained about the dryness of the air affecting polychrome wood (Legnér 2011, p.130) while in the 1920s the museum curator Axel Gauffin "*argued that heat and dirt from the pipes that were located almost directly beneath the paintings caused permanent damage to the art objects*" (Legnér 2011, p.133).

All these disadvantages called for a complete refurbishment of the climate control equipment and in the late 1920s the engineer Hugo Theorell was charged with the work. The objectives were clear – *"When the question finally arose of installing a new system and of how to install it, beyond the usual considerations about comfort and hygiene for people staying in the premises, it was*

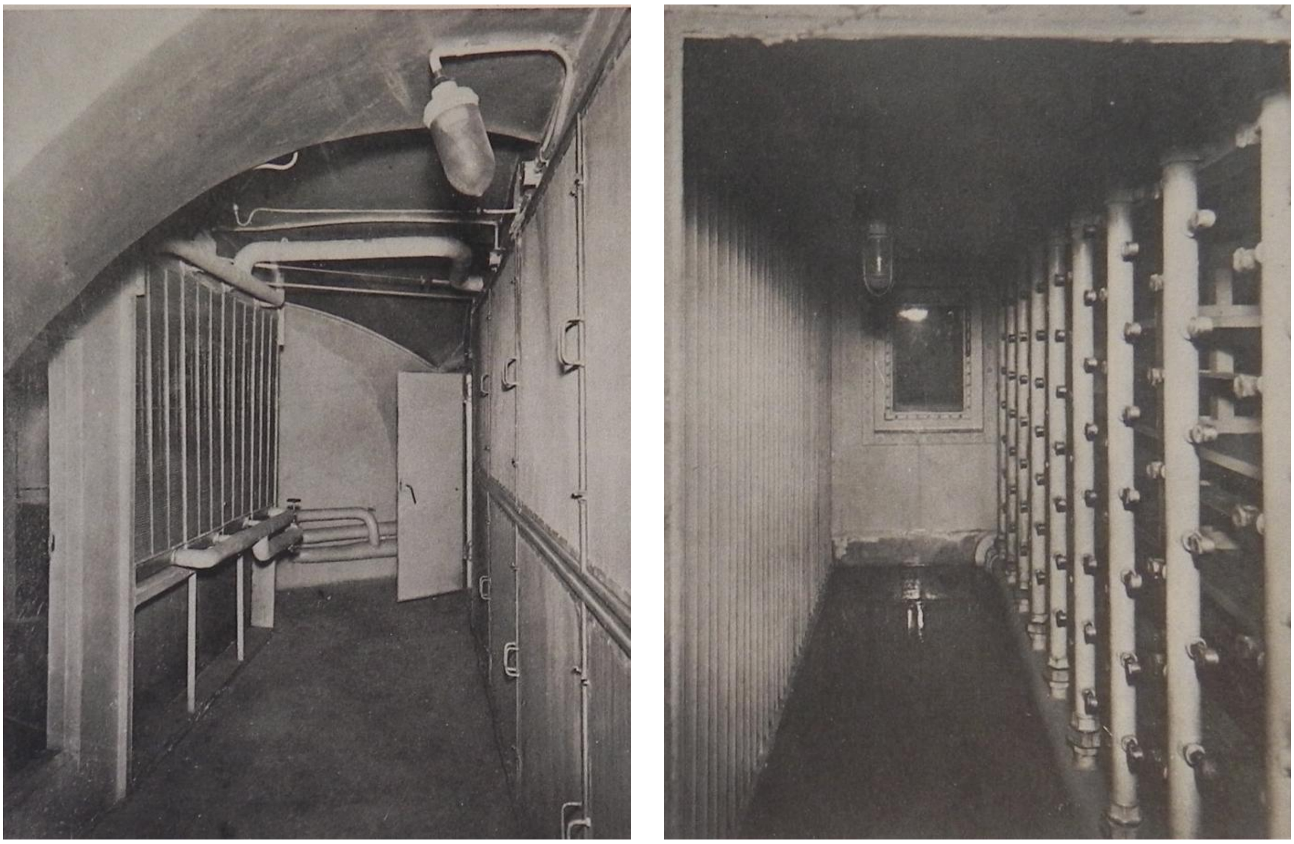

Fig. 1.16 – Nationalmuseum, Stockholm: heating chamber with hot water batteries (left) and air filters (right); humidification chamber with water spraying system.

necessary to take into account the perspective of the conservation of the collections"[27] (Theorell, 1934) – but the procedures to obtain these results were more controversial.
Theorell proposed a hot water low pressure system but questions arose on how to install radiators inside the galleries: if the devices could be easily placed (and hidden) under the windows in external rooms, things were much more complicate in the halls, in the monumental staircases and in the larger sky-lighted exhibition rooms. Since his first idea of disguising them with a fireplace shape was rejected by the museum, the engineer found a clever alternative: he installed heating batteries in the underground but also inside attics, mezzanines and other service rooms, using them as plenums and then blowing conditioned air into the rooms through electric fans.
Another discussed point was the introduction of air humidification. Legnèr (2011, p.134) states that, despite Gauffin's recommendations and his worries about wooden objects, the engineer did not consider the lack of humidifcation a serious risk: "*In his final report, Theorell did not contemplate the importance of RH levels, only considering that temperature was not supposed to vary abruptly. (…) the climatic needs of the collections were undervalued by the engineer*". During the first winter of operation of the new system, cracks appeared on panel paintings and consequently the installation of humidifiers was decided and executed in 1932.
This episode is not mentioned by Theorell in his description of the system in *Mouseion* in 1934, where he wrote: *"The purpose of this system for the treatment of the air is not only to supply the rooms with fresh and tempered air, but also, in winter, to maintain in the museum rooms a humidity level high enough to avoid the risk of cracks in wooden objects or in other hygroscopic materials, preserved in the rooms. The air entering the system is heated, filtered and then heated a second*

[27] English translation from the French by the author. Original text: "*Quand se posa enfin la question du nouveau système à adopter et du mode d'installation, il fallut, en dehors des considérations habituelles de confort et d'hygiène pour les personnes séjournant dans les locaux, tenir compte du point de vue de la conservation des collections*"

time before being delivered by a fan into a humidification chamber. Here the air is saturated by water showers falling from a certain number of spraying devices. (...) In order to eliminate water drops added to the air after this operation, the air passes through an absorbent filter and is then heated again, in order to maintain the desired relative humidity"[28] (Theorell 1934, p.150).

Also in this building, a learning-from-errors approach seems to have led the process of equipping the building with a more suitable heating and climate control system, as testified by the series of different devices installed over the time. What is more, the Nationalmuseum, beside showing an interesting episode of discussion between a conservator and an engineer, can also introduce a further point since Thorell's system was installed in an existing monumental building: when climate control was required, was the approach used in existing and historic buildings different from the one used for new and built-on-purpose museums?
In museums and exhibitions spaces, a great attention in hiding and covering up technological devices was something common, as they were considered ugly and not appropriate to the decorum of a place dedicated to art, history and culture. In historic environments, which enhanced some peculiar features of the museum interiors, this point could be particularly stressed. Introducing heating systems and climate control was particularly controversial and required special attention.
This topic was also related to wider discussions such as the use of historic buildings as museums and the re-use and restoration of historic buildings, which were largely debated at that time.
In *Muséographie* a whole chapter, edited by the Italian Roberto Paribeni, was focused on the *Adaptation des monuments anciens et autres édifices à l'usage des musées* (OIM 1935a, pp.180-197) while an article by Gustavo Giovannoni entitled *Les édifices anciens et les exigences de la muséographie moderne* appeared in *Mouseion* in 1934 (Giovannoni 1934, pp. 17-23).
It should not be surprising that both authors were Italians, since, as they underlined, the adaptation of historic buildings to museums was (and still is) very typical of this country.
Among other features characterising historic buildings, Giovannoni quoted *"The wide and thick walls that protect objects against the outdoor variations of temperature and humidity"*[29] (1934, p.21). He also suggested that some of the functions needed by modern museums could be hosted in modern buildings carefully added and connected to the old ones, where modern techniques, *"may find applications even more extensive and direct, not anymore as palliative treatments, but as organic elements"*[30] (Giovannoni 1934, p.22).
Similarly Paribeni observed that *"in general, the nature of the construction materials and the thickness of the walls acting as buffers of temperature and relative humidity, can, at worst, avoid the artificial conditioning of the atmosphere"*[31] (OIM 1935a, p.186).
Relying on passive methods was quite a common climate control strategy in museums inside historic buildings. In Louvre, for example, "*the only room of the Louvre Museum which is equipped with air conditioning is the new conference hall*" and "*the ventilation of the attics where the new*

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[28] English translation from the French by the author. Original text: "*Le but de cet appareil pour le traitement de l'air est non seulement de ravitailler les locaux en air frais et tempéré, mais aussi, en hiver, d'entretenir dans les locaux du musée un degré d'humidité suffisamment élevé pour éviter tout risque de fissures dans les objets en bois ou en d'autres matières hygroscopiques, conserves dans ces locaux. L'air arrivant dans l'appareil est chauffé, filtré, puis chauffé une seconde fois avant d'être refoulé, par un ventilateur, dans une chambre d'humidification. L'air y est saturé au moyen de douches d'eau tombant d'un certain nombre d'appareils de dispersion. (…) Dans le but d'éliminer les gouttes d'eau qui sont entrainées par l'air après l'opération, l'air traverse un filtre absorbant et est ensuite chauffé à nouveau, de façon à conserver l'humidité relative désirée"*
[29] English translation from the French by the author. Original text: *"les murs larges et épais qui protègent les objets contre les variations extérieurs de la température et de l'humidité"*
[30] English translation from the French by the author. Original text: "*pourront trouver des applications encore plus vastes et plus directs, non plus sous forme de palliatifs, mais comme éléments organiques"*
[31] English translation from the French by the author. Original text: *"d'une façon générale, la nature des matériaux de construction et l'épaisseur des murs agissant comme régulateurs de la température et de l'humidité relative, peuvent, à la rigueur, dispenser d'une conditionnement artificiel de l'atmosphère"*

painting rooms were placed, is provided by openings directed following the prevailing winds"[32], even though climate control installations were expected in the near future (Jaujard 1935, pp.18-19).

By the 1930s, indeed, since current technology had made it possible, active climate control in historic buildings hosting museums began to be not only suggested – *"Modern technology, central heating, artificial lighting and facilities of all kinds can solve many of the disadvantages typical of old buildings"*[33] (Lauterbach 1935, p.75) – but even considered necessary by some authors: *"In many cases it is necessary to adapt an existing structure to the settlement of a museum. (...) Similarly, it must be possible to install a heating system and set the indoor conditions so that they are appropriate to the objects that the building will contain"*[34] (Markham 1935, p.12).
Unlike new museum buildings, when a heating system had to be installed, hot water systems were generally considered more suitable for historic structures than air systems, mainly because they were less invasive; as Bushbeck stated about the Kunsthistorisches Museum in Wien, *"It is likely that a ventilating system, which would introduce humid air into the rooms, would be preferable in theory. But it was not possible to install such a system in a monumental building built around 1880; on the other hand, such a system would cause serious problems due to water condensing inside the air ducts"*[35] (1935, p. 56).
Paribeni as well, writing about air conditioning and heating, gave other reasons to prefer certain types of water systems: *"Old buildings (...) generally offer much space for the installation of heating ducts. But because of the fire hazard, it is better to choose the hot water system and the distribution of heat will be preferably done by radiating panels which, besides a more rational heat radiation, can be more easily hidden than tubular radiators*"[36] (OIM 1935a, pp.185-186).
He also added: *"The excessive drying of the environment, caused by central heating, has often made preferable the open fire system, especially in buildings with limited dimensions"*[37] (OIM 1935a, p.186).
This last statement is confirmed by an article appeared in Mouseion, which summarized the book *Historic House Museums,* written by Laurence Vail Coleman for The American Association of Museums, even if quite different conclusions were also presented*: "Many historic houses have been equipped with a modern heating system, despite the difficulties involved in the dissimulation of radiators and heating vents in rooms with a old character. If open fires are satisfying, this type of*

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[32] English translation from the French by the author. Original text: *"le seul local du Musée de Louvre qui soit muni de dispositifs pur la climatisation de l'air est la nouvelle salle de conférences";* "*la ventilation des combles ou ont été installées les nouvelles salles de peinture est assurée par des ouvertures dirigées dans le sens des vents dominants*"

[33] English translation from the French by the author. Original text: "*Les moyens techniques modernes, le chauffage central, l'éclairage artificiel et les installations de toutes sortes permettent d'obvier à plusieurs des inconvénients inhérents aux bâtiments anciens*"

[34] English translation from the French by the author. Original text: "*Dans beaucoup de cas il est nécessaire d'adapter une construction existante à l'aménagement d'un musée. (...) De même, il doit être possible d'installer un système de chauffage et d'aménager l'intérieur, dans des conditions qui conviennent aux objets que l'édifice est destiné à recevoir*"

[35] English translation from the French by the author. Original text: *"Il est probable qu'un système d'aération, qui introduirait de l'air humide dans les salles, serait préférable en théorie. Mais il n'a pas été possible d'installer un tel système dans un édifice monumental construit vers 1880; d'autre part, un tel système soulèverait de grandes difficultés par suite de la condensation de l'eau dans les canalisations d'air humidifié".*

[36] English translation from the French by the author. Original text: "*constructions anciennes (…) offrent en général, beaucoup d'espace utilisable pour l'aménagement des conduits de chauffage. Mais en raison des risques d'incendie, on aura intérêt à choisir de préférence le système à eau chaude et la distribution de la chaleur se fera avec avantage au moyen de panneaux réflecteurs qui, outre un rayonnement calorique plus rationnel se dissimulent plus aisément que les radiateurs tubulaires"*

[37] English translation from the French by the author. Original text: "*Le desséchement excessif de l'atmosphère, occasionné par le chauffage central, a souvent fait préférer le système des féaux ouvertes, particulièrement pour les édifices de dimensions réduites"*

heating is preferable (...). In cases where the installation of a boiler is required, preference will be given to low pressure steam heating with gas or oil burners. (...) Hot water heating requires the installation of radiators too bulky, while steam radiators can be more easily embedded into the walls or hidden by other means known by architects and engineers"[38] *(*Anon. 1934, pp.279-280).

Considerations we can draw on the application of climate control in historic buildings do not differ so much from those already expressed about installations in new buildings: after innumerable and not always successful attempts, it seems that by the 1930s climate control installations were universally considered a required feature for museum collections.

Air conditioning systems represented the state of the art and the favourable solution to engineers and conservators but still they involved problems which limited their spread, in particular high costs. Hot water systems, and even passive strategies, were therefore widely used as an alternative.

This could lead to the conclusion that, since an ideal environment could not be obtained, some kinds of alternative "adaptive strategies" were generally followed by conservators, architects and engineers to obtain the best possible conditions for the collections as well as suitable museum environments.

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[38] English translation from the French by the author. Original text: *"Nombre de maisons historiques ont été dotés d'une installation moderne de chauffage, malgré les difficultés que comporte la dissimulation des radiateurs et bouches de chaleur dans des pièces à caractère ancien. Si l'on peut se contenter de feux ouvertes, ce mode de chauffage est préférable (…). Dans les cas où l'installation d'une chaudière s'impose, on donnera la préférence au chauffage a la vapeur à basse pression avec des bruleurs à gaz ou au mazout. (…) Le chauffage à eau chaude nécessite la pose de radiateurs par trop encombrants; les radiateurs à vapeur peuvent plus facilement être encastrés dans les murs ou dissimulés par d'autres moyens connus des architectes et des ingénieurs"*

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Chapter 2
Determining the ideal conservation environment in the postwar period

2.1 The protection of artworks during the Second World War

Fig. 2.1 – British museum underground storage during the WWI in Holborn Post Office Tunnel, 1918

In the second half of the 1930s the debate between conservation professionals started to be strongly influenced by inklings of the incoming war.

Already during First World War the prescriptions of the 1907 Hague convention proved to be anachronistic and not efficient, due to the development of modern war strategies and military technology. The protection of artworks and monuments in wartime came back on the agenda from 1936, with the beginning of the Spanish Civil War. Once again, a key role on the spread of conscious preventive measures was played by the OIM. In the meeting of the OIM held on October 12th and 13th, the Belgian jurist Charles de Visscher observed: "*In legal terms, it should be firstly noted that the thirty-years old prescriptions, the Hague Conventions, the only ones today in force, are completely obsolete today. The prohibitions of bombing that they formulate, still inspired to the traditional distinction between defended and undefended places, are related to a narrowly circumscribed localization of the theatre of operations which is in clear contradiction with the reality of modern war from the triple point of view of the extension of the area of fighting in a strict sense, of the spread of military objectives and of the extension of bombing range*"[1] (Visscher 1936, p.182). Proposals for a new convention were made (Anon. 1937) but the rather skeptical point of view by the same OIM is well rendered by the words of the president of the Commision International de

[1] English translation from the French by the author. Original text: "*Sur le plan juridique, il faut constater tout d'abord que les prescriptions anciennes de trente ans, des Conventions de La Haye, les seules qui soient en vigueur, se trouvent entièrement dépasses aujourd'hui. Les interdictions de bombardement qu'elles formulent, encore inspirées de la distinction traditionnelle entre places défendues et non défendues, se trouvent liées à une localisation étroitement circonscrite du théâtre des opérations qui est en contradiction manifeste avec les réalités de la guerre moderne au triple point de vue de l'extension de la zone des hostilités proprement dites, de la dispersion des objectifs d'intérêt militaire et de l'extension du rayon d'action des bombardements*"

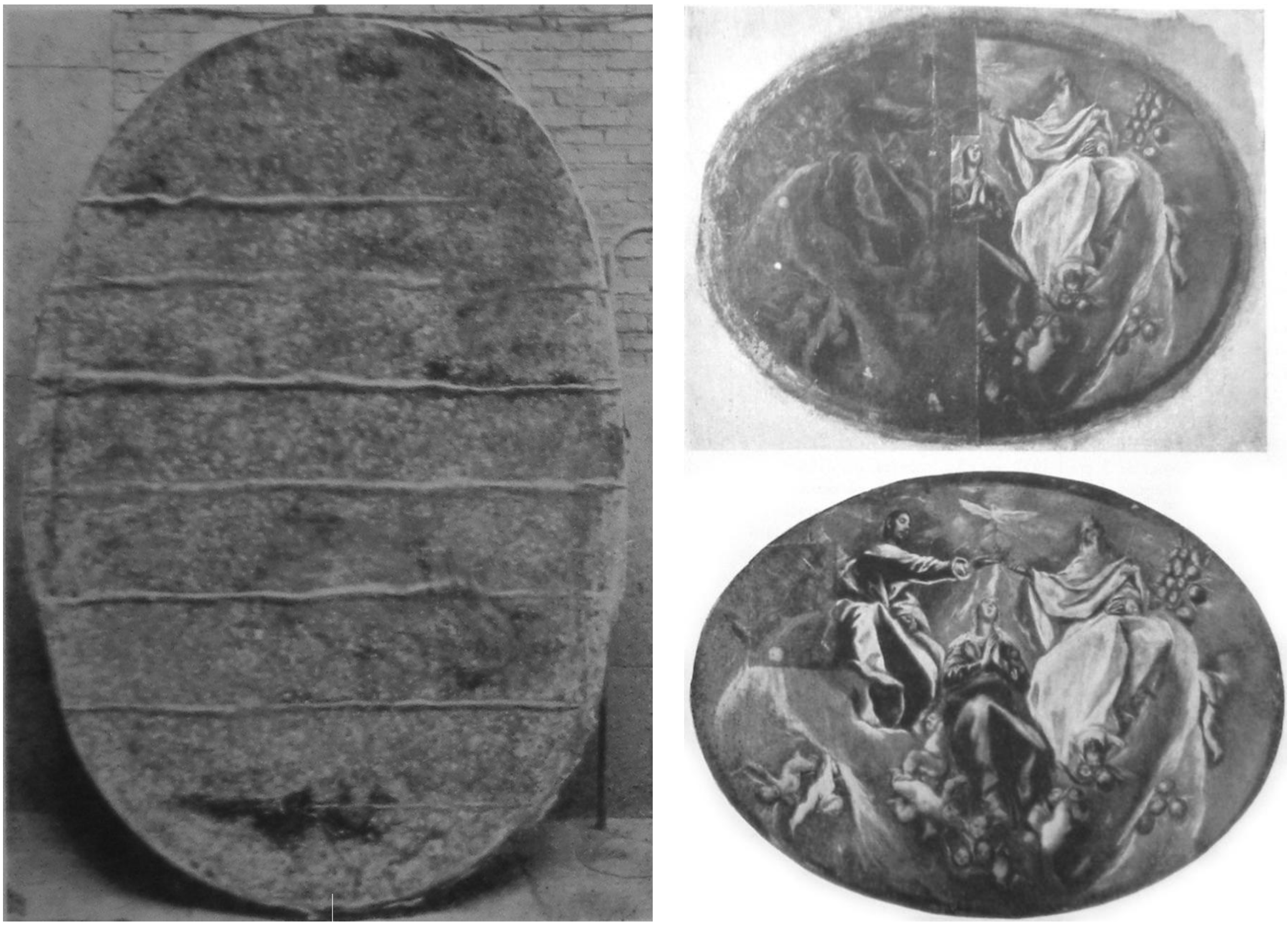

Fig. 2.2 – Example of the consequences of an incorrect storage: El Greco's *The Coronation of the Virgin* as found after several months in the underground floors of the Bank of Spain (left) and in two phases of the following restoration (right) (da Renau 1937, pp. 16-17)

Cooperation Intellectual: *"If (...) we were wise enough to save monuments and artworks, it would be better to start by being enough wise not to make war at all"*[2] (Foundoukidis 1936, p.191).

Given the inefficiency and inapplicability of international conventions, the OIM opted for a more realistic approach, based on the development and spread of mitigation strategies: *"an action for the protection of monuments and artworks in wartime, to be effective, must start preparing in peacetime a technical protection suitable to shield to the maximum possible extent those monuments and artworks from the hazards of military operations and civil disorders"*[3] (Foundoukidis 1936, p.193).

Regarding museum collections, that generally meant the storage of specimens and artworks in dedicated spaces, preferably underground, to protect them from air raids and bombings. Repositories could be located in the underground levels of existing museums (Stix 1937) but in case of more serious risks, it would be preferable to have collections completely evacuated out of the museum and moved to repositories located in safer zones.

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[2] English translation from the French by the author. Original text: "*Si (…) on a assez de sagesse pour épargner les monuments et le œuvres d'art, il vaudrait mieux commencer par avoir la sagesse de ne pas faire la guerre*"

[3] English translation from the French by the author. Original text: "*une action en faveur de la protection des monuments et œuvres d'art en temps de guerre doit, pour être efficace, tendre a préparer dès les temps de paix, une protection technique propre à soustraire dans toute le mesure du possible, ces monuments et œuvres d'art aux risques des opérations de guerre et même de troubles civils*"

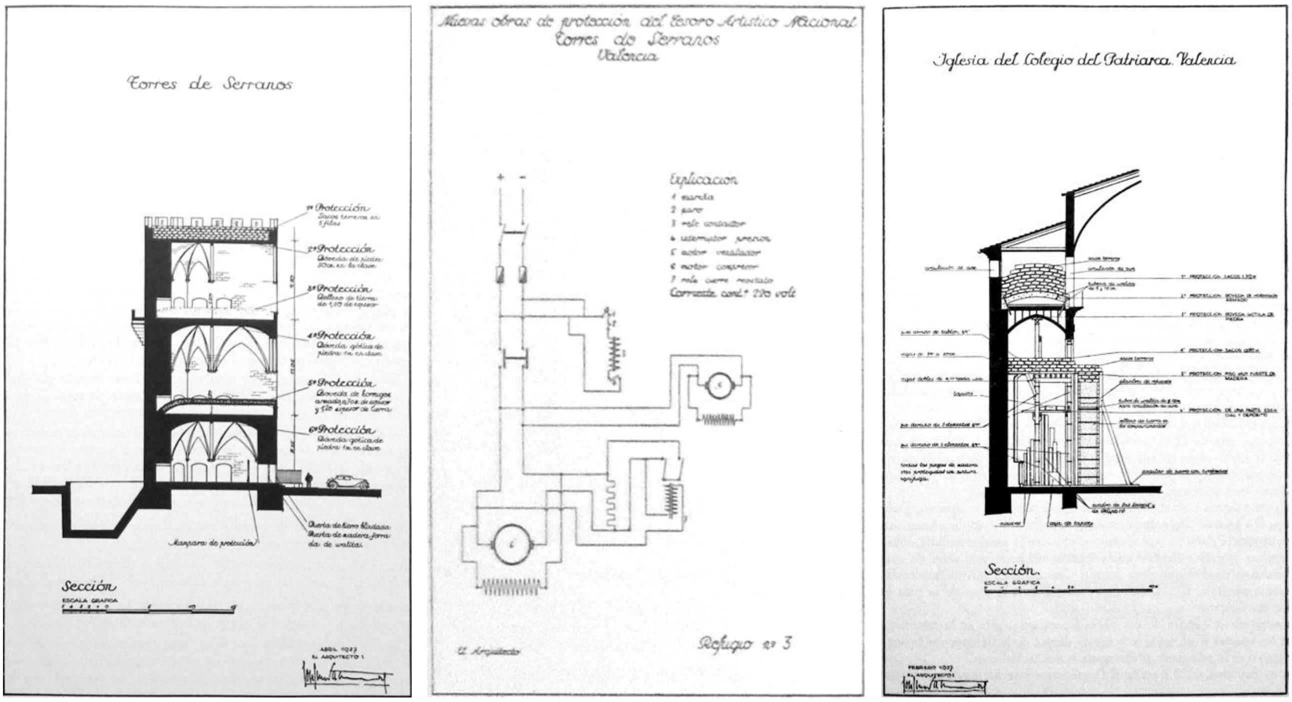

Fig. 2.3 – Storages for Spanish collections in Valencia: section and scheme of the ventilation system of the storage in the Towers of Serranos, section of the storage in the Church of the Colegio del Patriarca.

Obviously, proper conservation conditions had to be provided. Past experiences had showed the risk for artworks involved in an inaccurate storage in underground environments. As described in paragraph 1.2, the underground repository used by the British Museum during the First World War (fig. 2.1), even if equipped with ventilation and radiators, failed in providing proper conservation conditions: after the war numerous specimens presented decay, mainly caused by the damp environment (Caygill 1992, Plenderleith 1998).
The research carried out in the years between the wars had developed a deeper knowledge on climate-induced decay: some climate specifications for museums had been already developed and conservators were now more aware of the risks involved in storing artworks in uncontrolled environments.
This knowledge was thus applied in many wartime repositories and that is why the protection of museum collections during the war was extremely influential on the development of knowledge on the effects of hygrothermal conditions.

The Spanish Civil war was the first tragic occasion in which conservators had to face new problems and difficulties imposed by air bombings which, in the meantime, had become much more extensive and destructive. José Renau, Director General de Bellas Artes of the Republic of Spain, described clearly such a step forward: "*The Spanish Civil War can be truly considered as an international experience. Our country is, in fact, the field of experimentation of the most modern means of destruction, the most advanced technique of war. (...) Indeed, this has revealed the presence of new dangers that threaten seriously the existence of the valuable historical treasures of peoples, of the great artworks of humanity. This war also presents all the characteristics of a new and unexpected fact which, for its own nature, defies and exceeds all the expectations and calculations*"[4] (Renau 1937, p.60).

[4] English translation from the French by the author. Original text: "*La guerre d'Espagne peut véritablement être considérée comme une expérience internationale. Notre pays est, en fait, le champ d'expérimentation*

In the same article, published by Mouseion to spread the experiences of the Spanish Civil War, some interesting cases related to the environmental conditions inside war storages were described. Four canvases by El Greco were stored in the underground floors of the Bank of Spain in Madrid, to protect them against bombings. Here, unluckily, the very damp unventilated environment had a deleterious influence on the pictures, as demonstrated by their poor conditions after some months: "*We found them in a deplorable state, completely covered with blooms of a parasitic type and of a type caused by humidity*"[5] (Renau 1937, p.26).
When Madrid became too unsafe, it was decided to move the most important masterpieces of the national collections there preserved to Valencia, including the Prado ones, and the *Dirección General de Bellas Artes* was in charge to find and prepare safe repositories. The main storage was placed in the towers of Serranos, middle-age masonry buildings that had to be partially modified and refurbished. The thickness of the walls and of the vaults provided not only a good base with regard to solidity against bombs and explosions, but also a stable indoor climate, though rather humid. Anyway, it was thought that both factors had to be improved.
A manually adjusted air conditioning was thus installed in the towers, equipped with chillers, compressors and evaporators. Air was dehumidified by cooling it until the dew-point and then introduced indoors and mixed with outdoor air. This way RH could drop to around 60% and temperature remained stable at around 18°C. The artworks were stored in closed wooden boxes but were regularly inspected. In case consequences of unsuitable climate conditions were noticed, the system was consequently regulated (Renau 1937, pp.53-54). Before the end of the Civil War the artworks had to be continuously moved until they were brought to Geneva in 1939 under the protection of the League of Nations (Nicholas 1994, p.52).

An influential pre-war publication was the handbook edited in 1939 by the Trustees of the British Museum: *Air Raid Precautions in Museums, Picture Galleries and Libraries* (British Museum 1939). The book collected the indications from the directors and the laboratory staffs of the British National Museums, Pictures Galleries and Libraries and was set up at the instance of the Standing Commission for Museums and Galleries. Three methods of protection were described: protection in place, transfer to a shelter within the building (or nearby) or, finally, the evacuation in repositories in safe zones. Regarding the latter two methods, a specific paragraph was dedicated to environmental conditions (*Humidity, Temperature and Ventilation*): *"In selecting the storage-rooms, therefore, particularly if a basement must be chosen, careful consideration should be given to the relative humidity of the atmosphere (…). Certain moulds absorb moisture particularly readily, and have been found to grow in a relative humidity as low as 68 per cent.; in general, the relative humidity of the atmosphere should not be allowed to rise above 70 per cent., and authorities should aim at a relative humidity of 60 per cent. combined with a temperature of 60°F. Humidity may be reduced by raising temperature and increasing ventilation. Extra heating alone may be sufficient, and apart from possible damage to bindings, books will stand comparatively high temperatures. But vellum cannot be exposed to heating above 80°F. without danger of becoming brittle and discoloured. Extra heating without ventilation, however, is seldom effective, and every*

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des moyens de destruction les plus modernes, de la technique la plus avancée de la guerre. (…) En effet, celle-ci a révélé la présence de dangers nouveaux qui menacent gravement l'existence des précieuses richesses historiques des peuples, des grandes œuvres d'art de l'humanité. Cette guerre présente en outre tous les caractères d'un fait nouveau et inattendu qui, par sa nature même, déjoue et dépasse toutes les prévisions et tous les calculs"

[5] English translation from the French by the author. Original text:"*on les trouva dans un état lamentable, entièrement recouvertes d'efflorescences parasitaires et d'un genre de vers amenés par l'humidité*"

effort should be made to ensure the free circulation of air. Doors should be perforated or fitted with ventilators, and partition walls should, if necessary, be pierced." (British Museum 1939, p.42).
The same year a special issue of *Mouseion* was published, entitled *La Protection des Monuments et Œuvres d'Art en Temps De Guerre* (OIM 1939). In the first part indications and references from both Reanu's article and the British Museum handbook were merged, summarised and integrated with other sources related to the research promoted by the OIM as *Muséographie* (OIM 1935a) and *Conservation des peintures* (OIM 1938). In the second part a draft version of a convention for the protection of artworks and monuments in war period was presented. A few years later this publication, especially its second part, was eloquently abstracted in the U.S.A. handbook *The protection of cultural resources against the hazards of war* as follows: "*It is divided into two parts: 'Methodes techniques de protection', which is most useful, and 'Protection Internationale', which now makes sorry reading*." (CoCoCR 1942, p.42).
Anyway, the publications were not always coherent and some of the assessments diverged. As an example, in the British handbook protection on premises was generally preferred to evacuation, due to risks derived by long transfers: "*Evacuation will only be advisable if the repository chosen is definitely less exposed to air attack (...) and if adequate provision is made for the security of the evacuated material from damage by fire and damp, and from loss by accident in transit or by theft. (…) Since even slight vibration will be harmful to pictures of certain classes, and may cause serious damage to any painted surface in delicate condition, pictures will often be exposed to greater risk by being moved to safer storage than by being left in place and there provided with whatever protection may be possible.*" (British museum 1939, p.45). On the contrary the OIM manual argued: *"A handbook on the protection of artworks in wartime, in reporting the technical principles of protection, must necessarily recommend the most radical methods of preservation. (...) Thus, the technical part of this book is opened by the principle of complete evacuation, considered as the 'ideal' measure for protecting objects. Nobody will discuss the rationale of this concept; in presence of hazards which cannot be quantified in advance, better safe than sorry"*[6] (OIM 1939, p.9).

The OIM recommendations were instead more concordant to the British ones on the methods for providing a suitable environment to the recovered collections. Both in case of repositories on premises, both in case of evacuation in safer buildings, an RH of 60% was indicated as set point (OIM 1939, pp.84,91).
In repositories, electric heating was suggested, *"which will provide the most safe and flexible heating", as well as "a ventilation without sudden changes of temperature and humidity"*[7] (OIM 1939, p.82). Repositories were usually meant to be located in castles, private dwellings or public buildings in the countryside or small towns, far enough from potential military objectives. Here, supposing that protection from air raids was not needed, underground rooms (such as cellars, caves or abandoned tunnels) were unadvisable: *"This possibility will be taken into account only for objects securely packaged and not suffering humidity. For paintings, however, the needs for a ventilation and a relative humidity maintained similar to those of an exhibition rooms, will not allow*

[6] English translation from the French by the author. Original text: "*Un manuel consacré à la protection des œuvres d'art en temps de guerre devait nécessairement, dans l'exposé des principes techniques de sauvegarde, préconiser le méthodes les plus radicales de préservation. (…) Ainsi, la partie technique du présent ouvrage s'ouvre par le principe de l'évacuation totale, considérée comme la mesure 'idéale' du protection des objets. Personne ne contestera le bien-fondé de cette conception; en présence des risques dont on ne peut d'avance mesurer l'étendue, on ne saurait être trop prudent*"
[7] English translation from the French by the author. Original text: "*qui fournirait le chauffage le plus sur et le plus souple*"; "*une aération sans brusques changements de température er d'humidité*"

the use of these shelters, which are almost always quite humid"[8] (OIM 1939, p.86). The most suitable rooms had to be carefully chosen and, if needed, refurbished and adapted to improve their environment. Again a specific paragraph was dedicated to heating and air conditioning, with some interesting considerations: *"regarding heating, the scheme for rooms addressed to receiving _ evacuated artworks in most cases will not have to be adapted to visitors requirements, as in the case of a museum. Thus, a relatively low temperature will be satisfying, i.e. one that will not be too much in contrast with outdoor air: this is a significant advantage, since unless external temperature is very low, the problem of ventilation will be simplified; furthermore, one will not have necessarily to consider the installation of central heating, which would then require, inevitably, air conditioning devices. On this last point, the old buildings, because of their structure with a huge amount of wood, simplify the problem: in wet days, timber floors and panels absorb the water vapour in excess in the air and, in dry days, the same material releases the moisture which has stored. If heating by stoves or by vents will be satisfying, since these are generally installed in this kind of buildings, care must be taken in placing the objects away from direct radiation of heat sources. The disadvantage of dust will be reduced if artworks are kept partially packed."*[9] (OIM 1939, pp.87-89).
Limited and careful ventilation through the windows was then suggested and, most of all, the importance of the acclimatization of hygroscopic materials was underlined: "*The problem of the acclimatization of artworks is certainly the most delicate among those raised by the principle of evacuation of artworks"*[10] (OIM 1939, p.89).

In August 1939 evacuation works started all around Europe (see Nicholas 1998 and OIM 1940a) but, despite all the efforts of museum directors, conservators and staff in general, the outcomes of the evacuation and safe storage of museum collections were contradictory.
In the occupied zones of continental Europe, museums and repositories were often subjected to looting (e.g. in eastern Europe and France). Elsewhere they fell in the middle of German defensive lines, as in Italy.
Regarding the Reich's collections, propaganda and politics motivations led to a certain delay in the evacuation of some institutions: the largest part of the collections of Berlin museums did not leave the city until June 1944. As a result of these hurried operations, an impressive mass of artworks was stored in caves all around Germany (e.g. Grasleben, Hattorf, Ransbach, Kaiseroda, Schönebeck, Siegen, Merkers, Heilbronn, Benterode) often with serious consequences on their

[8] English translation from the French by the author. Original text: "*Cette possibilité n'entrera en ligne de compte que pour des objets bien emballés et ne pouvant souffrir de l'humidité. Pour des tableaux, en revanche, les nécessités de l'aération et d'un degré hygrométrique maintenu à la moyenne d'un local d'exposition, ne permettent pas d'utiliser de tels abris, presque toujours assez humides*"
[9] English translation from the French by the author. Original text: *"en ce qui concerne le chauffage, le régime prévu pour les locaux destinés à recevoir des œuvres d'art évacuées n'aura pas, le plus souvent, à se concilier avec les exigences des visiteurs, comme c'est le cas dans un musée. On pourra donc se contenter d'une température relativement basse, c'est-à-dire qui ne fera pas un contraste trop important avec l'air du dehors: c'est là un avantage appréciable, car, à moins de température externe très basse, le problème de l'aération sera simplifié; de plus, on n'aura pas à envisager nécessairement l'installation d'un chauffage central, ce qui exigerait alors, inévitablement, des appareils de conditionnement de l'air. Sur ce dernier point, les édifices anciens, en raison de leur structure qui comporte une fort proportion de bois, simplifient le problème: par temps humide, la matière ligneuse des planchers et des parois absorbe l'excédent de vapeur d'eau en suspension dans l'air, et par temps sec, cette même matière cède l'humidité ainsi emmagasinée. Si l'on peut se contenter d'un chauffage par poêles ou par bouches de chaleur, comme en comportent généralement les bâtiments de ce genre, on prendra soin de placer les objets à l'écart du rayonnement direct de sources de chauffage. L'inconvénient des poussières sera réduit si l'on conserve l'œuvres d'art partiellement emballées*"
[10] English translation from the French by the author. Original text: *"le problème de l'acclimatation des œuvres d'art est certainement les plus délicat parmi ceux que soulève le principe de l'évacuation des œuvres d'art"*

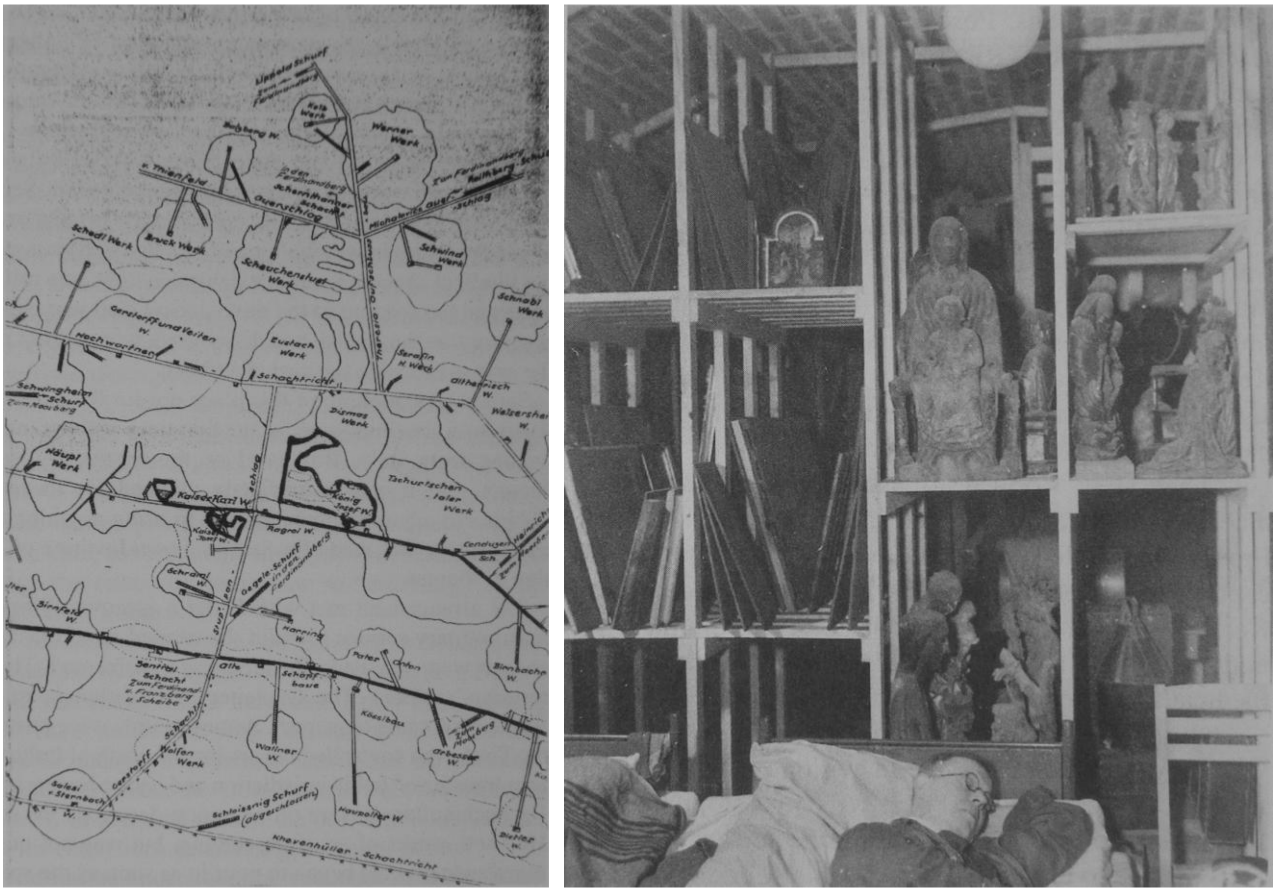


Fig. 2.4 – Plan of Alt Aussee salt mines and interiors of a repository in Siegen mine

preservation. Nicholas (1994) gave a well documented analysis of these events. An exception was Hitler's personal collection, which was carefully stored in the salt mine of Alt Aussee in Austria. Here an Austrian official found a suitable environment for conservation, as demonstrated by "*his discovery of a little chapel inside the mines in which oil paintings had been hanging since 1933 without ill effect"* (Nicholas 1994, p.314). In Alt Aussee and in the nearby mine of Lauffen also many Austrian collections were stored, included the paintings of the Kunsthistoriches Museum (Haupt 2005).

At the end of the war, the most successful operations were probably the British ones. As Caygill wrote about the British Museum, this "*can be attributed both to luck and judgement. Part of the luck stems from Britain being an island which was not invaded; the judgement from careful planning and, at least in the Second World War, the high value placed from the outset on scientific advice to the best conditions in which to store objects*" (Caygill 1992, p.29)

2.2 ‘Perfection or nothing’. From the British war-repositories for artworks to the spread of air-conditioning in museums.

“*It was a question of perfection or nothing*”. These words by Harold J. Plenderleith (1943, p.97), Head of the Research Laboratory of the British Museum, summarise very well how the problem of recovering the national art treasures was approached by British authorities.
Despite of the indications in the pre-war publication (British Museum 1939) which also considered protection on the premises, the choice of the two main London museums, the British Museum and the National Gallery, seemed to be oriented from the beginning towards a total evacuation.
Both the institutions prepared detailed evacuation plans, organised exercitations for the staff and even transportation practices on vehicles and trains.

In the early years of the war, collections were mainly moved to castles, country houses and public buildings in remote places. The National Gallery collections were moved to the Pritchard Jones Hall at the University College of North Wales, in the dining room and garages at Penrhyn Castle in Bangor, Wales, at the National Library of Wales in Aberystwyth (Saunders 1992, p.103). Other Welsh repositories were in Caernarvon Castle, Plas-yr-Bryn at Bontnewydd and Crosswood (or Trawsgoed), while some other pictures remained at Avening in Gloucestershire (Bosman 2008, p.25). The British Museum storages were in the Aldwych Underground Railway tunnel in London, shared with the Victoria & Albert Museum, in a country house in Boughton, near Kettering, and in Drayton House, both in Northhamptonshire. Some rooms were also shared with the National Gallery inside the National Library of Wales and not far from there, under a hill known as Grogyhan, a bomb-proof underground repository was also built in 1939 (Caygill 1992, p.34).
These accommodations proved to be generally satisfactory, though some interventions were required to provide the desired environmental conditions. At Crosswood, an antiquated hot-water heating system caused RH to fall lower than 30%. To increase the moisture content of the air old blankets and felt were thus soaked in a nearby stream and hung in the library where paintings were stored. Large RH fluctuations and stagnant air in Penrhyn Castel’s rooms were counteracted by improving air tightness through a better sealing of doors and windows and by installing fans to increase air circulation (Saunders 1992, p.103-105). Here another very peculiar risk affected the collection: “*one of our troubles at Penrhyn Castle is that the owner is celebrating the war by being fairly constantly drunk. He stumbled with a dog into the Dining Room a few days ago; this will not happen again. Yesterday, he smashed up his car, and, I believe, himself a little – so perhaps the problem has solved itself for the moment*” wrote Davies, Assistant Keeper, in his letter to the Keeper William Gibson (Bosman 2008, p.25).
At Grogyhan underground repository, “*the intake ventilation duct was equipped with fans and a battery of electric heaters, and there was a provision against the emergency of electrical break-down by an independent auxiliary greenhouse heating equipment and manually operated fans*” (Plenderleith 1943, p.96).
By 1940, anyway, major concerns were led by the evolution of war events: after the invasion and fall of France, the range of German air raids extended, air bombings intensified and many of the repositories were now under the path of German bombers flying to Liverpool and Manchester. What is more, there was the actual menace of an invasion of Great Britain.
“*Nowhere above ground was safe in the special sense applicable to unique and irreplaceable objects. Even the fire-risk assumed new proportions in some respects. Thus, inevitably, the question was raised whether deep shelter could not be found, and if it could, what new hazards and imponderables would introduce*” (Rawlins 1943a, p.123)
Both the National Gallery and the British Museum precipitously started to look for new repositories

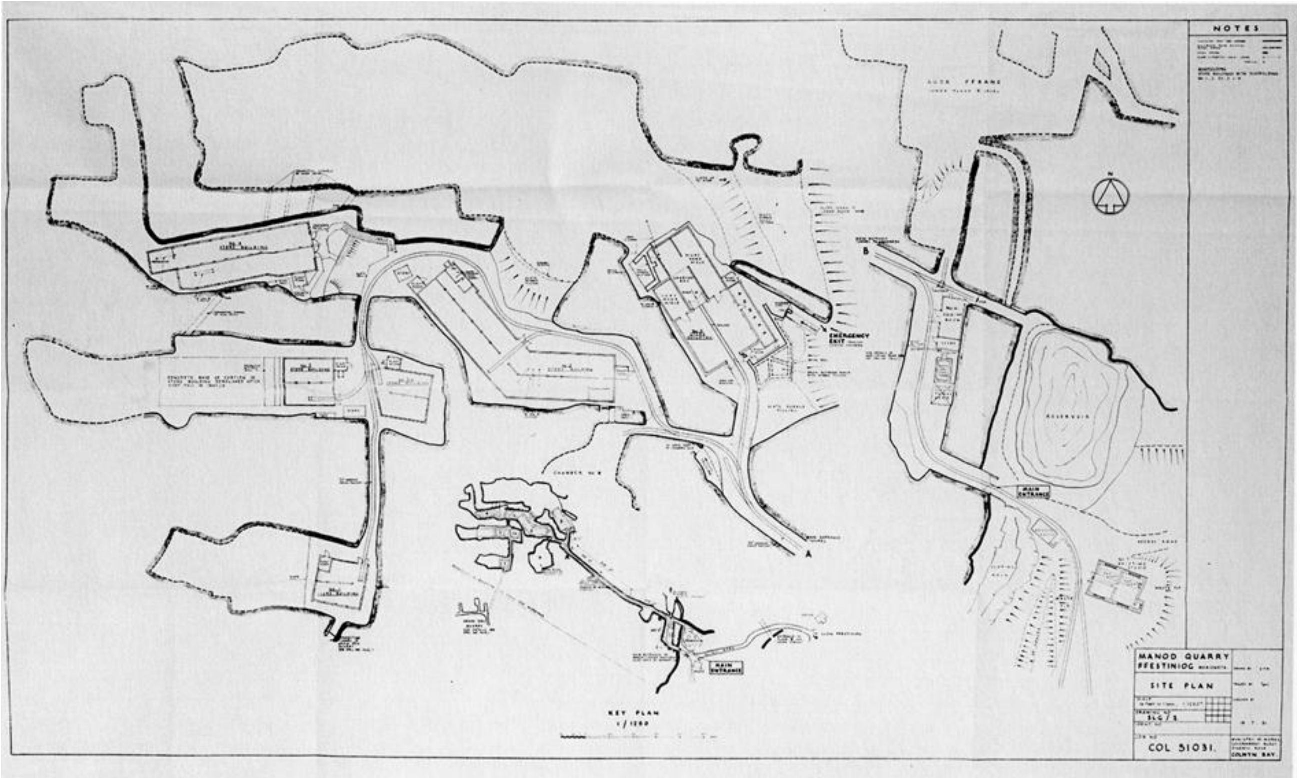
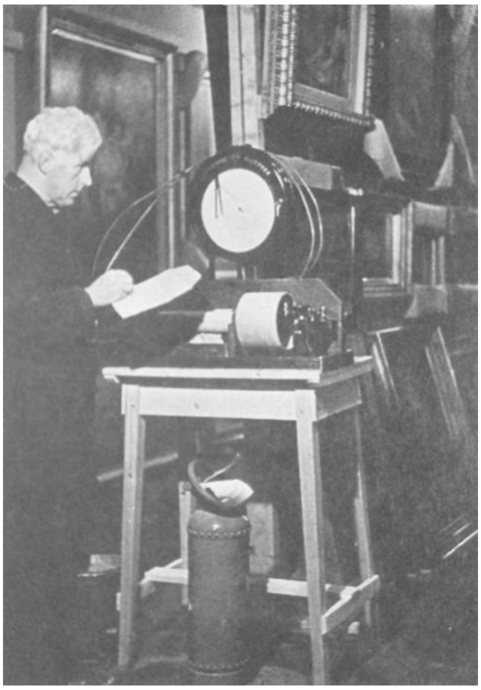


Fig. 2.5 – Manod Quarry: Plan of the repositories of the National Galleries

in safer places; since more than ever priority was now bomb-proofing, the choice focused on abandoned quarries and mines. If the advantages of such an arrangement were clear, the drawback was obvious: "*The chief enemy is dump*" (Rawlins 1942, p.113).

Martin Davies, Assistant Keeper, and Ian G. Rawlins, Scientific Adviser and Head of the Laboratory of Physics, were in charge to find a suitable location for the collections of the National Gallery: "*Site after site was rejected on grounds such as those of possible flooding, presence of noxious vapours, insecure roofs, difficult access, probability of becoming a target later on for indirect reasons, and so forth. (...) Six precious weeks went by with nothing to show for them but negation. Then, almost by chance, the outlook changed. A site offering sufficient space to house the whole collection, and possessing between 200 ft. and 300 ft. of rock cover, appeared. The natural temperature within was 47°F. [8,3°C] and the relative humidity 95-100 per cent. Tradition locally had it that the temperature was unchanged through-out the year.*" (Rawlins 1943a, p.123).
It was the Manod slate quarry near Blaenau Ffestioniog in Wales.
The site offered many other favourable features: access was not easy but possible by cars and lorries, danger of flooding and material falling was considered low or negligible, no noxious vapours were detected and electricity was supplied by the local network. Most of all a quick calculation showed that good environmental conditions could be obtained by raising the temperature (and consequently lowering the relative humidity) through heating alone, without de-humidification (fig. 2.6).
Rawlins thoughts of what values had to be provided in the repository were not exactly what was recommended in the 1939 publication: "*there is some reason to suspect that the traditional values of 60°F. and 60 per cent R.H. have been accepted more on account of the comfort of visitors to galleries than on behalf of the contents. While temperature per se is not of the greatest moment, relative humidity assuredly is. It seems likely that a range of between 50 and 55 per cent at around*



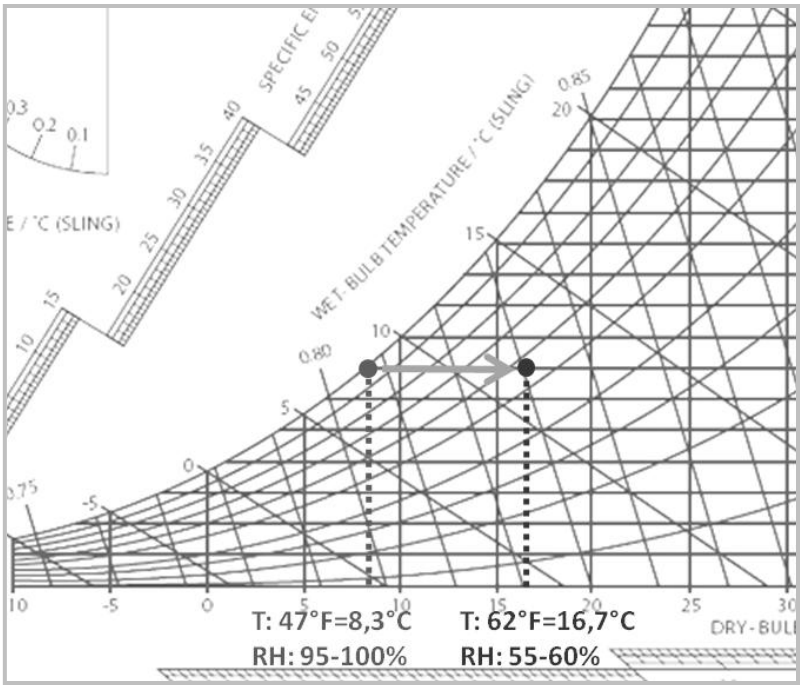


Fig. 2.6 – An hygrometer consisting of disc-type temperature recorder and aspirating system was used fo monitoring the environmental conditions inside the repository (from Saunders 1992, p. 108)
Fig. 2.7 – Psychrometric chart (extract): warming saturated air from 8,3°C to 16,7°C, a RH between 55-60% can be obtained.

60°F. in nearly ideal” (Rawlins 1942b, p.112)
It is not clear where this latter range comes from. In another publication he claimed that: “*Experience shows that a relative humidity of between 55% and 60% at a temperature of 60°F. is sound practice, the tolerance in the former being about ±5%*” (Rawlins 1942-43, p.345). This statement probably refers to the experiments performed at the National Gallery before the war which have been described in paragraph 1.2. It was shown that such a range of RH corresponded to the equilibrium moisture content of wood samples acclimatised within the galleries throughout a year. “*It was for this reason that 58 per cent R. H. was established at the wartime repository*” (Keeley, Rawlins 1951, p.195).

Once that set-points were established, the question was how to arrange the quarry so that they could be provided, which meant, thanks to the support from the Ministry of Works, carrying out huge work and designing a suitable conditioning system: “*Much of what will be needed is a matter for engineering rather than for physics*” (Rawlins 1942-43, p.345)
It was obviously impossible to warm the whole air volume inside the quarry, so the choice was to build separate free-standing buildings and then to condition their indoor environment. Here a very strict control of hygrothermal conditions was required, since paintings had to be stacked in rows without any casement or glazing, so that they could be regularly inspected by conservators. The buildings were built as simple envelopes: light brick walls with an inside coating in wooden wall-boards. Roofs were of fabricated material, floors in concrete. Much more efforts were put on climate control and on the design of the heating system.
Each building was equipped with a separated plant chamber, accessible without entering the painting rooms, except the largest two which were equipped with two plant chambers each. The stable quarry air passed into the chamber through grilles. Here an electrical fan drew air firstly through filters and secondly through electrically heated batteries.
As already told, desired conditions could be provided and maintained by heating alone but

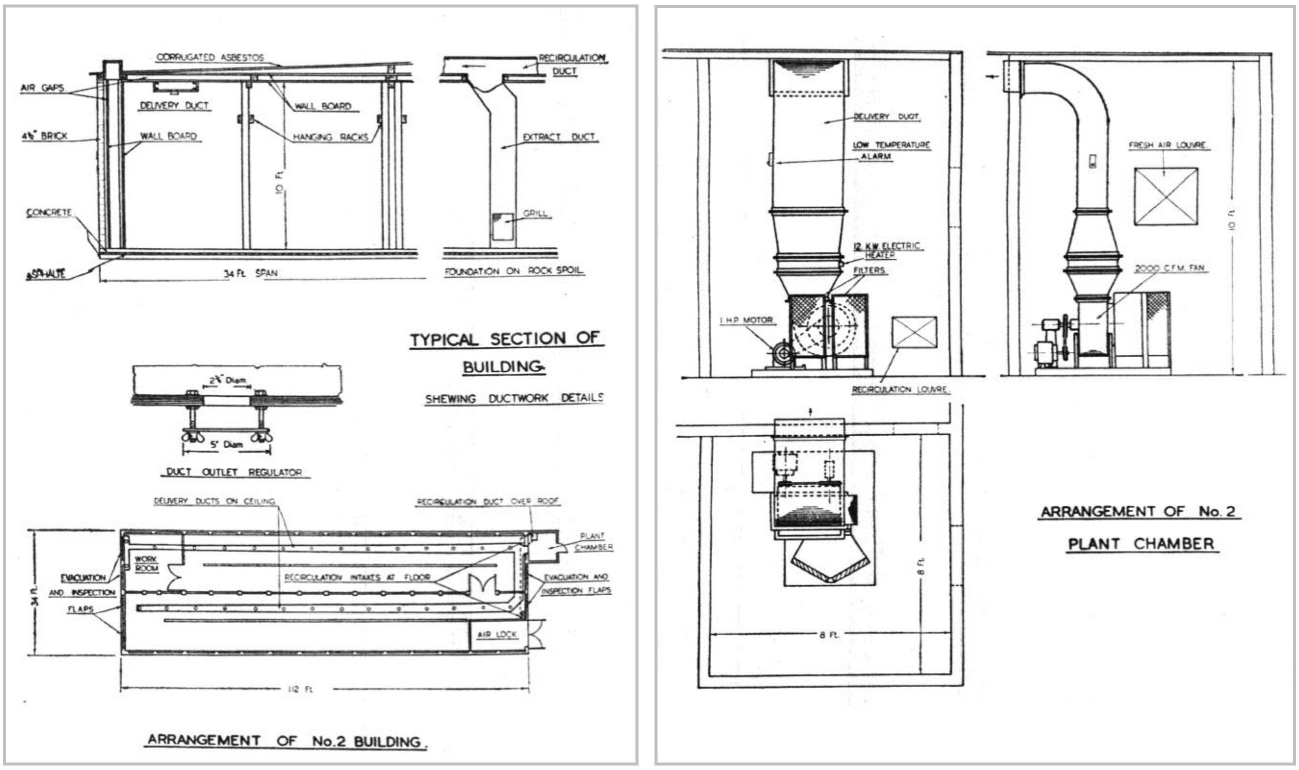


Fig. 2.8 – Plan and section of a repository in Manod Quarry (Building No.2) with details of the ductwork (left);plant chamber with details of the air conditioning system machinery (right)

dehumidification was necessary in an early phase to dry the rooms before the paintings were moved in. Temporary refrigeration units, connected to the recirculation ducts, were installed for the purpose. The delivery ductwork, hanging on the ceiling, was equipped with dampers and low-velocity adjustable outlets. Air was thus gently spread inside the repository. Partial and total recirculation was possible through ducts placed on the top of the roofs.

To limit energy consumption the system normally worked on almost full recirculation, providing about 4 air changes per hour. When the staff had to work inside the rooms, the recirculation louvres were closed and the fresh air intake opened so that fresh air could be provided. In both modalities the system was designed to work as a plenum: the slight outward pressure thus helped in preventing infiltration of dust and cold and damp air from the outside.

Indeed, this caused problems in some parts of the quarry, where the air got warmer. As a consequence the thermodynamic efficiency of the system decreased and temperature had to be raised up to maintain a constant 58% RH. To overcome the problem calcium chloride was thus used as pre-drying agent and powerful fans installed to draw air from the colder part of the quarry.

In the end the system proved to be very satisfactory: "*experience of a full year's working has shown that the plant gives, as an example, a relative humidity of 57 per cent at 64°F., with a variation in the former of less than 2 per cent over a period of many months. In general, the temperature in the various buildings are some 2°-3° F. higher than anticipated if the correct relative humidity is to be obtained*" (Rawlins 1943a, p.126). Detailed technical description of the system were provided by Fletcher (1943) and Pallot (1946).

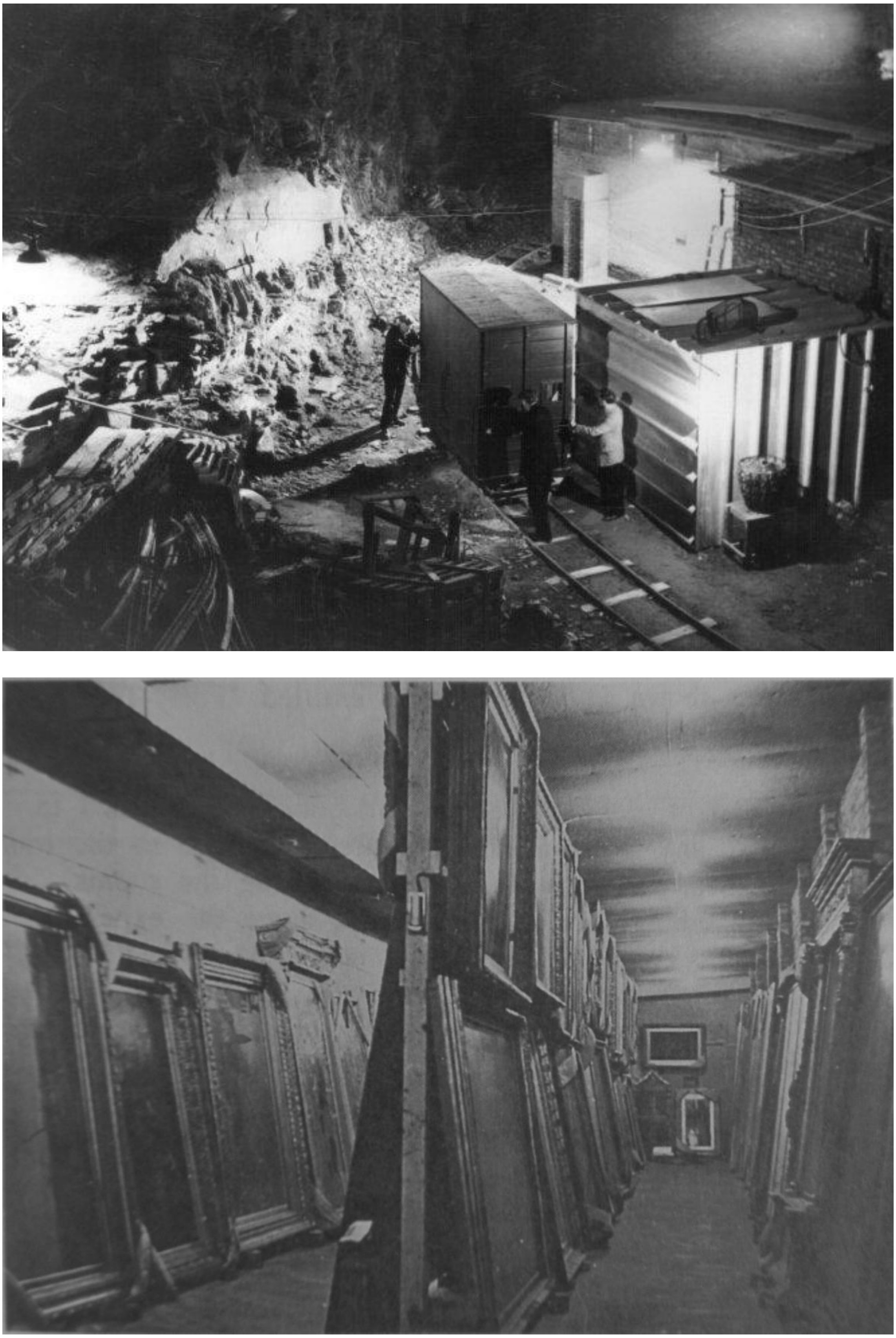


Fig. 2.9 – National Gallery repositories in Manod Quarry: outside and inside the shelters

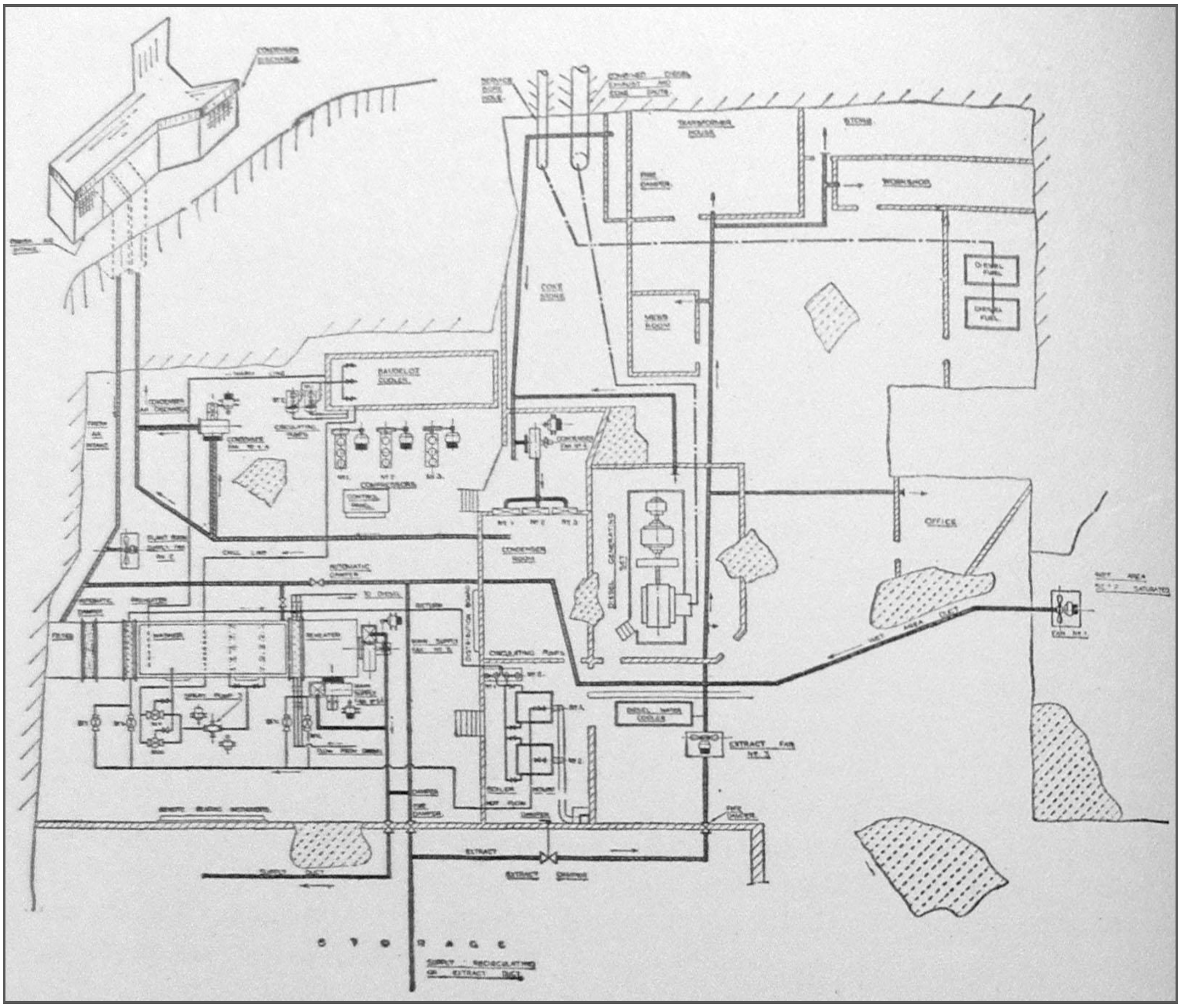


Fig. 2.10 – Plan of the building services of the repository in Westwood Quarry

At the end of 1940 the British Museum staff was facing the same problems and the solution found was not dissimilar. The conditioned artificial tunnelling under Grogyhan hill proved to be satisfactory, even if the works were more costly than anticipated. The experience gained in this occasion suggested that a huge underground repository would be the best solution, but much more floor space was now needed: "*It had been suggested to the Museum that some worked-out stone quarries in the west country might be suitable if one of them could be converted from its normal use for growing mushrooms. A quarry at Westwood, near Corsham, Wilts, was earmarked at the beginning of 1941 for the British Museum and the Victoria & Albert Museum.*" (Caygill 1992, p.37)
The site was large enough for the requirements (2250 m^2) and accessible by lorries but considerable structural works, including floor-levelling and waterproofing, had to be carried out, once again under the direction of the Ministry of Works.
Not only paintings but objects and specimens of any type had to be stored (e.g. furniture, carpets, textiles, books and manuscripts, antiquities and ethnographical objects) and, once again, environmental conditions played a key role for their conservation.
As Rawlins did, also Plenderleith aimed to have a strict control on the underground environment and defined his objectives: "*it may be asked whether it is possible to define atmospheric conditions which are entirely safe for all kinds of museum objects. (...) In point of fact the constant conditions*

recommended for paintings are 60 per cent R.H. at 60° F [15,6°C], and while these conditions would of course be ideal for collections of any kind, variations of 5° and 5 per cent either way would not be deleterious in museum and library repositories." (Plenderleith 1943, p.95). A paper on mould growth on binding materials by Groom and Panisset (1933) seems to have been the basis for the definition of an upper limit of 70% RH, beyond the level of which it was absolutely not allowed to rise.
Nevertheless, a 1946 article on Mouseion by A. C. Pallot, Senior Engineer of the Ministry of Works, states that the set point were 58% of relative humidity and 18,3°C (65°F) of temperature, which were exactly the same values obtained at Manod.

Obtaining these conditions in Westwood was surely harder than in Manod, since the storage rooms were dug directly in the stone and, despite walls waterproofing, humidity infiltration was unavoidable. As a consequence heating alone was not enough and a full air conditioning system, equipped with a dehumidification unit, had to be installed. *"This installation consisted of three methyl-chloride compressors of 12 HP. Each one was equipped with Baudelot refrigerators for maintaining the water feeding the spraying washers at a temperature from 1.1° to 3.3°C. Compressors were controlled by thermostats for chilled water and the entire system was designed to automatically adjust the temperature of the air distributed (...). To reheat the air after it was cooled to the point of condensation, component boilers were installed, which were manually loaded and burning about 200 tons of coke per year"*[11] (Pallot 1946, pp.25-26).
Air recirculation could be partial or total, with fresh air drawn in from outside or, partially, from an unused part of the quarry. Pre-heating was thus also needed but variations in outdoor air, and the discontinuous heat supply by boilers manually fed, made the regulation of the system quite hard. All the main components of the system were doubled to overcome the possibility of breakdowns and to allow maintenance.
After one year of operation it was noticed that the saturated air in the unused wet part of the quarry remained stable at constant temperature of 11,3°C. In 1943 the system was thus modified to exploit this possibility and increase its efficiency: only the cool and wet air of the quarry was drawn in and dehumidified by the air washers. At the same time it was then used to absorb heat from the condenser serpentine of the cooling system, which now worked as a reheater. Since preheating was not necessary anymore and almost all the heat was supplied by the condenser, the boilers could be turned off. As a result operation costs were halved and hygrothermal conditions were more stable.
According to Pallot (1943, p.32) the upgrade of the system was the first application in the United Kingdom of the principles of the heat pump.

By the end of the war these two storages preserved an impressive amount of extremely valuable collections. At Manod *"in addition to National Gallery paintings, the quarry came to house works from the Courtauld Institute, National Portrait Gallery, Soane Museum and Victoria and Albert Museum in London, the Walker Art Gallery in Liverpool and the Fitzwilliam Museum in Cambridge, to mention but a few. The Royal Collection had arranged for drawings by Leonardo, Holbein,*

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[11] English translation from the French by the author. Original text: "*Cette installation se composait de trois compresseurs au chlorure de méthyl de 12 HP. Chacun, munis de réfrigérateurs Baudelot destinés à maintenir à une température de 1.1° à 3.3°C. l'eau alimentant les vaporisateurs de lavage. Les compresseurs étaient contrôlés par des thermostats à eau réfrigérée et toute l'installation fut conçue pour un réglage automatique de la température de l'air distribué (…). On installa, pour réchauffer l'air après refroidissement jusqu'au point de condensation, des chaudières à éléments, se chargeant à la main et brûlant environ 200 tonnes de coke per an*"

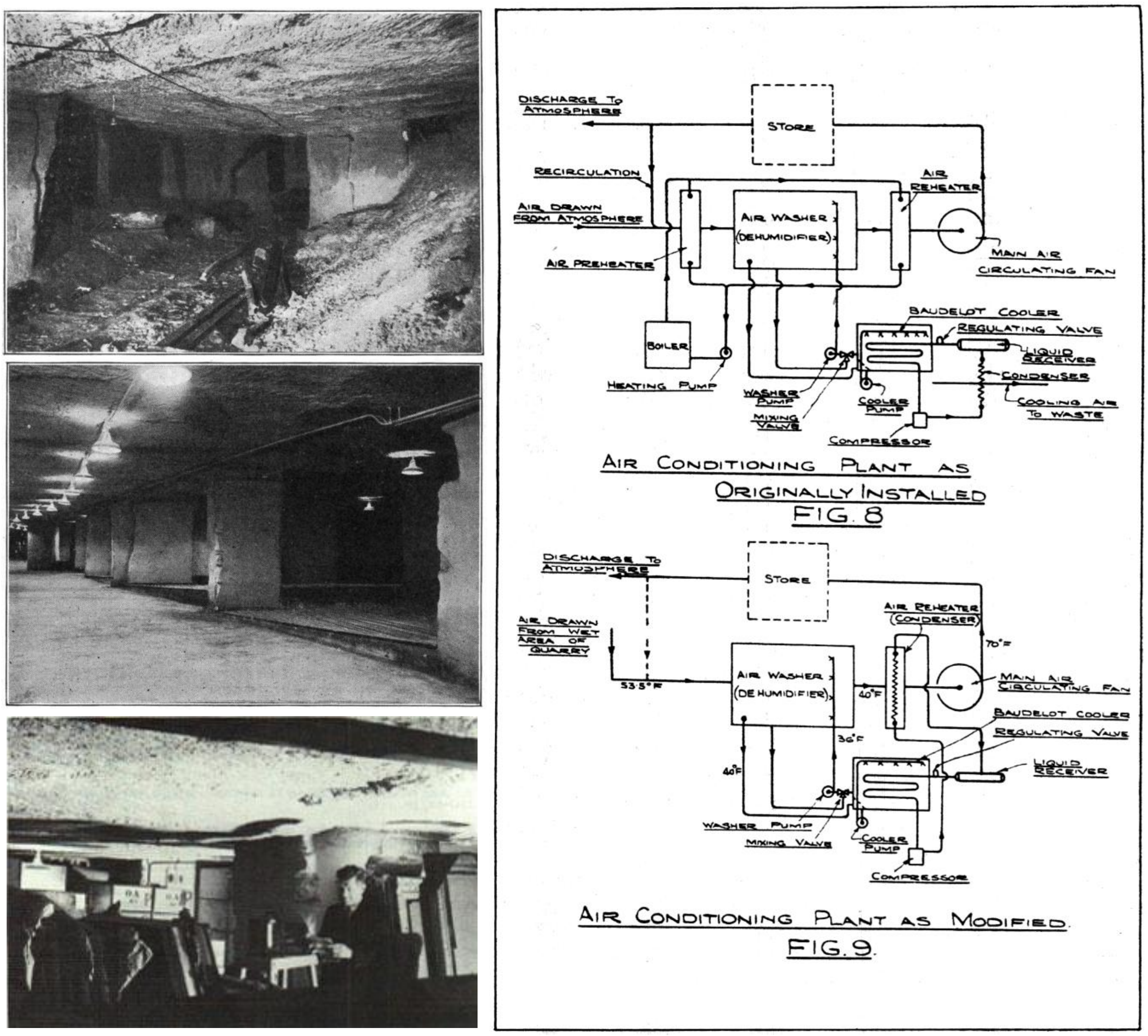

Fig. 2.11 – Westwood Quarry before and after the adaptation works; the storage interiors in 1942 (left); schemes of the air conditioning plant before and after being modified (right)

Claude and Michelangelo (...) and paintings joined the drawings." (Bosman 2008, p.88). At Westwood "*not only the cream of the British Museum, the Victoria & Albert Museum and the National Portrait Gallery collections, but also items from private collections and from some 30 other institutions. Benedictional of St Aethelwold, the Winchester Bible, the Shakespeare Deed from the Guildhall, St Chad's Gospels from Lichfield Cathedral, the portrait of Richard II and King Harry VII's altarpiece from Westminster Abbey, the Aberdeen Bestiary, the Exter Book, stained glass and the Magna Carta from Salisbuty Cathedral, Hereford's Mappa Mundi, the Savernake Horn, the Loyd coin collection, the Stonyhurst Gospels and the Burns manuscripts from Edinburgh.*" (Caygill 1992, p.40).

Given the excellent results reached, it is not surprising that, even before the end of the war, both Plenderleith and Rawlins agreed in figuring out the outcomes of their war experiences. If the former stated that "*Much valuable experience has been gained and it is a comforting reflexion that this knowledge will be applied in the remodelling of our museums after the War, so that the national treasures can be adequately housed and suitably displayed*" (1943, p.97), Rawlins' observations were even more incisive: "*A sizable body of data relating to temperature, relative humidity,* *condition and reaction of materials is being assembled, and may well take its place in contributing towards the post-war design of museums and galleries, and to the choice of environment considered best for works art. It is possible that full air conditioning of such institutions in large cities and certain other places might be found to be financially desirable, when the sums spent annually in restoration and repair of paintings are critically reviewed. Careful inspection will always be needed, but the experience so far of housing a collection of pictures below ground under controlled conditions scientifically planned, is decidedly encouraging. It would be a pity if some of this could not be translated into terms appropriate in times of peace. (…) [The pictures] are at present enjoying a climate of such salubrity that the greatest problem for the future is to foresee how they will react when they leave it.* " (1943a, pp.127-128). His predictions would have soon been confirmed by facts.

A general cleaning program was carried out during the permanence of National Gallery paintings at Manod by the restorers A. W. Holder and H. Ruhemann. They could work in daylight in a studio built just outside the entrance of the quarry. The conservation conditions of the paintings were so good that the duration of their cycle of maintenance and repair from cracking and flaking reduced considerably. London's eight months became a single month in the first year at Manod and, by the end of the conflict, interventions were completely unnecessary. But, as Rawlins imagined, once back at Trafalgar Square artworks once again started to suffer decay and required repeated restoration works.

In this regard, postwar years at the National Gallery were characterised by the well known "cleaning controversy" The result of the international debate hence originated was the so-called *Weaver Report on the cleaning of pictures in the National Gallery*, which was written in 1947 and then published and commented in a dedicated issue of the UNESCO review *Museum*.

Beside their opinions on the cleaning methods, the authors observed: "*Although it is generally known how large is the extent to which abrupt changes in temperature, and especially of relative humidity, affect the condition of works of art, it is necessary to lay much more emphasis on this subject. It is understood that experimental work has been done in this field both by the Ministry of Works and by the Scientific Adviser to the National Gallery. It is understood also that equipment for an installation sufficient to provide for part of the collections of the National Gallery is now available, and a plan is developed. The remarkable arrest of deterioration of the pictures during their time at Manod Quarry (where temperature and relative humidity were under control), followed by the difficulties (buckling and flaking of paint, and warping and cracking of panels) which developed in many of them after their return to London is sufficient evidence that control of atmospheric conditions is by far the most important single means of their proper conservation*" (Weaver, Stout, Coremans 1950, p.134). As a consequence their recommendation: "*That for the general conservation of the pictures a scheme of full air conditioning be introduced as soon as practicable*" (Weaver, Stout, Coremans 1950, p. 135).

In other words, it was probably not so meaningful to debate on how to apply conservation techniques to single artworks when the gallery environment was the first cause of decay for the whole collection. Furthermore, technical development and lower installation and operation costs of air conditioning systems had made them accessible, at least for the major institutions. As an example full air conditioning had already been installed in the Washington National Gallery of Art, inaugurated in 1941: *"In recent years the use of air conditioning for a large number of various types of buildings spread widely, but this new gallery is equipped with one of the first large installations*

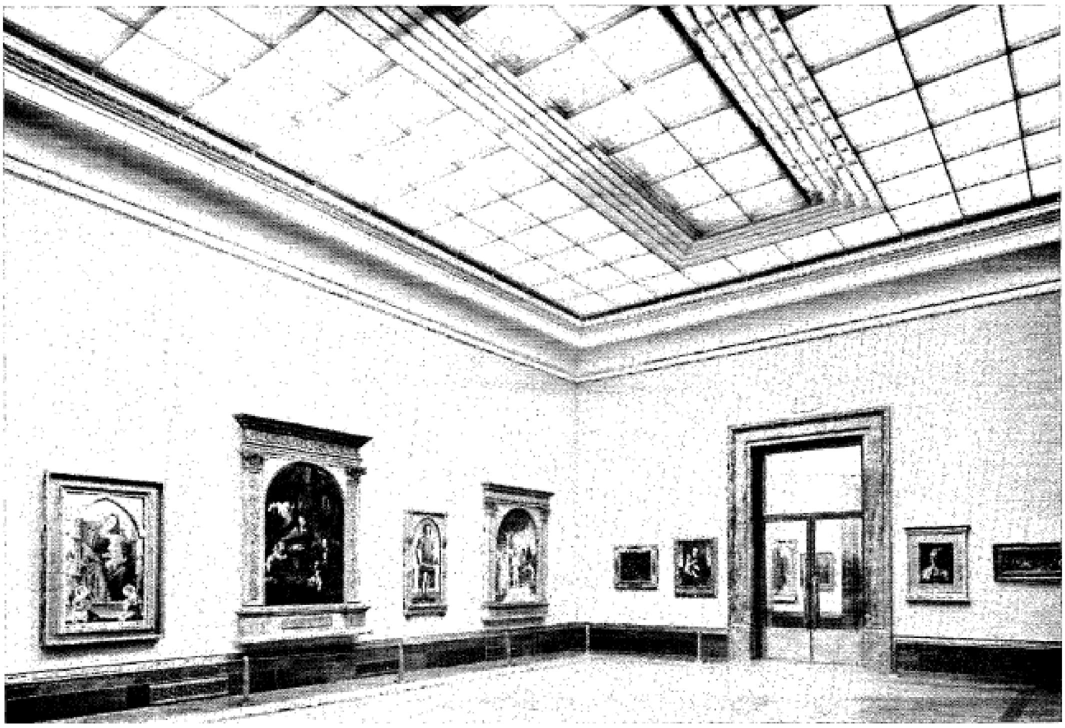

Fig. 2.12 – National Gallery, London. Room XXIX refurbished with air conditioning

known in the world of museums. It is mainly because of the protection guaranteed to artworks that this system was adopted."[12] (Eggen 1946, p.134).

In 1950, the time was ripe also in London for the National Gallery: *"Many attempts have been made to deal with the question of heating and ventilation but none has been backed by the present degree of technical knowledge because, until the last quarter of a century, the equipment and knowledge to produce good air conditioning were not available. Indeed, such has been the development in this branch of engineering that, in the case of the National Gallery, it remained only to achieve joint planning by the responsible authorities - the Trustees and Director of the Gallery, the Architect, the Engineer responsible for the building - in order to develop a comprehensive and aesthetically acceptable scheme."* (Keeley, Rawlins 1951, p.194)

Room XXIX was thus finally equipped with full air conditioning, soon followed by five more rooms after a period of testing. The description of the system is useful to give us an idea of what was considered a state-of-the-art air conditioning system for a museum: "*The design of the air-conditioning plant is based upon the well established pattern of the filtration of fresh air, mixed with recirculated air. The makers' guaranteed efficiency is 99.9 per cent for particles down to two microns. The filtered air then passes through a pre-heater battery, of the hot-water pattern, thermostatically controlled by a dew point element placed beyond the humidifying chamber. This chamber with its finely divided water sprays is capable of controlling the amount of moisture in the air stream. When the heat content of the mixed air entering the washer exceeds the desired amount, the pre-heater is automatically "cut" and chilled water from a refrigerating plant is admitted to the spray water, thus reducing the saturated air to the desired temperature.*

[12] English translation from the French by the author. Original text: "*Depuis quelques années le recours au conditionnement de l'air pour un grand nombre de bâtiments de différentes catégories s'est largement généralisé, mais cette nouvelle galerie est équipée d'une de premières grandes installations connues dans le monde des musées. C'est surtout en raison de la protection qu'il assure aux œuvres d'art que ce système a été adopté.*"

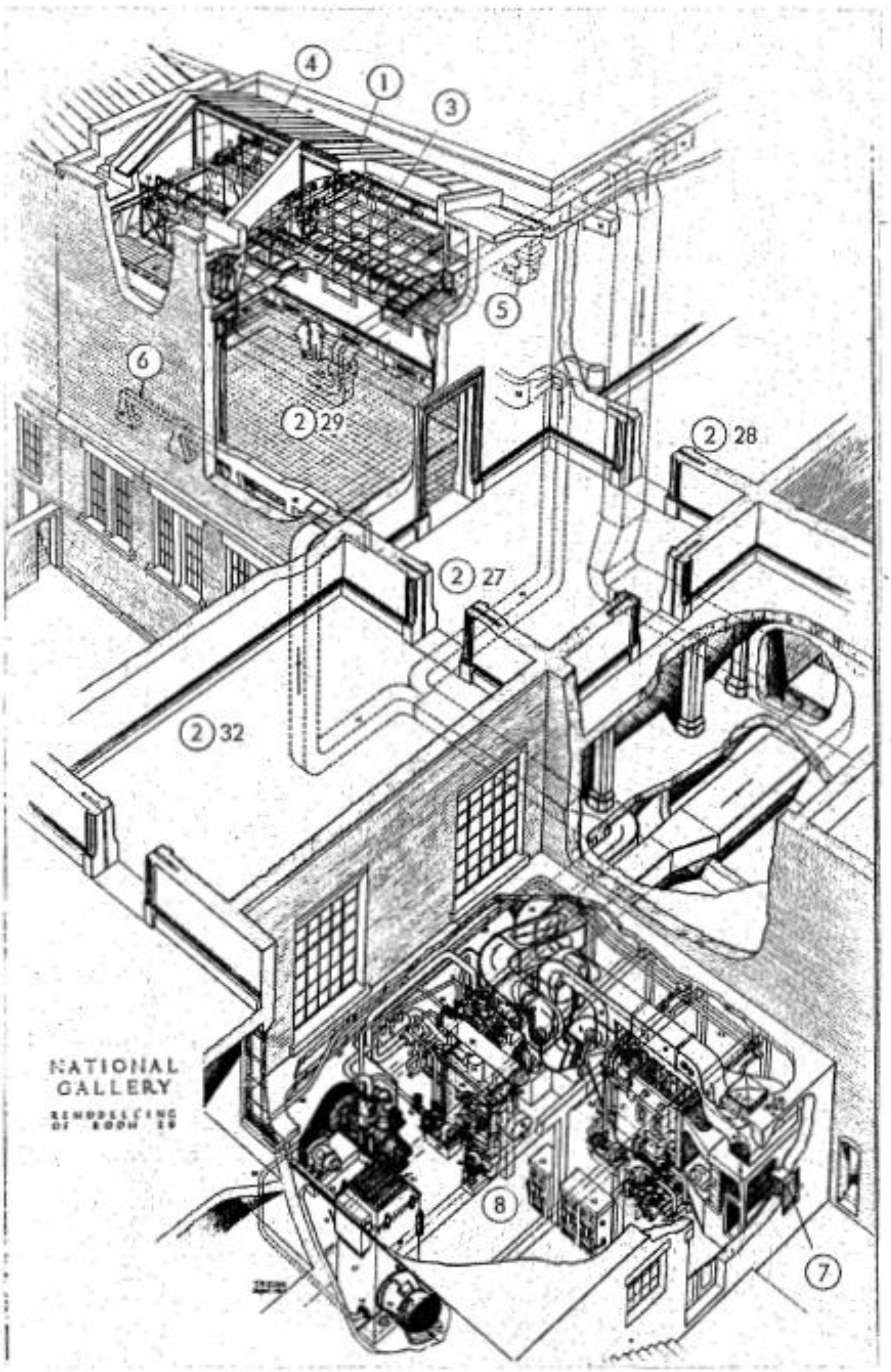

Fig. 2.13 – National Gallery, London. Scheme of the air conditioning: 1) Glass roof to gallery; 2) Rooms 27, 28, 29, 32; 3) Laylight with built-in fluorescent tubes for supplementary lighting; 4) Travelling cradle; 5) Conditioned air supply to gallery; 6) Used air taken from gallery; 7) Fresh air intake; 8) Plant room

The saturated air stream is then warmed to whatever temperature is required in the gallery and regulated automatically by an element placed in the return air duct from the gallery. Thus the air leaving the plant has been cleaned by filters, given its required amount of moisture, and finally warmed to the desired degree for the comfort of the spectators and the welfare of the pictures." (Keeley, Rawlins 1951, p.196-197). Temperature and humidity set-points were deliberately overlapped on those of Manod, which proved to be so effective.

The successful recovery of the British collections during the war, was in the meantime becoming an absolute reference for conservators and had such an impact to be quoted several times in the following decades as evidence of the effectiveness of those hygrothermal values and as confirmation of the absolute need of air conditioning in major museums.
Plenderleith, for example, referred to the parameters adopted at Westwood and Manod repositories both in the 1956 edition of his famous work "*Conservation of Antiquities and Works of Art"* (Plenderleith 1956) and in the special issue of the review Museum, entitled "*Climatology and conservation in museums",* written with P. Philippot.
Here the results of a research promoted by ICOM in 1955 to study the effects of indoor climate on collections, were reported: a questionnaire was distributed to 64 institutions, including museums, libraries and archives in 11 countries, asking them to indicate what were considered the ideal preservation conditions.
Curiously, the responses to the questionnaire indicated quite variable values but they were only reported by the authors as an appendix to the publication with the following explanation: *"The recommendations of curators concerning the most favourable conditions in galleries, in reply to the questionnaire, frequently reflect the actual conditions in the museums for which they are responsible and of which they have personal experience, rather than those defined as ideal by the specialists. They are presented, as a matter of interest, in Annex I"* (Plenderleith & Philippot 1960, p.254)
The average RH values collected stood in a range between 50 and 70% but 60% was referred as an ideal value. Once again it is interesting to note what reasons were given: "*The figure of 60 per cent has the interest and guarantee of having been subjected to very thorough testing during the period of the second world war, when it was found to afford complete and absolute protection to a large variety of objects, including furniture and paintings kept in the special repository constructed for the British and the Victoria and Albert Museums in England*" The Manod experience was then quoted because "*it provides the strongest argument in favour of the air-conditioning of picture galleries and, incidentally, of maintaining 58 per cent RH for the protection of panel paintings on wood*" (Plenderleith, Philippot 1960, p. 254-255).
The article explicitly recommended full air conditioning systems in museums or, if not possible, portable air conditioning units to be placed in rooms. Some examples of climate control installations were added at the end of the publication.

The responses to the ICOM questionnaire and the discussion by Plenderleith and Philippot, with the explicit contrast between "*actual conditions*" and "*those defined as ideal by the specialists*" reveals how the point of view on those questions was changing.
On the one hand, the wartime recovery of collections represented, especially in United Kngdom, the successful accomplishment of that path of reciprocal influence between museography, technique and scientific research that was described in chapter one. On the other hand it paved the way to a new conception of the museum environment since, thanks to the development of modern air conditioning, museums had at their disposal all the instruments to provide their collections with a (supposedly) perfect artificial climate.

From now on debates and research would shift from the discussion on how to provide suitable environmental conditions to the definition of ideal hygrothermal parameters for artworks.
It must be also underlined that a key role in promoting this new approach to the discussion was played by the new international organizations born after the war, such as ICOM, IIC, ICCROM.
Not by chance many of the founders or the most prominent members of these organizations were the same scholars we met in these pages: in 1950 Stout, one of the authors of the *Weaver Report*, was appointed as first president of the IIC, while Rawlins as first secretary; Plenderleith was the first treasurer of the IIC and in 1959 became the first director of the ICCROM.

2.3 The Museum Environment by G. Thomson and the emergence of preventive conservation theories

The growing interest on museum climate control after the second world war was testified by the first conference explicitly dedicated to the topic of the 1967 *London Conference on Museum Climatology* organised by the IIC. We read in the preface of the contributions: "*The study of how the environment in a museum affects its contents, and of how to ensure that their ageing processes are slowed to a minimum has come to be called Museum Climatology. (...) Today, just as in medicine, the ultimate objective is seen to be the prevention of disease. Hence a fair proportion of the best scientific and technical work in museums is coming to be devoted to the subject of museum climatology"* (Bromelle 1968). The book, edited by Garry Thomson, was divided in four sections: *Air pollution*, *Humidity control*, *Lighting* and *Climate and museum design*.
Attention to the museum environment was strictly related with the stress on prevention of decay, which was another issue attracting museum professionals' interest in those years and which would later be developed in the theories known as preventive conservation.

Gael de Guichen, in a recent conference in Italy, has proposed to divide the path of preventive conservation into different phases: *"the first one from 1965 to 1975, when awareness on the question arose; then from 1976 to 1985, when the term properly got into the debate; after that, from 1986 to 1995, the strategy was designed"*[13] (Guichen 2003, p. 15-16; see also Caple, pp.12-14).
A look at Thomson's most popular book, *The Museum Environment* would confirm Guichen's words. In the preface of the first edition the term is introduced and the book described as "*based on the growing need for a summary of the 'preventive medicine' of conservation*" (Thomson 1978) while in the second edition the authors noticed that "*interest in preventive conservation was growing strongly*" (Thomson 1986). An international conference entirely and specifically dedicated to preventive conservation was held in 1992 in Paris (ARAAFU 1992) followed by the IIC conference in Ottawa in 1994 (Ashok, Smith 1994).
Guichen underlined the link between the war-recovery experience and the research on museum climate carried on in the 60s and 70s by scholars such as Plenderleith and Thomson and he was himself very active in spreading the new theories as a member of the ICCROM. He was among the organizers of a travelling exhibition on this topic, called *Conservation in Museum* (Guichen 1978) and author of the publication *Climate in museums* (Guichen 1980) which was used in the homonymous course held at ICCROM. The aim of his action was clear: to "*lead to a wider understanding of the fact that preventive conservation must take priority over remedial restoration*" (Guichen 1978, p.63)
The contemporary conception of preventive conservation is obviously not limited to the strict control of hygrothermal parameters in museums and nowadays it can be hard to describe briefly all the issues involved (risk management, indoor air quality, lighting control, pest management, etc.); a good definition could be: *"an agreed plan of action to slow the rate of deterioration and reduce risks for museum collections. The focus is on the surrounding of the collections, thus actions could range from building maintenance, to control of staff practices, influencing public attitudes, climate control and legislation"* (Menegazzi, Putt 1998) or, in other words: "*non-interventive actions taken to prevent damage to and minimize deterioration of a museum object*" (NPS 1999, p. 3.20)

[13] English translation from the Italian by the author. Original text: "*la prima dal 1965 al 1975, dove vi è stata una presa di coscienza del problema; poi dal 1976 al 1985, in cui il termine entra effettivamente in scena; in seguito, dal 1986 al 1995, in cui si delinea la strategia"*

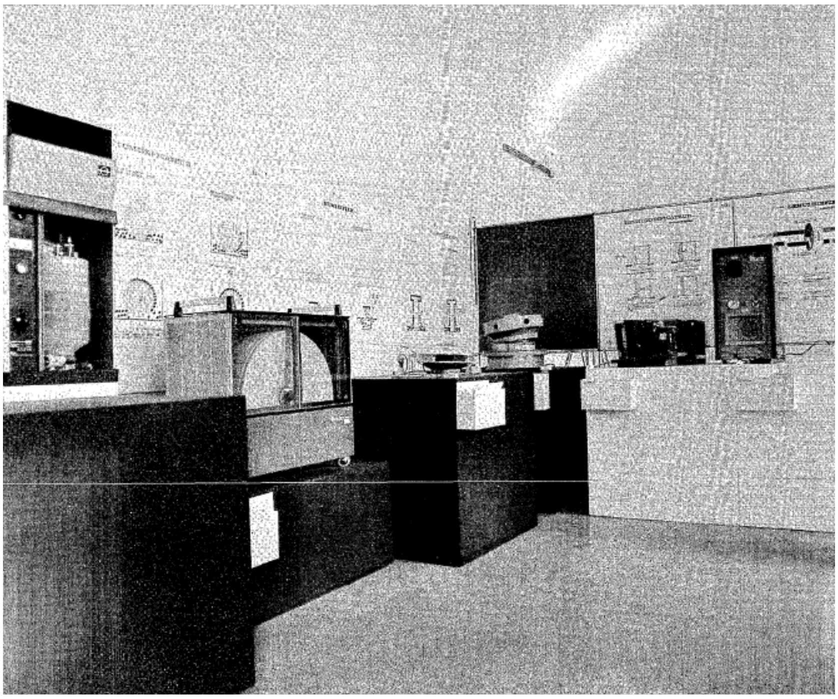

Fig. 2.14 – *Conservation in Museum* exhibition at ICCROM, Rome. Different components and equipments for climate control are shown so that visitors can see how they work

It is probably beyond the objective of this thesis to expand on the contrast between preventive and interventive conservation or to treat in depth the never-ending debate between “conservators” and “restorers”. However, what must be stressed is the point that the definition of ideal environmental parameters, or “*magic numbers*” as they have been ironically called (Michalski 2007), was probably enhanced by the rise of preventive conservation theories.
As highlighted by the definitions reported, in preventive conservation the focus is on what surrounds the artwork, in an attempt to preserve it from decay by external factors. As a consequence good practices concerning the control of hygrothermal parameters tended to consist of providing museum professionals with recommendations defining an ideal conservation environment which had to be meet.

The most popular work of this kind is surely the above mentioned *The Museum Environment* by Garry Thomson. The book is still significant for many of those involved in preservation and climate control within museums and its success was probably due to its effective dissemination of awareness and knowledge on the risks to which museum collections were exposed.
It was divided in two parts: the first one addressed to curators, the second one more focused on scientific issues behind the recommendations.
The method followed by Thomson in determining the best RH levels was very simple: “*we first find upper and lower danger limits and then decide the most suitable RH within this range*”. Having an upper limit at 65/70% to avoid mould growth and a lower limit at 40/45% to avoid embrittlement, “*for Europe the choice is commonly 55%, midway between the danger limits”* (Thomson 1986, pp.86-87). Suggested limits and their rationale were more or less those indicated by Rawlins and Plenderleith 35 years before. Thomson could probably be influenced by his personal experience as scientific adviser of the National Gallery in London.
Criticism has underlined that poor scientific evidence for these recommendations is produced (Brown, Rose 1996, pp.18-19 and Erhardt, Tumosa, Mecklenburg 2007, pp.12-13) as they were

probably based on common practice and widespread literature at the time. It was not clear how a departure from these thresholds would have resulted in terms of increased damage.

Anyway the greatest paradox of Thomson's book is probably that problems that followed were caused by its own success: suggested values were spread all over the world and widely quoted and requested by those unqualified museum professionals to which the book was addressed but this often resulted in an uncritical application. The appendix added to the 1986 second edition, where preferable values were summarized in a schematic way and divided into two classes, probably had the consequence of increasing this risk of incorrect and uncritical use.
Class 1 was defined as "*appropriate for major National museums, old or new, and also for all important new museum buildings*"; suggested yearly RH range was 50 or 55 ± 5% with a temperature of 19 ± 1 ° C in winter and 24 ± 1 ° C in summer. A very strict range that only (and not always) through powerful full air conditioning or high-performing showcases could be provided. "*The aim of Class 2 is to avoid the major dangers while keeping cost and alteration to a minimum. For example, some of the most important historic houses and churches may have to be limited to Class 2 operations. Neither ducted air conditioning nor automatic light control are assumed for Class 2*" (Thomson 1986*, p. 268).* Here the RH range had to be kept within the danger limit (40-70%) and temperature had to be regulated in function of RH.
Unluckily, as Brown and Rose (1996) noted, Class 2 soon became synonymous with second class, and in many conservators' minds a first class environment would obviously have been preferred in any case.
The risks involved with this kind of misunderstanding were immediately underlined and a 1988 book review (Weintraub) observed:"*this is not so much a weakness of the author, but rather of the reader*". It is a rather agreeable statement since Thomson proved to be quite well aware of the limits of his recommendations. Changes and fluctuations in relation to climate, seasonal fluctuations and local context were highlighted (Thomson 1986, pp.87-92). Different set-points were established for tropical or arid zones; problems that could occur with incorrect climate management identified (e.g. condensation and frost in colder countries). A paragraph was soundly entitled "*Rh is often a matter of compromise*" (p.116) and, in the discussion of allowed variation, it was affirmed: *"the question of how constant RH needs to be to ensure that no physical deterioration will occur remains at present unanswered. The standard specifications of ±4 or ±5% RH control is based more on what we can reasonably expect the equipment to do than on any deep knowledge of the effect of small variations on the exhibit."* (*p.118*).
On one hand this statement confirms how recommended climate conditions were more influenced by supposed performances of air conditioning systems than by scientific knowledge on artworks reactions to variations. On the other hand it simply echoes the words by Thomson himself in the Preface: "*we have a very uneven knowledge of how fast things in the museum change and what causes these changes, and yet we have to erect this framework of preventive conservation before rather than after our research has reached a dignified level of completion*".

In the following years, the progress of research would have generated harsh criticism on the Thomson-derived approach to the management of the museum environment.
Curiously the turning point of the discussion would have been one of the first international conference dedicated to that preventive conservation which Thomson had so much promoted: *Preventive conservation practice, theory and research* (Ashok & Smith 1994).

As Guichen noticed: *"We arrive this way to 1996, the year during which the debate reached the harshest criticism, precisely because the discipline had become increasingly acknowledged and structured"*[14] (Guichen 2003, p. 15-16).

[14] English translation from the Italian by the author. Original text: *"Si arriva così al 1996, anno in cui il dibattito raggiunge i massimi livelli di criticità, proprio per essere diventata una disciplina sempre più consolidata e articolata*"

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Chapter 3
Environmental standards, historic buildings and preservation: an open question

3.1 Beyond “traditional” museum standards? Recent research on climate-induced decay in conservation environments

As written above, the IIC Conference held in Ottawa in 1994, *Preventive conservation practice, theory and research* can be considered a milestone in the discussion of environmental control in museums. After decades of application of “Thomson-type” restrictive standards for preventive conservation, a series of problems emerged. The real need for such strict parameters was questioned considering that high running costs and technical requirements involved did not result in significant additional benefits for the collection, since in the meantime experimental research had demonstrated that many materials could withstand higher fluctuations in relative humidity before irreversible change happened or adapt in the long period to conditions until then considered problematic. The Ottawa conference gave the opportunity to many authors to discuss the usefulness, reliability and efficiency of such strict standards from different points of view.

The increasing number of exhibitions and loans between institutions exposed artworks to increased risks related to transportation: beyond shock and vibrations, hygrothermal conditions during transits were the among the main worries for conservators. Another issue was the narrowing of the conditions of the loans, with lenders requiring strict conservation conditions to protect themselves

Art in Transit: Studies in the Transport of Paintings (Mecklenburg 1991) had already collected many materials on this topic, including groundbreaking studies on the reactions of materials to climate variations.

In Ottawa Ashley-Smith, Umney and Ford (1994) highlighted the inconsistencies between irrational requests from lenders and ignorance about the real conditions to which objects were exposed.

Another interesting point was made by Brown who showed that the achievable accuracy in RH measurements was larger than the generally suggested range of 55 ±5% RH: *“there is no point in setting a specification which cannot be measured”* (Brown 1994, p.41). Also it was noticed that single point measurements could not be representative of hygrothermal variations in large volumes.

Criticism on Thomson’s specifications had already appeared in North America, especially in Canada, where the suggested values could hardly be kept in cold and dry winters and the concept itself of an absolute ideal climate had early been questioned (Rogers 1976).

Larger allowable fluctuations were suggested one year before the Ottawa conference by Micalski. In his incisive paper *Relative humidity: A Discussion of Correct/Incorrect value,* he compared conventional specifications with the results of experimental data on the reactions of different types of hygroscopic materials to RH fluctuations. His conclusion was that “*For collections dominated by rigid organic materials (wood and paint), we must accept that the data supports common sense, not magic numbers. (...) Overall, high risks begins outside the range 25%-75% RH. Slight mechanical damage will accumulate on highly vulnerable assembles at ±20% RH but this is virtually eliminated by ±10% in wood, ±5% in paint. Middle RH can be the local mean, or international norm. If tight control sacrifices the long-term reliability of the 25%-75% RH limits, or other issues like fire and pests, I believe it is counter-productive to the total well-being of most collections*” (Micalski 1993).

In Ottawa another important paper appeared: *Relative humidity re-examined* by Erhardt and Mecklenburg. A comparison among the effects of RH on different types of decay affecting different types of materials led to the conclusion that “*it is obvious that there is no ‘ideal’ RH for museums. Examining the effects of relative humidity does not lead to convergence on an ideal RH, but to a set of values and ranges (i) that may be more or less precise or accurate, (ii) that may apply only to*

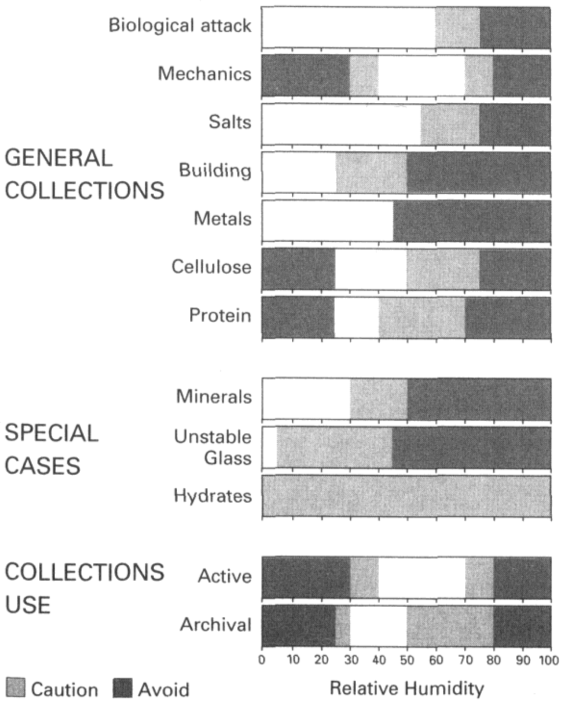

Fig. 3.1 – Allowable RH ranges in relation to various factors

specific types of material or object, and (iii) at which different types of damage may stop, start, increase or decrease. These values and ranges may or may not overlap, and often are in conflict" (Erhardt & Mecklenburg 1994). The authors observed that the most common settings in museums were probably widely accepted because they minimize the fastest and most visible forms of damage.

These controversial conclusions, especially regarding mechanical decay, were obtained using an innovative method: finite element analysis was applied to artwork materials and prediction of composite objects behaviour calculated through computer modelling. The first time this method was presented was in 1982 (Colville, Kilpatrick, Mecklenburg) and it was then further developed and applied when Marion Mecklenburg joined the Conservation Analytical Laboratory (CAL) at the Smithsonian Institution.

In 2003 research carried out at the CAL resulted in the new environmental guidelines at the Smithsonian for general collections and public spaces: temperature at 70±4°F (approximately 21±2°C) and relative humidity at 45±8%. An overview on research at CAL, nowadays called Museum Conservation Institute (MCI) has been presented by Erhardt,Tumosa and Mecklenburg (2007).

Besides studies on materials, targeted research had been carried out in the meantime in the field of physics and meteorology applied to cultural heritage. Studies involved both monuments exposed to outdoor conditions and indoor microclimates, in order to define the relationship between the object to be preserved and its closest surroundings and specific attention was paid to innovative methods for performing measurements and data gathering. Results allowed to understand the drawbacks of HVAC systems incorrectly applied to conservation environments and generating sharp gradients, undesired fluctuations and damaging effects.

This research characterised the ISAC-CNR group in Italy and was summarised in the seminal work by Dario Camuffo (1998): *Microclimate for Cultural Heritage*.

Table 3 Temperature and Relative Humidity Specifications for Collections

Type	Set Point or Annual Average	Maximum Fluctuations and Gradients in Controlled Spaces: Class of Control	Short Fluctuations plus Space Gradients	Seasonal Adjustments in System Set Point	Collection Risks and Benefits
General Museums, Art Galleries, Libraries, and Archives All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability.	50% rh (or historic annual average for permanent collections) Temperature set between 15 and 25°C *Note*: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 21°C, but sometimes 55% or 60% rh.	**AA** Precision control, no seasonal changes	±5% rh, ±2 K	Relative humidity no change Up 5 K; down 5 K	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		A Precision control, some gradients or seasonal changes, not both	±5% rh, ±2 K	Up 10% rh, down 10% rh Up 5 K; down 10 K	Small risk of mechanical damage to high-vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.
			±10% rh, ±2 K	RH no change Up 5 K; down 10 K	
		B Precision control, some gradients plus winter temperature setback	±10% rh, ±5 K	Up 10%, down 10% rh Up 10 K, but not above 30°C	Moderate risk of mechanical damage to high-vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.
		C Prevent all high-risk extremes	Within 25 to 75% rh year-round Temperature rarely over 30°C, usually below 25°C		High risk of mechanical damage to high-vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.
		D Prevent dampness	Reliably below 75% rh		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.
Archives, Libraries Storing chemically unstable collections	Cold Store: −20°C, 40% rh	±10% rh, ±2 K			Chemically unstable objects usable for millennia. Relative humidity fluctuations under one month do not affect most properly packaged records at these temperatures (time out of storage becomes lifetime determinant).
	Cool Store: 10°C 30 to 50% rh	(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)			Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.
Special Metal Collections	Dry room: 0 to 30% rh	Relative humidity not to exceed some critical value, typically 30% rh			

Note: Short fluctuations means any fluctuation less than the seasonal adjustment. However, as noted in the section on Response Times of Artifacts, some fluctuations are too short to affect some artifacts or enclosed artifacts.

Fig. 3.2 – Chart reporting climate guidelines for collections from the ASHRAE handbook

A paragraph of this book particularly focused on *"the best type of microclimate for conservation"* and it was observed:*"For the materials most used in creating works of art, some recommended values (or spans) of T and RH can be found in the literature, with the aim of determining the conditions of physical well-being, suitable for and appropriate conservation. (...) However, a fundamental question arises: are microclimate norms and guidelines always useful and should they be always followed?"* (Camuffo 1998, p.68). The author underlined the important distinction between the general properties of materials and the complex behaviour of specific and aged artifacts and, referring to objects composed of hygroscopic materials, specified that the climatic conditions to which an artifact had adapted had to be taken into account and considered priority.
The same considerations are on the basis of the concept of historical climate.

Despite these developments in research, the reassuring recourse to preservation standards has generally continued to be widespread practice. The Italian standards presented in paragraph 0.1 are an example of this approach (UNI 1999, MiBAC 2001).
In those years T. Padfiled observed that "*The guidance on humidity that is available to museum managers and architects is, I think, far below the quality that we could achieve by coherently presenting our present knowledge. Poor understanding of humidity fundamentals encourages the imposition of standards that are wrong, or needlessly strict, in the particular circumstances, because people who do not understand the issues tend to shelter behind semi-official standards so that they cannot be blamed if things go wrong. This attitude inhibits the use of cheap, alternative methods of climate control. I do not doubt that the present relative humidity standard has caused unnecessary investment in expensive and complicated equipment"* (Padfield 1994).
Can we then talk about a crisis of the "strict standards/air conditioning" paradigm in the 1990s? And how was this research transferred to operative applications?

The Smithsonian guidelines have already been mentioned. Another interesting application is the chapter for climate control in museums, galleries, archives and libraries in the handbook of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2007). These guidelines were developed at the end of the 1990s in collaboration with the Canadian Conservation Institute (Michalski 1999).
Here specifications for conservation environments are classified in progressive classes of control, ranging from AA to D and all the information is resumed in a table in which risks and benefits for the collections are associated to every class of control (fig. 3.2). Different ranges of temperature and relative humidity are thus linked to an assessment of the risks involved for the collections. The focus is shifted on the conditions expected within the building and, as a consequence, on the performance achieved by the HVAC system installed.
As an example, the AA class of control has a precision control of RH all year long (±5%), while class C, preventing all high-risks extremes, has RH within a 25-75% range and T should stay below 25°C most of the time.
Interestingly, another chart reports a classification of the climate control potential in buildings: possible class of control are suggested on the base of the typical building construction, type, use and climate control system; limits for climate control are indicated (fig.3.3).
These specifications are based on risk assessment, a method largely used in the field of preventive conservation (Ashley-Smith 1999) and here applied to environmental issues in order to understand where the thresholds for significant additional risks lie. This approach is being further developed (Michalski 2007).

A different point of view on environmental control specifications was recently provided by European standards, which mainly focus on defining procedures and give methodological indications rather than prescriptions.
This is the case of the EN 15757:2010 '*Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials'*, the EN 15758:2010 '*Conservation of Cultural Property - Procedures and instruments for measuring temperatures of the air and the surfaces of objects'* and the EN 15759-1:2011 *'Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship'* (CEN 2010a, CEN 2010b, CEN 2011).
The EN 15757:2010 is of particular interest. The standard incorporates and develops many enunciations from a previous Italian standard, the UNI 10969:2002 '*Cultural heritage. General principles for the choice and the control of the microclimate to preserve cultural heritage in indoor*

Table 4 Classification of Climate Control Potential in Buildings

Category of Control	Building Class	Typical Building Construction	Typical Type of Building	Typical Building Use	System Used	Practical Limit of Climate Control	Class of Control Possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single-glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low-level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilating	C (if benign climate) D (unless hot, damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low-level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate controlled	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

Fig. 3.3 – Chart reporting a classification of climate control potential in building from the ASHRAE handbook

environments' (UNI 2002), including the concept of "historical climate", i.e. "*Climatic conditions in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least one year) and to which it has become acclimatized"* (CEN 2010a, p.6).
As a consequence, the most appropriate preservation conditions for hygroscopic materials should be derived from the study of occurred decay in relation to the object's past climatic history and, therefore, from a scrupulous study and analysis of the existing environment surrounding the object. Special attention to the conditions to which the objects have been exposed can be found even in quite old specifications, such as those from the 1930 conference in Rome (see paragraph .1.2).
A similar concept, known as "proofed fluctuation", was also developed by Michalski. The rationale is that hygroscopic materials develop a sort of memory of the largest fluctuations they have reacted to, in the form of deformations or cracks which can work as a sort of expansion joints. It is derived that the object should be able to react without further damage to following smaller fluctuations. Obviously things are more complicated: fatigue, response time and relaxation time of hygroscopic materials must be considered to improve the validity of this approach (Michalski 2007).
Relaxation time is taken into account in the procedure to determine safe RH ranges, which is the most innovative part of the EN 15757:2010 standard and is described in annex A. Its development can be followed through articles by their proposers (Bratasz, Camuffo & Kozlowski 2007, Camuffo et al. 2009, Bratasz 2010).
The seasonal cycle is obtained from the central monthly moving average for each computed value. In this way it is possible to distinguish seasonal fluctuations from short-term fluctuations by subtracting the Moving Average from the instantaneous value. The lower and upper limits of the target range are then calculated as ±1.5 Standard Deviation of the difference between these two values calculated on the whole monitoring period, corresponding to the 7^{th} and 93^{rd} percentiles in an ideal Gaussian distribution of the values. Further consideration on the EN 15757 standard and its use can be found in the introduction to the second part of the thesis (pp.96-97).

Both the ASHRAE specifications and the EN 15757 in my opinion are very significant since they suggest a link between the conditions to which an object is exposed, i.e. its conservation environment or historical climate, and the potential for climate control within the architectural structure in which objects are exposed. This has important consequences, especially when conservation environments are the result of historic structures, and it will be further discussed in paragraph 3.2.

The debate on environmental standards and conservation is still going on and even these recent proposals for a relaxation in museum standards find their opponents and originate doubts.
Andreas Burmester (2000) has efficiently summarised and discussed the terms of the debate, underlining some uncertainties involved even in recently developed standards.
A proposal from him and others on climate control in museums, based on a progressive quantification of allowable fluctuations depending on time (hourly, daily, weekly, seasonally) can be found in Berchtold et al. (1999).
In the meantime other issues entered the discussion and are gaining growing importance.
Rebeca Alcantara (2002) published for ICCROM *Standards in preventive conservation: meanings and applications* underlining difficulties in applying strict environmental standards in developing countries in tropical zones, due to high costs involved and limited funding of the institutions.
Climate change and consequent needs for energy savings and greenhouse gases reduction gave a new pulse towards a rethinking of the museum environment. Research is thus following a different approach, not necessarily based on those ideal and strict values generally involving high energy consumption and associated costs.
A pioneering research on energy use and climate control in British museums was published in 1994 (Cassar 1994), including an interesting comparative analysis on energy consumption in different institutions (Oreszczyn Mullany NiRiain1994). Energy saving in museums and its impact on containing costs seemed to have boosted the request for a relaxation in standard in the 1990s.
Going back to the Smithsonian, a first comparative estimate of the cost required by close RH control appeared in 1993 and it has been claimed that "*ongoing implementation of the new guidelines in Smithsonian museums resulted in cost savings of $2.7 million in just the second half of 2006 (out of $32 million total energy costs for all of 2006), and $1.5 million in the first quarter of 2007"* (Erhardt, Tumosa, Mecklenburg 2007, p.15). The topic of the costs involved by different climate control strategies has been studied in deep by Artigas (2007).
The need for energy efficiency in museums has recently also met the request for sustainability in the field of conservation, as testified by the growing interest towards the so-called *'green museums'* (Brophy & Wylie 2008, Madan 2010).
A milestone in the research on the impact of climate change on cultural heritage was the European research project *Noah's Ark* which mainly focused on risks for built heritage exposed to outdoor conditions. An atlas of risk maps for European cultural heritage was published (Sabbioni, Brimblecombe, Cassar 2010).
These topics are being further developed in the ongoing European project *Climate for Culture* (Leissner & Kilian 2010): the objective is to couple climate change predictions with building hygrothermal modelling in order to define future risks for collections preserved in historic interiors.

Many recent conferences dealt with the discussion on a new approach to environmental control in museums environments. *Museum Microclimates*, held in Copenaghen in 2007, collected state-of-the-art research in the field of environmental conservation of artworks (Padfield & Borchersen 2007) while the IIC roundtable discussion *Climate change and museum collections* (IIC 2008) focused on the effects of climate change and on the strategies to reduce carbon footprints of

museums. A key event which made it evident how the impetus for more relaxed hygrothermal standards became widely accepted was the initiative of the Bizot group, the International Group of Organizers of Large Scale Exhibitions: in 2008 Nicholas Serota and Mark Jones, respectively Director of the Tate Gallery and of the Victoria & Albert Museum, promoted a re-discussion of the environmental needs of the artworks on loan or exhibition. Another IIC roundtable, organised in 2010 and entitled *The Plus/Minus Dilemma: The Way Forward in Environmental Guidelines* (IIC 2010) discussed this topic.
The PAS 198:2012 standard (BS 2012) can be seen as an answer to these challenges: the aim of this procedural standard is to provide museum professionals with an instrument to evaluate the response of collections to environmental factors and make strategic decisions for their management.
In 2012 as many as two important international conferences were explicitly addressed to the discussion on museum standards: the *Indoor Air Quality 2012* conference hosted the round table *Standards and guidelines – Hindrance or help?* while the Doerner Insititut celebrated its 75 years with the conference *Climate for Collections. Standards and uncertainties*.

What lies between the lines of this paragraph, mainly devoted to the environmental standards for collections, is that if climate control to provide a suitable museum environment is a hard task within a built-on-purpose building, this is often even harder, if not impossible, in historic structures, such as houses, dwellings or buildings which were built with traditional technologies and not designed to work with modern air conditioning or other modern climate control installations.
The problems caused by a close climate control in such buildings will be discussed in the following paragraph.

3.2 Environmental standards and historic buildings: problems, contradictions and new perspectives

The installation of climate control in historic buildings is a specific topic partially overlapping what has been discussed in previous chapters. It has been shown in paragraph 1.3 how climate control devices could be seen as arguable, especially in historic interiors, but in the end considered somehow necessary. Authors discussing conservation environments in the post-war period, like Plenderleith and Philppot (1960), underlined that full air conditioning was not possible everywhere but portable devices could be a good alternative in historic houses and older museums (par. 2.2). In paragraph 2.3 we saw that Thomson recognised the problem and that his more relaxed class 2 was considered good for *“the most important historic houses and churches”* (1986, p. 268).

Thomson was also among those discussing this issue in the 1980 IIC congress held in Vienna, *Conservation within historic buildings*. The introduction to the proceedings of the conference expresses very well the general terms of the question: “*There has been considerable development within the range of castles, monasteries, churches and historic houses, all with their woodwork, stone monuments, wall paintings and hangings, and art objects, subject to the consequences of varied and often extreme climatic conditions within buildings that are not always in good repair and where conditions seldom approach those of a well-organized museum. (…) Historic structures with their relevant contents exist in climates which range from the gentle coastal conditions of England to the harsh regime of Canada with extremes from -63°C to +45°C. The simple or complex heating of buildings (dependent in some cases on intermittent use), ventilation (often ingenious and sophisticated in old buildings), wind, wall insulation, the size and shape of buildings, and the condition of the foundations and of surrounding natural features, the siting and use of windows, all combine to form a complex variable, determining temperatures and relative humidities and their effect on organic and inorganic materials within. Intervention can deleteriously upset an established equilibrium unless it is preceded by careful monitoring over at least an annual climate period ”* (Bromelle Thomson & Smith 1980).
A look at the papers from the participants reveals heterogeneous opinions. All authors agreed on the importance of assessing existing environmental conditions through monitoring and analysis of the decaying processes, as in the paper by Accardo and Camuffo (1980); Beck and Koller (1980) provided a description of historic heating systems and a compared assessment of the effects of different heating systems installed in Austrian churches. Case studies with a careful introduction of modern climate control systems were presented by Briggs (1980), while Kadijsky (1980, p.30) stated that “*full climate control can only be achieved with the introduction of air-conditioning*”. On the other hand Feilden (1980) and Eames (1980) seemed to be more confident in relying on environmental performances of old buildings and more doubtful on the opportunity and feasibility of having a strict environmental control in historic buildings: *“It would be far better to advocate what could be physically and financially achieved (…). I suggest that we should not spend time trying to achieve an ideal stable environment for those items (…) which in all probability have resisted the ravages of time in almost identical circumstances, survived reasonably well and will probably continue to do so. (…) what I am suggesting is that in the context of conservation within historic structures we climb down from our ivory towers and offer the sort of advice and assistance which is capable of being acted upon”* (Eames 1980, pp. 32-33).

This last consideration was at the root of two linked symposia entitled *Museums in Historic Buildings*, which were promoted by APT and AIC in Montreal in 1990 and in New Orleans in 1991 and focused on conflicting needs between historic buildings and the collections they housed: “*the*

potential for conflict exists between the museum's need to preserve and interpret its collections and the preservation needs of historic structures" (Taylor 1996)
One of the reasons for major concern was the consequences of the implementation of climate control since, as already largely observed, the attempt to have museum standards in buildings which were not specifically designed to achieve and maintain those performance generally caused damage to the architectural structures and poor environmental conditions anyway.
The decay caused by condensation, either superficial or interstitial in windows and outer walls, when humidification was introduced, the difficult control of local gradients and microclimates, the problems caused by leaky envelopes, were among the most typical troubles encountered by conservators and administrators of historic houses.
The discussions which took place at these meetings *"confirmed the value of conservation approaches based on flexible, relevant principles rather than on fixed standards – whether for the benefit of object or structure*" (Stovel 1996, p.58). Stress on a teamwork approach and on decision-making processes was implied and solutions inevitably had to take the form of compromise which, as observed by Himmelstein and Appelbaum (1996), if well-crafted "*it is the optimal solution to a problem*" and "*incorporates the best of all points of view by taking advantage of the specifics of a particular situation*".
The result of *Museums in Historic Buildings* conferences was the *New Orleans Charter for the Joint Preservation of Historic Structures and Artifacts*, a document addressing managers rather than professionals and *"intended to provide museum curators and other responsible administrators with a decision-making framework that integrates concern for the collection and the structure*" (Stovel 1996, p.57). Among the other principles enunciated by the chart, the most remarkable ones in my opinion are those establishing that "*the preservation needs of the historic structure and of the artifacts should be defined only after study adequate to serve the foundation for the preservation of both",* that *"measures which promote the preservation of either the historic structure or the artifacts at the expense of the other should not be considered"* and, finally that "*the most appropriate action in a particular case is one which attains the desired goal with the least intervention on the historic structure and the artifacts*" (APT/AIC 1991)

A practical application of those principles was described by Kerschner (1992, p.65): "*On considering environmental improvement for the artifacts housed in 33 buildings at the Shelburne Museum, it quickly became apparent that a traditional climate control system installed in each building was not a practical answer to our climate problems. Few museums have such a number and variety of exhibit buildings. However, many historic house museums face the challenge of integrating a climate control system designed primarily for new construction into a historic building. Problems created by extensive building changes required for installation of ducting and vapor barriers, high capital cost, maintenance and repair of equipment, monitoring the controlled environment, and long-term operating costs tend to discourage all but the most sophisticated and wealthiest museums from improving their environments."*
Environmental requirements of the collections were first evaluated and a relative humidity range of 35% to 60% was considered safe for the majority of collections and potentially attainable. Historic buildings were then carefully monitored and analysed to determine their response to outdoor conditions, their construction characteristics and their hygrothermal properties. They were finally classified on the basis of the level of climate control they could safely support (Conrad 1995).
Finally low impact climate control actions were planned and applied with a constant monitoring of their effect. Good results were shown to be provided by a reduction in winter temperatures and by the installation of humidistatically controlled conservation heating or humidistatically controlled ventilation systems.

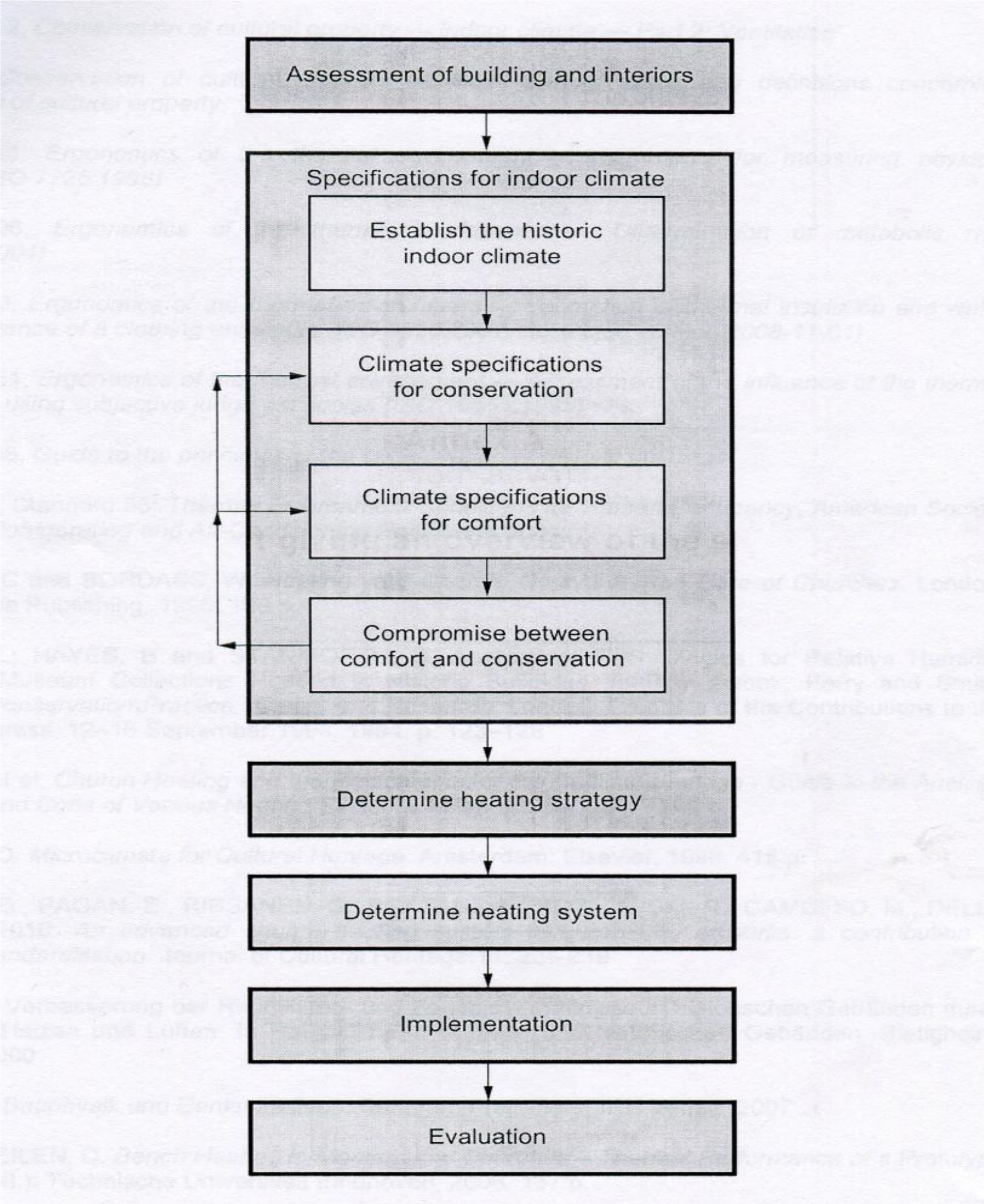

Fig. 3.4 – Flow chart of the decision making process for climate control in churches from EN 15759-1:2011

The success of this effective approach is testified by the inclusion of the building classification system in the ASHRAE handbook chapter 21 (see previous paragraph and fig. 3.3) while other interesting papers dealing with climate control strategies within historic houses and coming to similar conclusions were presented at the Ottawa conference a few years later (Stolow 1994 and Staniforth Hayes & Bullock 1994).

Beyond the topic of collections within historic houses turned into museums, growing interest was paid to the problems related with climate control in historic churches. Here inconveniences are generally caused by the wrong application of heating systems which are installed only for visitors' comfort in buildings where conservation is not always the priority and specialized staff is lacking:
"After having used cold churches for centuries, the habit of heating them has become quite common, often causing more or less evident damage" (Camuffo 2006, p.13).

Seminal research in this field was carried out in Europe, thanks to community research projects like *Friendly-Heating* and *SENSORGAN*. The former dealt with the study of specific heating strategies for churches which could provide human comfort without affecting cultural heritage conservation while the latter aimed at developing sensors and devices for the monitoring of very sensible cultural objects such as pipe organs preserved in churches.
Results and contributions from these projects were summarised in the publication *Church Heating and the Preservation of the Cultural Heritage. Guide to the Analysis of the Pros and Cons of Various Heating Systems*: the book aimed to "*provide scientific support for the choice or the use of heating system to reduce, as much as possible, the negative consequences of heating for a better conservation. The problem is enormous given the quantity, quality, variety and the vulnerability of the artworks present in churches*" (Camuffo 2006, p.13)
Anyway, the most interesting outcome of these researches was probably their contribution on the development of European standardisation.
The relevance of the concept of historical climate and the stress on the effects of acclimatisation suggested in the EN 15757 standard, mainly derived from the observation that many objects were preserved very well even in unheated environments such as churches, despite of hygrothermal conditions that would be supposed to cause extensive damages.
On the other hand, the EN 15759-1:2011 *'Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship'* is a good example of a process-focused standard: instead of giving prescriptive specifications, the document is intended as a guide to help in decision-making processes, as testified by the final flow-chart (fig.3.4).

It must be underlined that, as in the case of the building classification system introduced by Conrad, analytical tools specifically developed for climate assessment within historic buildings have actually influenced the development of standards which are being more and more spread and used. And it is not by chance that these analytical tools have in common the focus on understanding and studying the existing environmental conditions before intervening in historic buildings, rather than applying specifications established a priori for artworks conservation in built-on-purpose museums. Artwork and building needs can be in conflict since, as it has been shown, interventions to obtain fully controlled climate conditions could be very dangerous for the material integrity of an old structure. Nevertheless an effective climate control strategy can be designed if the link between preservation of artworks and analysis of the architectural structure containing them is not ignored.
In the following chapters I will try to show that the analytical study of indoor environments should be included in the complex process of knowledge applied to historic buildings and considered as a fundamental tool not only for the preservation of artworks, but for the preservation of buildings too.
Case studies will show that a historical climate, i.e. a conservation environment within an historic building, is necessarily the result of its constructive characteristics, of its hygrothermal behaviour and of its role in mediating between outdoor and indoor conditions. In this perspective the comparative use of tools derived from research on architecture and construction history, such as geometrical survey, the analysis of the decay of materials and the reconstruction of historical use, can provide priceless information.

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Part 2

The historical climate as a tool for studying and preserving heritage buildings

The different meanings we can attribute to the concept "historical climate" have already been discussed in the Introduction (paragraph 0.2). The second part of the thesis will focus on the application of the different methodological approaches that can be derived by those meanings to case studies. As the title of this section suggests, the aim is not so much to individuate a perfect or universal analytical method, but to show how an integrated application of different approaches, mostly related to the concept of historical climate, can be useful in many complex cases.
The focus will be shifted from the historic development of climate control strategies in conservation environments - mainly in museums - to the analysis of the indoor climate within historic buildings which are nowadays used as museums or to display artworks and collections.
Here different instances have to be considered: not only do suitable hygrothermal conditions have to be provided for preserving collections and for human comfort as well, but this should also be obtained in compliance with conservation needs of the buildings. It has already been shown what a hard task this is, the problems that can occur and some of the tools developed to face them (see paragraph 3.2).

Among other things, the EN15757:2010 standard – '*Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials'* – was chosen to be used as a frame reference, as well as the procedure there described for determining RH target ranges. The standard "*proposes a methodology leading to general specifications to limit climate-induced physical damage of organic hygroscopic materials*" (CEN 2010a, p.4). Therefore, it only deals with one category of materials and one category of decaying mechanisms.
The standard recommends the priority of the historical climate "*to which the objects have become acclimatized for a long time*" (CEN 2010a, p.7). The procedure described in Annex A should be used just in case changes have to be made on the climate control strategy in environments "*that has been proved not to be harmful to the preservation of objects*" (CEN 2010a, p.7) or in case that objects have to be moved into another microclimate.
For all these reasons, the extended use of this procedure as a general assessment tool is quite controversial and questioned by many authors. Nevertheless, this standard was chosen for being used in the assessment of the indoor climate in the two case studies analysed, since it defines a generally agreed procedure, recently approved and explicitly based on the historical climate conditions to which artworks or objects have been exposed.
As a consequence, the procedure suggested by this standard was not applied to cases where the historical indoor climate proved not to be harmful – which sounds quite in conflict with the standard premises – but for comparative assessments of the indoor climates in complex historic buildings with many rooms, some of which may offer better conservation conditions than others.
In both case studies an indoor climate monitoring and assessment was requested by conservators because they observed decay in collections that could be related to environmental factors and poor climate stability in the historic buildings housing the collections.
Their objective was to understand if improvements in the climate control could be made but, at the same time, it was clear that it would have been almost impossible to have the indoor climate of the buildings matching traditional museum standards. The main task was to develop climate control strategies in order to preserve the buildings and limit risk for the collections.
In this perspective the EN 15757:2010 procedure was used to make a general risk assessment mainly focused on the relation between the observed mechanical damage and the indoor climate stability provided by historic buildings. The standard provides a quick and rather simple method to identify the most risky fluctuations and distinguish them from natural seasonal variations. In this way it is possible not only to locate periods and events in which these fluctuations are

concentrated, but also a parameter is provided for the comparison between the indoor climates of several rooms or parts of the building in order to understand which ones are likely to be the most dangerous and less appropriate areas for displaying artworks.
A further aim of this research was thus to understand whether the EN 15757:2010 could be coupled and integrated with other analytical methods – and if so how – and how to use this integrated approach as a tool for studying and analysing the hygrothermal performances of historic buildings and for directing potential future interventions where they are more needed and effective, when full air conditioning is not a possible or desirable option.

The two historic buildings here presented as case studies are Villa Reale in Milan, Italy, and Skokloster Castle in Sweden.
They are both very peculiar and interesting historic buildings, sharing many features in common but, at the same time, offering the opportunity to analyse the consequences of different conditions.
First of all they were not built for the purpose of hosting museums but are nowadays being used for displaying valuable and heterogeneous collections. This change in use, which is something quite usual in Europe, resulted in some difficulties, related to the peculiar needs of a museum which may be in conflict with the preservation of the buildings.
Secondly, the two case studies allow a comparison between two opposite climate control strategies, either active or passive, applied to historic buildings in different climatic zones, making possible an assessment of the behaviour of the historical structures in relation to these strategies.
In Villa Reale we have some rooms heated by an old air heating system, still in operation, and some others by radiators; in Skokloster Castle the old systems for heating the rooms, fireplaces and stoves, are never used.
As a consequence, the analyses performed at Villa Reale focused on the influence of the historic heating system on the indoor climate, while those performed at Skokloster Castel aimed to assess more specifically the performance of the building envelope, especially in relation to air exchange.
The two buildings have a further feature in common, which make them very appropriate for this study: since they were turned into museums (and even before) indoor climate has always been controlled more or less in the same way, so that in both cases it could be claimed that the building and the collections have been sharing the same climate control strategy for many decades.
In other words, it would have been hard to find case studies where the term “historic” could be used more appropriately to describe the resulted conservation environments.
An integrated and multidisciplinary approach to conservation environments within historic buildings was thus developed: not only the analysis of present conditions is involved, but also the study of those elements, such as the historic structures and the historic heating systems, which can help us in understanding the past climate control strategies (fig. 4.1).

The final chapter of the second part will deal with the outcomes of the research in building conservation practice.
Not only will the findings derived from the case studies be discussed in a more general context, trying to figure out how they could be used and applied to the study of historic buildings, but also will the topics presented in the first part be drawn on. The aim is to show that ‘learning from the past’ is more than a hackneyed set phrase, but a fruitful attitude: even in indoor climate studies, it can be used to gather knowledge on forgotten practices and tools which can be efficiently used still today.
At the same time, the recent developments in research on indoor climate control for conservation may have significant consequences on how interventions on historic environments have to be made. The introduction of the concept of historical climate leads to a shift from the adoption of

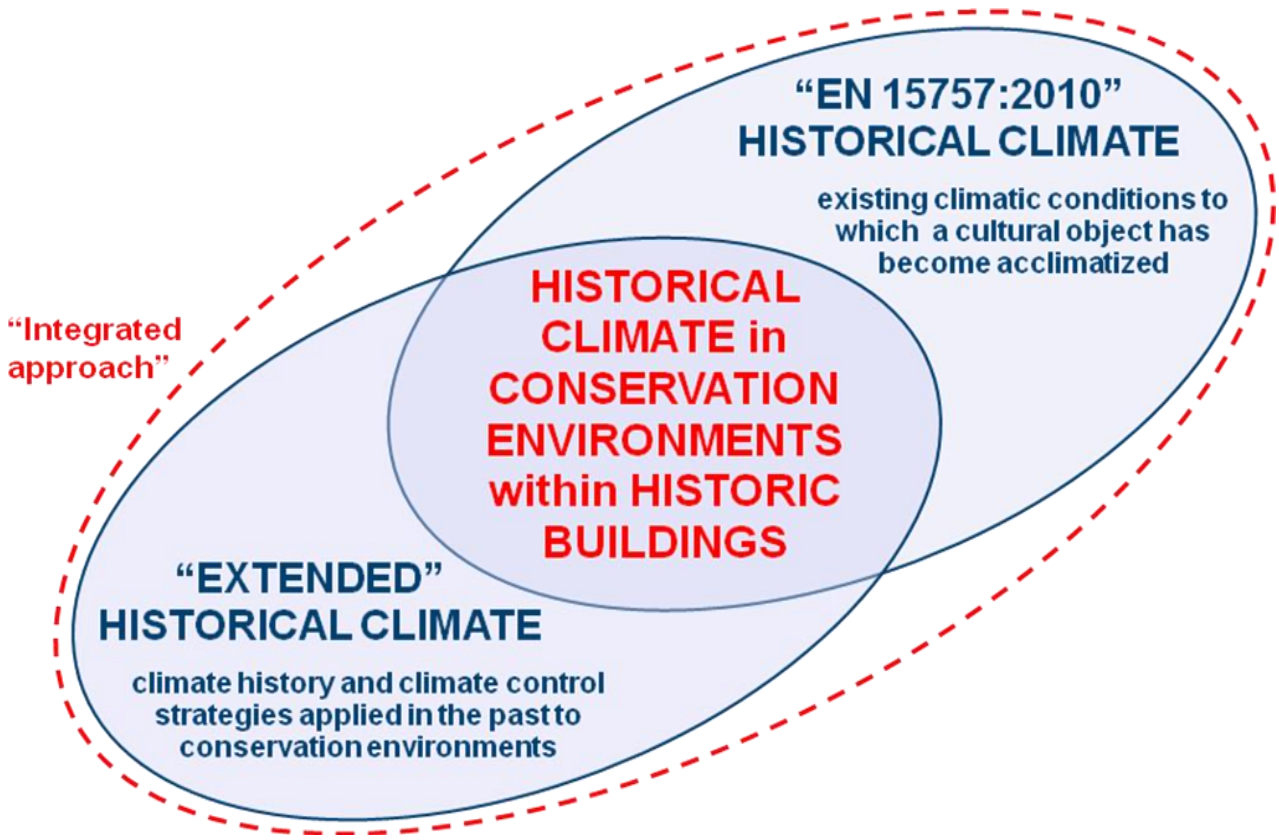


Fig. 4.1 – Scheme representing the integrated approach proposed as a tool for studying the historical climate in conservation environments within historic buildings

ideal conservation values to the analysis of existing conditions and, as a consequence, to the study of the interactions between the building and the environment.
The important challenges we are already facing in building conservation practice, like those related to sustainability and to energy-efficient management of historic buildings, cannot stand isolated anymore, independent of a deep knowledge of the specific hygrothermal behaviour of historic structures and of the consequent development of innovative analytical methods for studying it.

Finally, it must be underlined that these studies have been carried out by research teams of which the author was a member.
Villa Reale has been studied by the research team of the Laboratorio di Analisi e Diagnostica del Costruito of Politecnico di Milano. I was involved from the beginning in the research project, founded by Fondazione Cariplo, and I took part to all its phases but my specific task was the final analysis of gathered data.
Skokloster castle has been studied by the Conservation Department of Gotland University. The building is a case study in the Swedish national research project on energy efficiency in historic buildings called S*para och bevara*, supported by the Swedish Energy Agency, and in the European research project *Climate for culture.* Here my task was the assessment of the influence of air exchange in the stability of the indoor climate of the castle and I completed it during a stage at Gotland University in 2011.

Chapter 4
The assessment of historical climates: case studies

4.1 The influence of an historic heating system on a museum climate: Villa Reale in Milan, Italy

Fig. 4.2 – Villa Reale, Milan. The main façade viewed from the garden

4.1.1 Method and approach

Villa Reale is a late 18th century building, nowadays housing the Gallery of Modern Art of Milan (GAM). The Villa has a three-storey main body and two two-storey side wings. The north side is characterized by a central court facing the street, while there is an English landscape garden in front of the south façade. In 1921 the Villa was turned into a museum and is nowadays housing a modern-art collection consisting of paintings, mainly on canvas, and sculptures in marble, bronze, gypsum and wax.

Climate control in the galleries is still based on old heating systems: radiators are installed in the wings while in the main body an old air heating system still supplies the galleries with non-filtered air at uncontrolled values of temperature and relative humidity, causing conservation problems for the artworks. A recent incorrect retrofitting of the services has even worsened the situation.

Cracking, flaking and detachments of the paint layer were observed on some paintings of the 19th and early 20th centuries and conservators started to worry about the material conservation of the collections, assuming a potential relationship between the decay of the artworks and poor indoor climate. Moreover, the environmental conditions, particularly in summer, are generally considered not comfortable by visitors and museum attendants.

Nevertheless, any potential intervention should be characterised by the lowest impact on the existing building and on the old air-heating system, which should be considered a rare material evidence of historical technology and something that have to be preserved too.

Given the complexity of the situation, it was clear that it would be almost impossible to guarantee an environment in compliance with traditional hygrothermal specifications for Italian museums, e.g those suggested by the UNI 10829:1999 (UNI 1999) and by the D.M. 238 law of 2001 (MiBAC

2001). A specific research project was thus developed by Politecnico di Milano in collaboration with Comune di Milano (the city administration owning the building and the collections) and the museum staff.
The research was mainly focused on obtaining guidelines for a possible retrofitting of the climate control systems and for a change in the climate control strategy. These should be oriented to improve indoor climate conditions in relation to the comfort of visitors and the conservation of artworks, trying at the same time to limit negative consequences on building conservation and to obtain an energy efficient system.
In our minds, the focus had to be shifted from the implementation of “ideal” indoor climate targets to deeper knowledge and evaluation of the existing conditions and of the building features. In this perspective the historical climate in Villa Reale presented a rare opportunity to apply the integrated approach to indoor climate analysis described in the previous paragraph.
The lack of reliable past monitoring data and the modifications occurred to the museum throughout the time make impossible to state that present conditions correspond exactly to past conditions. At the same time the quite frequent changes in the collection and in the displaying of artworks do not allow to establish a direct correlation between the conditions we can survey today in the building and the decay occurred to the collections in the past. Nevertheless, it could be claimed that basically the same heating systems have been running since the foundation of the museum and thus that the collections have been exposed to similar conditions for about 90 years (even though the WWII period should be excluded). Furthermore it was possible to study in situ the complex interactions between an old air heating system and the artworks. The collected information could even be used to improve our knowledge on the conditions to which collections were exposed in other old museums equipped with similar heating systems in the past.
In a broader sense, this case study could also make possible a sort of ‘applied historic research’ which, starting from the analysis of the hygrothermal behaviour of a 19th century dwelling and its historic services, could give useful indications today for developing low impact and energy efficient mitigation strategies for historic buildings.

The research was characterised by a multidisciplinary approach, involving analytical tools and research methods derived by different scientific fields to better understand the climatic behaviour of the building, even in its historical evolution, and to give a quantitative definition to problems caused by climate conditions. The method has been described in Del Curto et al. (2011)
Three main actions were planned:

• <u>Study of the construction history.</u>
Research focused on the many different ways the building has been used during its history, on the spread of central heating systems during the 18th and the 19th centuries and on the installation of these comfort features in such high-class dwellings. This part of the research was mainly carried out through bibliographic and archive research and was integrated with other tools, such as a geometric survey of the building and endoscopic inspections of the air ducts.

• <u>Indoor climate analysis.</u>
The indoor environment was analysed focusing on the connection among building envelope, museum activities and heating systems. Two levels of analysis were thus required: T and RH were monitored in continuum to detect indoor climate variations; some rooms were also analysed by micro-mapping performed at different moments for a detailed description of the main parts of the building.

Fig. 4.3 – Thermography is used to analyse the effects of the historical heating system in winter and summer.

• <u>Risk assessment for collections</u>
Future interventions on the building should be strictly linked to the analysis of the decay mechanisms currently affecting paintings and sculptures. Data gathered from the indoor climate analysis were used to identify and describe climate-induced risk factors.

The author was specifically involved in the second and third action, of which method and results will therefore be more extensively presented. Nevertheless, aspects related to the first action will be summarised in paragraph 4.1.2.

As above mentioned, two steps were planned for the campaign.
Starting in the Autumn of 2009 data on hygrothermal conditions were gathered in situ through portable instruments, in different moments and in specific conditions. Data were then interpreted to detect some relevant areas in which to perform continuous monitoring of the same parameters. This procedure allows an accurate positioning for the loggers for the permanent survey and it was also regularly repeated once the monitoring in continuum started, to obtain a periodical comparison of the results.
Two methods for measuring in situ were mainly used: mapping and thermography.
Mapping was performed through a digital psychrometer composed of two coupled thermometers, measuring dry-bulb and wet-bulb air temperature, and of a fan driving air to them. Spot-measurements were performed along horizontal sections of selected rooms and along the main vertical cross sections of the building, following an ideal grid of about 1.5 x 1.5 m. Data were then processed by linear interpolation in order to obtain isoline maps showing the spatial distribution of temperature, relative humidity and mixing ratio. This method, in use since the 1980s (Camuffo 1983), is extensively described in Camuffo 1998 (pp 31-41) and was adopted in the UNI 10829:1999 standard (UNI 1999).
Infrared thermography was used not only for a general survey of surface temperatures of the inner walls (CEN 2010b, p.10) but also for evaluating the differential thermal behaviour of the building and of the artworks' materials through qualitative and quantitative information and for localising risky zones.

Results obtained from these two methods in the same room can also be compared. In this way the distribution of hygrothermal parameters of the air can possibly be related with surface temperatures' distribution so that heat and moisture exchanges can be assessed.
Thermal imaging gave good results also in the detection of the heating ducts cut into the walls. In this case it was coupled with an endoscopic inspection to measure the dimension of the ducts and assess their internal conditions.

It was possible to install a limited number of sensors for continuous monitoring and their positioning had to be carefully studied to optimise the data-gathering.
The attempt was to plan the dataset according to the preliminary results from mapping and thermography so that the most risky zones could be monitored but, at the same time, the average environmental conditions could be surveyed too, providing useful information on the building general behaviour. Other factors were thus considered in the selection of the rooms, such as their orientation and their position within the building.
Fifteen wireless WiSensys WS-DLTc sensors[1], one of which is positioned outdoors, register the values of T and RH with a sampling interval of 15 minutes. Data are collected into to two base stations and then periodically downloaded and analysed.
Since considerable convective flows and gradients were detected inside the rooms through mapping, it was decided that sensors had to be exposed to environmental conditions which had to be the most possible similar to those affecting the delicate paintings on canvas. As a result sensors were positioned close to walls at constant height (about 2 metres), trying to exclude special microclimates (e.g. corners) or materials with specific thermal properties (e.g. wooden door frames).
Continuous monitoring of air temperature and relative humidity has been running since November 2010. Results presented in the next paragraphs are mainly related to a 13-months period, from 21/06/2011 to 21/07/2012, to meet the indications of the EN15757:2010 procedure for the determination of the RH targets.
Here this procedure has been used for a comparative assessment of the indoor climate stability in a complex building with many rooms: it has been applied to an unheated storage which was indicated by the conservator as a good conservation environment and, at the same time, to exhibition rooms where conservation problems that could be ascribed to RH variations were noticed.
The trends in the different rooms were then compared: given that the storage did not present out-of-range fluctuations, while the other rooms did (fig.4.9), it was implied that out-of-range fluctuations could be considered a potential indicator of increased risk. Their magnitude, frequency and distribution in different rooms was thus analysed and weekly trends of different rooms were plotted to better understand which factors were causing risky conditions (fig.4.10 and 4.11).
On the other hand, also the ASHRAE specifications for museums (see paragraph 3.1) were used for establishing a general RH target range for the whole building: class C, i.e. 25-75% RH year-round, was considered a level of climate control which should be reasonably achieved within a building like Villa Reale.

[1] Characteristics of the sensors.
Operating limits -20°C to +80°C.
Measurement range: 10% to 95%RH non-condensing; -20°C to +80°C.
Measurement accuracy: ±3%RH from 20% to 80%RH, ±5%RH otherwise; ±0.4°C @ 25°C, ±1°C from 0°C to +50°C, ±2°C from -20°C to +80°C.
Measurement resolution: 0.1%RH, 0.1°C.
Long term stability Drift: < 0.5%RH per year.

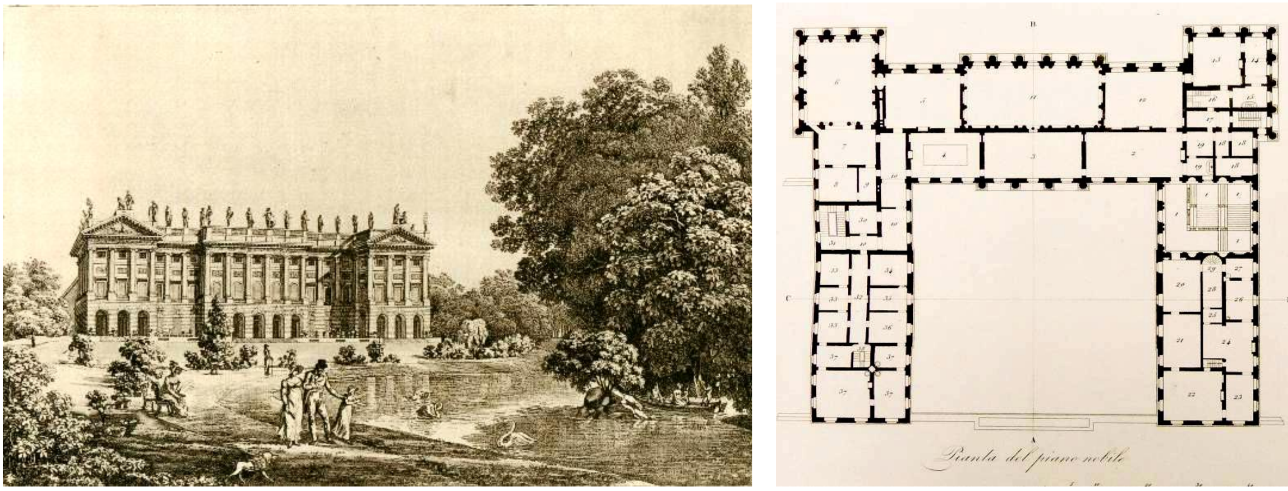


Fig 4.4 – View of Villa Reale from the Garden in an old engraving; Plan of the first floor of the Villa in 1844

4.1.2 Many histories for one museum environment

The Gallery of Modern Art of Milan (GAM), housed in Villa Reale, is the result of the intersection and the final confluence of many paths.

We have to consider the history of the building, including all the people who designed, lived or worked in the villa and their actions and interventions on it. At the same time we cannot forget the history of the collections: how they originated, how they have enlarged and how they were preserved until today.

At the Villa there is also a third significant history, which is of particular interest for this research: the history of the climate control devices installed within the building throughout its history and, as a consequence, the indoor climate history since it was turned into a museum.

Many works have studied the history of the building and of the collection (Rosa 1961, Bascapè, Celona & Bassi 1986, Fratelli 2004, Mazzocca 2007): they will be quickly summarized here, mainly focusing on the building construction history. On the other hand, I owe the reconstruction of the sequence of the heating systems installed at Villa Reale to the master thesis of Emanuela Villa (2008) and to the studies carried out by Carlo Manfredi.

The first construction phase of the building went on between 1790 and 1796. The Villa was designed by the architect Leopoldo Pollack for Earl Ludovico Barbiano di Belgiojoso, who was retiring at the end of his long career as an officer and diplomat for the Habsburg family in Sweden, England and the Netherlands.

It is likely that Earl Belgiojoso, due to the long periods he spent abroad, was well aware of the most recent trends in the design of European upper-class dwellings, which were influenced by the criteria of distribution as they were defined during the 18th century, particularly in French treatises.

His requests probably met Pollack's interests and it is not by chance that references to the model of the Maisons de Plaisance, proposed in his popoular work by Jacques-François Blondel (1737-38), have been noticed

The building, at the time known as Villa Belgiojoso, had a state apartment, reception salons, enfilades in double apartments overlooking the garden and rich technical facilities, including spacious kitchens and modern hygienic devices. Service areas were separated from living areas, through corridors and secret staircases. The main halls and rooms of the buildings face the garden and are exposed to the south and west. This would suggest that the orientation of the building was probably originally intended for exploiting the solar radiation in winter: at the time it was a common

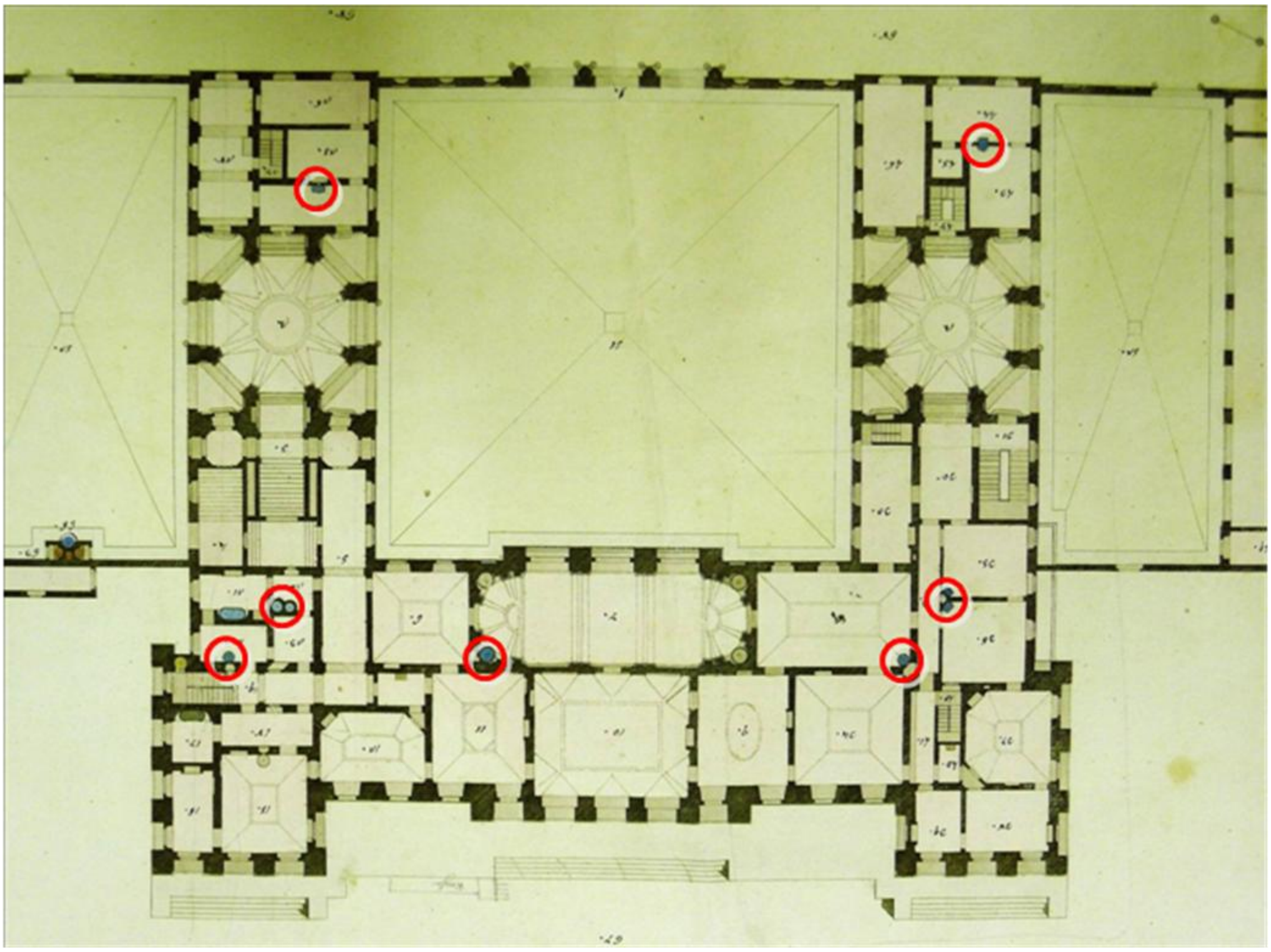


Fig 4.5 – Original plan of the ground floor of the Villa. Some of the stoves (highlighted) were designed to be charged by servants from corridors.

habit for Milanese highest classes to reside in the city in winter and to move in countryside villas during the warm season.

The satisfactory results of Pollack's design were acknowledged at the time as testified by the words of Margherita Sparapani Gentili, a Roman noblewoman visiting the Villa in 1794 (quoted in Bascapè, Celona, Bassi 1986). Even if the building interiors were still uncompleted, she admired the fine architecture of the building and the charming English landscape garden. She also described the stucco decorations of vaults and English wallpapers on the first floor and she was struck by the building services and by the elegant and sophisticated toilets, equipped with running water.

Documents suggest that in this phase the building was heated by different systems. Drawings show that large tile or masonry stoves of the Austrian model, that could be fed by servants from the corridors, were placed in the apartments (fig. 4.5). Other rooms had fireplaces, which could also contribute to improve the extraction of foul air through the chimneys. Portable iron stoves could be installed to integrate and uniform the heat distribution and were also used in auxiliary spaces.

In the troubled years until the birth of the Kingdom of Italy in 1861 the property of the Villa changed repeatedly. In 1803, after the death of Ludovico Belgiojoso, it was purchased by Francesco Melzi d'Eril, vicepresident of the Napoleonic Italian Republic, and given as a gift to Napoleon. During the French domination, Eugène de Beauharnais, Viceroy of the Kingdom of Italy, promoted the decoration of the first floor in Neoclassical style, with the contribution of the painter Andrea Appiani.

Fig. 4.6 – Meissner ovens in the underground level of the Villa before the 2002/06 interventions

During the European Restoration, the Villa kept being used as a state residence by the Habsburgs family and their governors. After the Five Days of Milan in 1848 and the First Italian War of Independence, the Austrians were back once again and Marshal Radetsky lived here.
It seems that the climate control strategy didn’t change so much in those troubled years: a very accurate archive research on budgets, estimates and bills has documented the maintenance activities on the heating systems, in particular since the 1810s (Villa 2008)
After the Second Independence War of Italy and the proclamation of Vittorio Emanuele II as King of Italy in 1861, the building became part of the royal properties of the House of Savoy.
The first evidence of the installation of a central heating system in the Villa dates back to the following years but it is not excluded that some systems of this kind were already present. In 1862 some rooms were refurbished for the visit of the Prince of Piedmont (the future King Umberto I) and the installation of two large brick ovens in the basement is documented. They heated nine rooms on the ground floor and seven more on the upper floor.
They were generally known as “caloriphere” or “Meissner ovens” since they were encoded by Meissner in the three 1820s editions of his treatise published for the first time in Vienna in 1821 (Meissner 1821). The system consisted of iron stoves with an external brick covering called *Mantel*, where cold air was warmed. Hot air got lighter and generated a convective flow through ducts towards the upper rooms (fig.4.6).
Even though similar solutions were already known in ancient times, this type of heating and ventilation system spread in continental Europe during the 19th century as growing attention was paid to comfort and hygienic conditions both in public buildings and in private houses (Manfredi 2008).
In Lombardy air heating systems found an early application in the Royal Palace in Milan in the 18th century (Forni 1997) and were used in some private dwellings designed by the architect Simone

Fig. 4.7 – Finned tubes inside the ovens and a radiator in the exhibition rooms.

Cantoni at the beginning of the 19th century (Manfredi 2008b) but the most probable reference for the installations in Villa Reale could probably be the third edition of the Traité de la Chaleur by Péclet (1860-61).
The final layout of the system at the Villa was composed of six large masonry ovens, five of which still exist. They were equipped with iron stoves, which originally burned wood, then coal. Other components of the systems were the underground horizontal ducts, drawing outdoor air from the garden to the ovens, and the vertical ducts cut into the thickness of the walls for air distribution.
In 1912 hot water radiators were installed in the lateral wings of the Villa, not served by the air heating system. It is likely that during this refurbishment the iron stoves inside the ovens were substituted by water-supplied heating batteries composed of finned tubes (fig. 4.7).

In 1920 the property of the Villa passed from the Royal House to Milan municipality. It was then decided to turn it into an exhibition space to host the civic collections of modern art.
The origins of the collection dated back to 1861, when the private collection left by the sculptor Pompeo Marchesi was given to the city (Fratelli 2012). This donation was followed by many others, becoming the core of the civic collection of modern art that since 1877 was displayed in a hall in the public gardens. In 1902 these artworks were merged with the collection of nineteenth century art owned by the Pinacoteca di Brera and the Brera Art Academy, known as Brera Modern Art Gallery (Marelli 2012). The new collection, exposed in the Sforza Castle, was named Civic Gallery of Modern Art (Forcella 1903).In 1921 the building and the collection started their shared history, as Villa Reale became the seat of the Gallery of Modern Art.
The GAM collection survived quite well the second world war, since artworks were evacuated to several repositories all around Italy (Salsi 2009). On the contrary the building was quite heavily damaged by air raids in 1943 and reconstructed after the war trying to recover the original Neoclassical environment (Rosa 1950). The old stables of the Villa, completely torn down, were reconstructed between 1951 and 1954 in modern style by the architect Ignazio Gardella as a Pavillion for Contemporary Art (PAC).
Three years later the same architect was commissioned of the refurbishment of the third floor, which, curiously, until 1931 housed a Didactic Nautical Museum (Manfredi & Colombo 2012) . The newly opened rooms were to display an heterogeneous collection of artworks, donated by the Grassi family: mainly modern paintings but also antique artworks, Asian sculptures and Persian carpets (Nicodemi 1962). Gardella designed modern style interiors, a sequence of elegant rooms

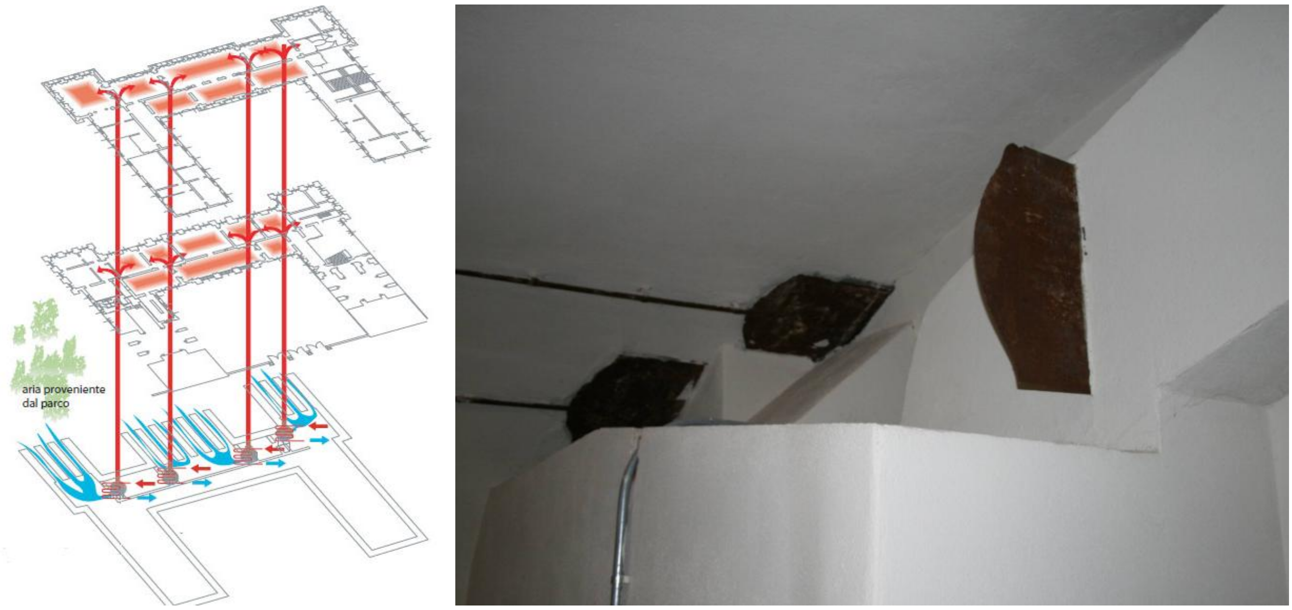


Fig. 4.8 – Scheme of the heating system (left) and tools for controlling the air flow into the ducts which are now blocked by the plaster layer (right).

connected to the rest of the museum by a monumental elliptical staircase. For climate control, Gardella opted for radiators placed under the small windows.
Already in 1936, in Villa Borletti, a private dwelling with pieces of art, he made a different choice and preferred to install air conditioning to have air heated and humidified and make it comfortable and at the same time suitable for the preservation of the paintings (Gardella 1936). His choice for extending and replicating the heating system already installed in the Villa was probably suggested by practical reasons and maybe budget limitations.
Between 1974 and 1985 we found a series of interventions by another modernist architecture firm, Albini-Helg-Piva: they designed new display cases for Medardo Rosso's wax sculptures in a corridor on the first floor (Helg & Piva 1978); they refurbished the rooms in the south-east corner of the ground floor to host another relevant donation from a private collector, the Vismara collection; they refurbished the rooms on the first floor of the north-west wing for the Marino Marini Museum, a collection of artworks given by the artist himself (Meneguzzo 1997). Once again modern design entered the Villa and once again the architects chose not to change the climate control strategy: the old radiators were left almost untouched.

The last intervention on the Villa was the general refurbishment which took place from 2002 to 2006 (Fratelli 2004, 2010a). The work, quite invasive, included also the underground level and the air heating system were involved. All the small openings giving access to the heating batteries, except one, were blocked by the new floors, so that it is not possible to inspect them anymore.
The old tools for controlling the air flow – some sorts of huge gate valves that could be controlled by hand to close the air ducts – were blocked by the new plaster layer (fig. 4.8).
These superficial and incorrect actions have probably worsened the environmental conditions of the galleries, since regulation of the heating system is now very limited. Since hot water is supplied to both the systems (air heating and radiators) by the same pipe circuit, nothing but the intake water temperature can be centrally adjusted and controlled.
Adjustment is only allowed locally and manually by some flaps for the air vents and by control valves for radiators.

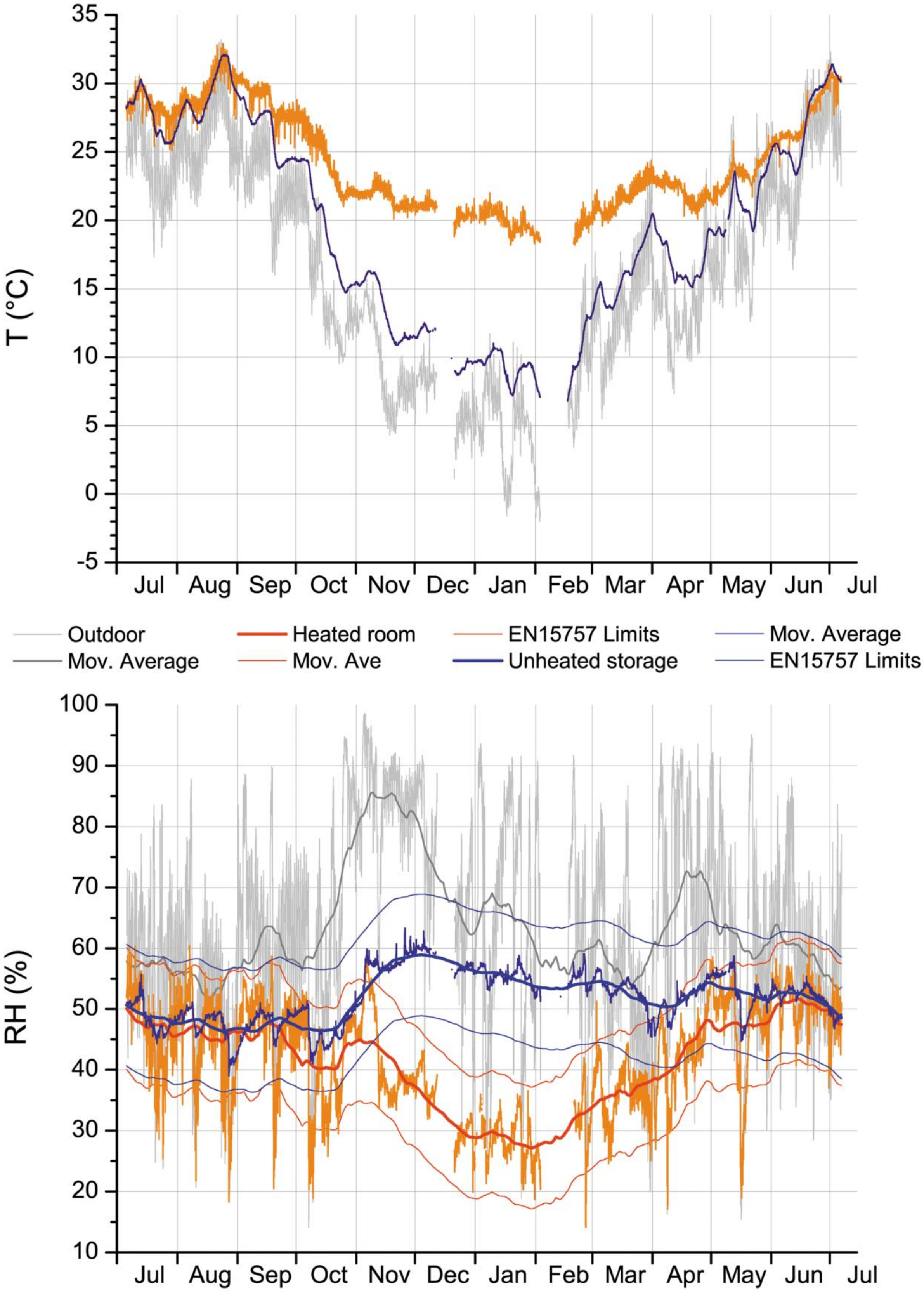


Fig. 4.9 – Yearly trends of T and RH in Room VII (orange), in the storage (blue) and outdoors (light grey)

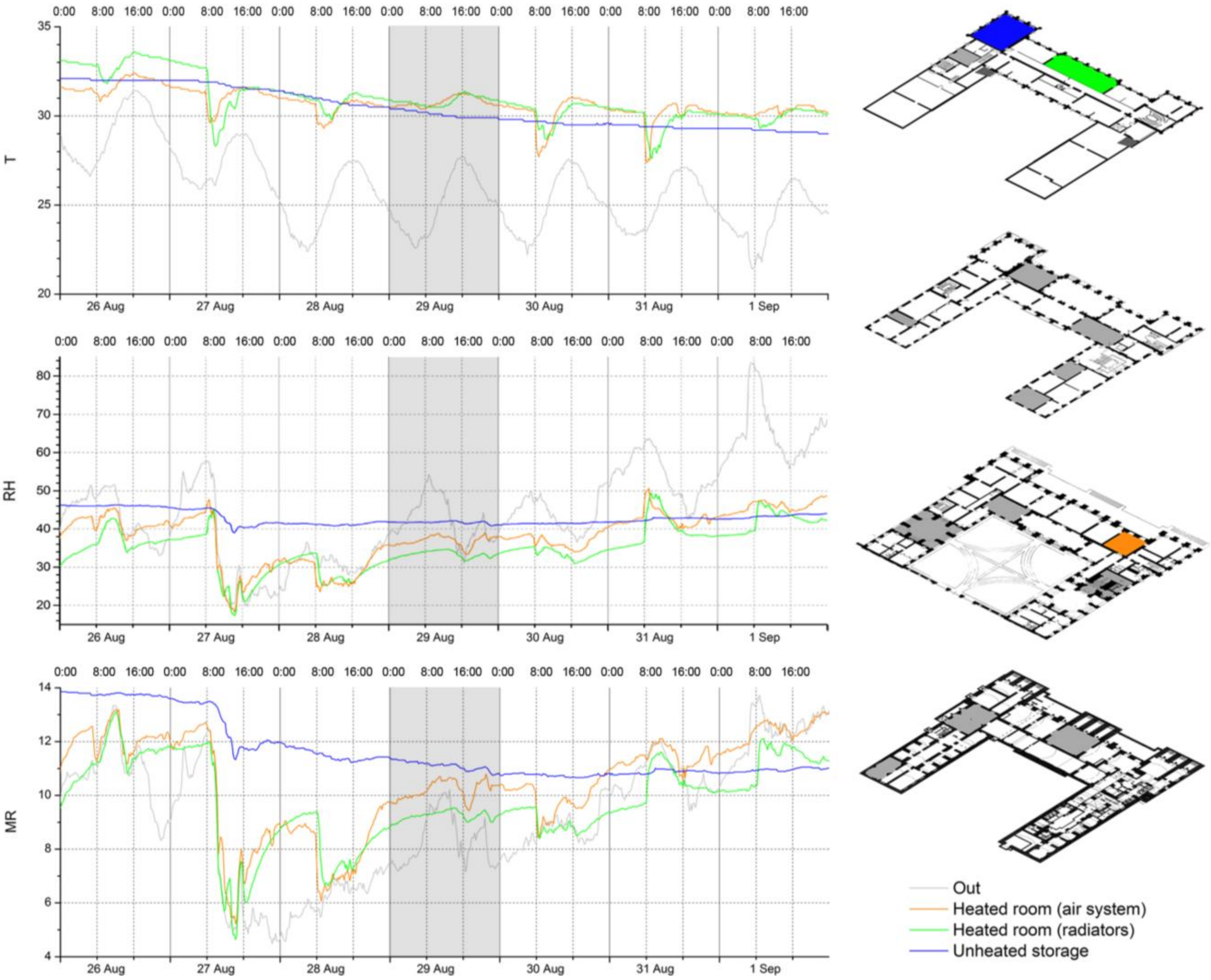


Fig. 4.10 – Weekly trends in summer in Room VII (orange), Room IV (green), and in the storage (blue). Outdoor trends are in grey while the light grey band highlights the closing day.

4.1.3 Discussion of the results obtained

Villa Reale has many rooms, each one characterized by its own indoor climate: underground storages, exhibition rooms (some heated by the air system, some others by radiators), workplaces for the museum staff, storages in the attics and a number of rooms currently not used and waiting for a refurbishment.

The heating system strongly influences the indoor climate of the Villa. This is clear when comparing the yearly trends of T and RH (fig.4.9) which have been monitored in an exhibition room at the ground floor, where the old air system works (orange line) and in an unheated storage in the attic (blue line).

The heating system was on since mid-October to the end of April. As a consequence, in wintertime the temperature in the exhibition room is much higher than in the storage where values are closer to outdoor ones. RH decreases to around 30% with drops under 20% in the coldest days, as the heating system is not equipped with humidification.

Risk for hygroscopic materials are favoured by such low values and by sudden variations. These have been analyzed following the EN 15757-2010 standard as described in paragraph 4.1.1.

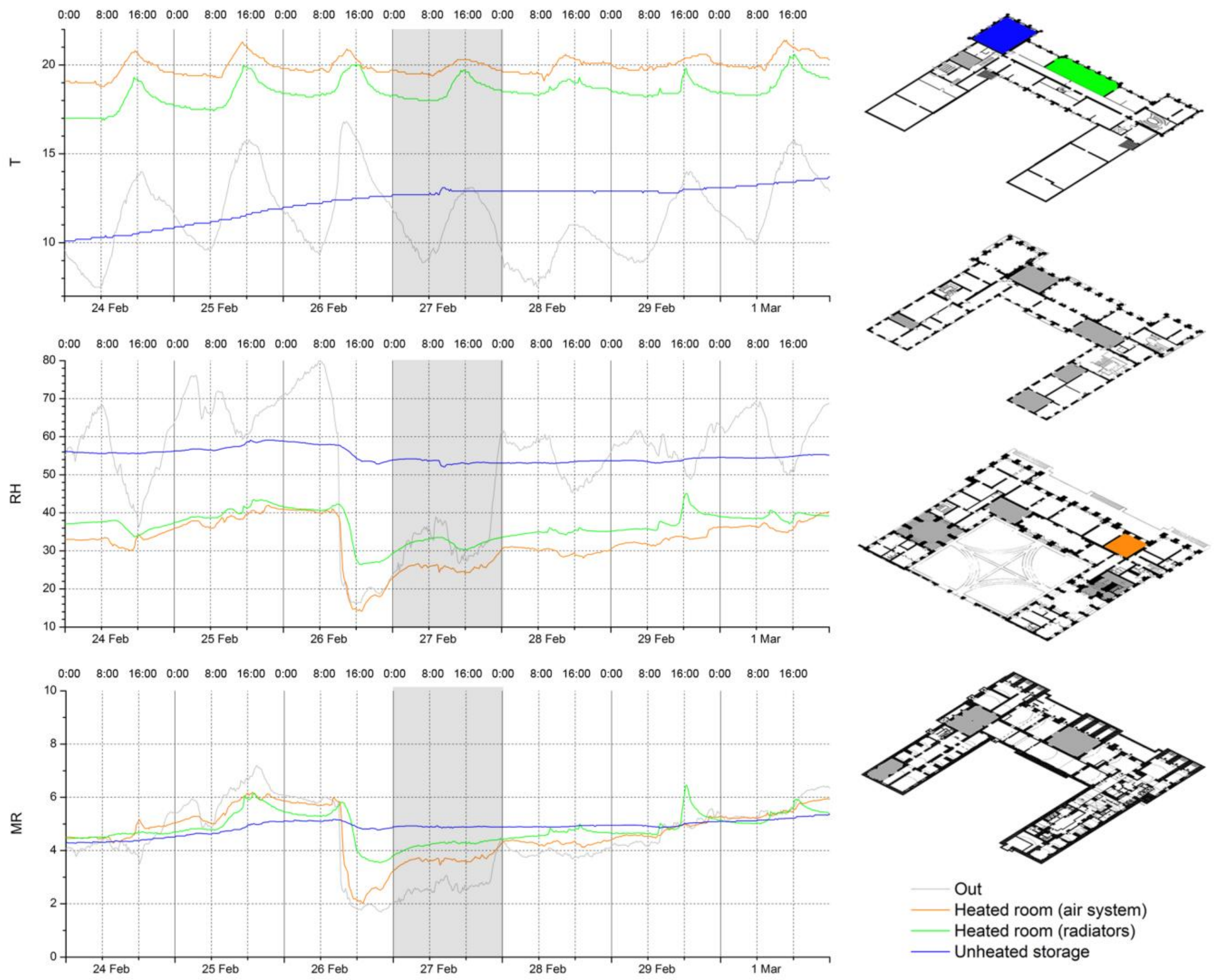


Fig. 4.11 – Weekly trends in winter in Room VII (orange), Room IV (green), and in the storage (blue). Outdoor trends are in grey while the light grey band highlights the closing day.

It seems as if the heating system has a stabilising effect on the variations in the exhibition room as shown by the comparison between winter and summer fluctuations. On the other hand RH and T are clearly much more stable in the unheated storage all year long.

When RH out-of-range variations were observed, the trends were further analysed looking at weekly and daily trends to understand the environmental behaviour of the building in the shorter period. Weekly graphs in summer (August 26th – September 1st) and winter (February 24th – March 1st), were thus used to compare the indoor climate dynamics of three rooms (fig. 4.10 and 4.11): an unheated storage (blue line), an exhibition room heated by the air system (orange line) and an exhibition room heated by radiators (green line).
The unheated storage shows constant values both in winter and in summer. Even though the wide wall surface is directly exposed to the outdoor climate (as this room is in the attic, at the corner of the building), this storage seems to smooth the outdoor fluctuations more efficiently than the two exhibition rooms. This is mainly because windows and shutters are always kept shut in the storage, enhancing the general thermal performance of the envelope and preventing the effects of a direct solar radiation. It is also likely that the large amount of materials stored inside the room can help in buffering the indoor RH values. On the contrary, in the exhibition rooms shutters are

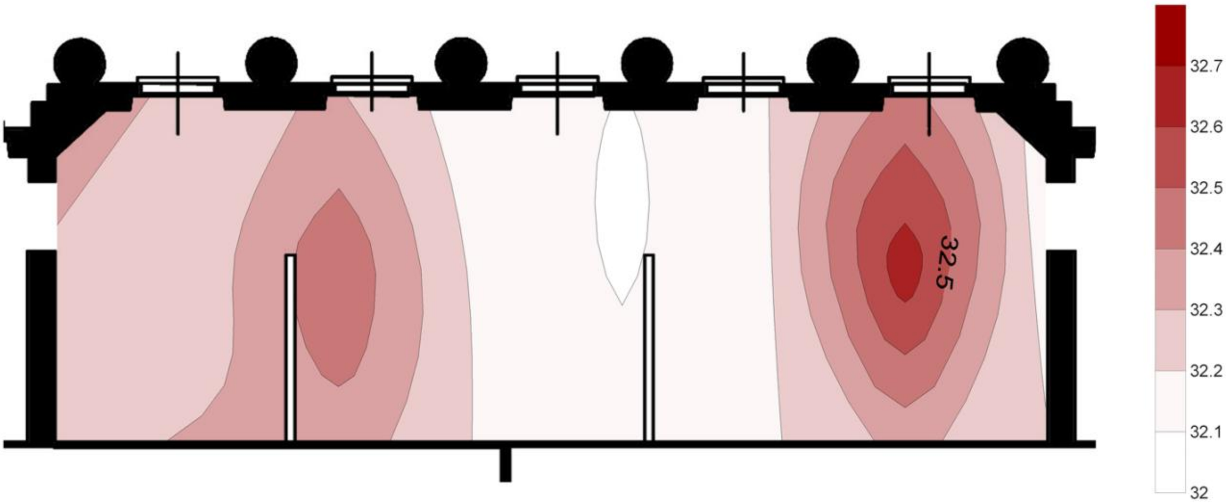


Fig. 4.12 – Temperature levels and gradients in a summer afternoon in the south-exposed Room IV (22/07/2010 - Outdoor conditions: T 31,8°C - RH 45,4%)

missing as they were removed in the past and, where they still exist, are generally kept open when the museum is open.
The museum staff often leaves the windows open during summertime, since there is not any cooling system. This way indoor air gets warmer and warmer during the day because of solar radiation, particularly in south-exposed rooms (fig. 4.12). Consequences are evident looking at daily trends (fig. 4.10): in the opening hours (9.00-17.00), the indoor climate of the exhibition rooms follows the outdoor variations. On Mondays, when the museum is closed and windows and shutters are more likely to be kept closed, daily variations are generally limited even in exhibition rooms.
It is interesting to observe how the indoor trend of mixing ratio (MR) follows a drop in outdoor MR (August 27th). In the morning the museum attendants open the windows and let cool air in since indoor temperature is higher than outdoor temperature. During the day, a drop in the outdoor humidity level is immediately transmitted to the exhibition rooms while the storage is less sensible to this sudden change. Indoor RH and MR fluctuations overlap outdoor fluctuations until the closing time when the museum staff closes the windows. During the night MR remains low outdoors while it rises indoors, probably due to the moisture released by the walls. As a consequence, another sudden drop in indoor humidity occurs the following morning (August 28th), when windows are opened again. Something similar occurs with peaks (August 31st, September 1st - green line).
In wintertime (fig.4.11) a drop in the outdoor RH and MR (February 26th) produces different consequences in the two exhibition rooms: the outdoor fluctuation is more moderated by the room heated by radiators, where the outdoor air only enters by infiltration, than by the room heated by ventilation, where outdoor air is directly drawn in after having been warmed by the heating system.

The interactions between the old air heating system, the room microclimate and the artworks have been further investigated through psychrometric mapping and infrared imaging.
A remarkable air stratification was observed when the same vertical air duct directly connects a room on the ground floor with a room on the first floor. Analyses in situ performed in different seasons in the rooms along the main cross-section of the building, show a continuity of air stratification through the connected floors, generating the most unfavourable conditions in the first floor room.

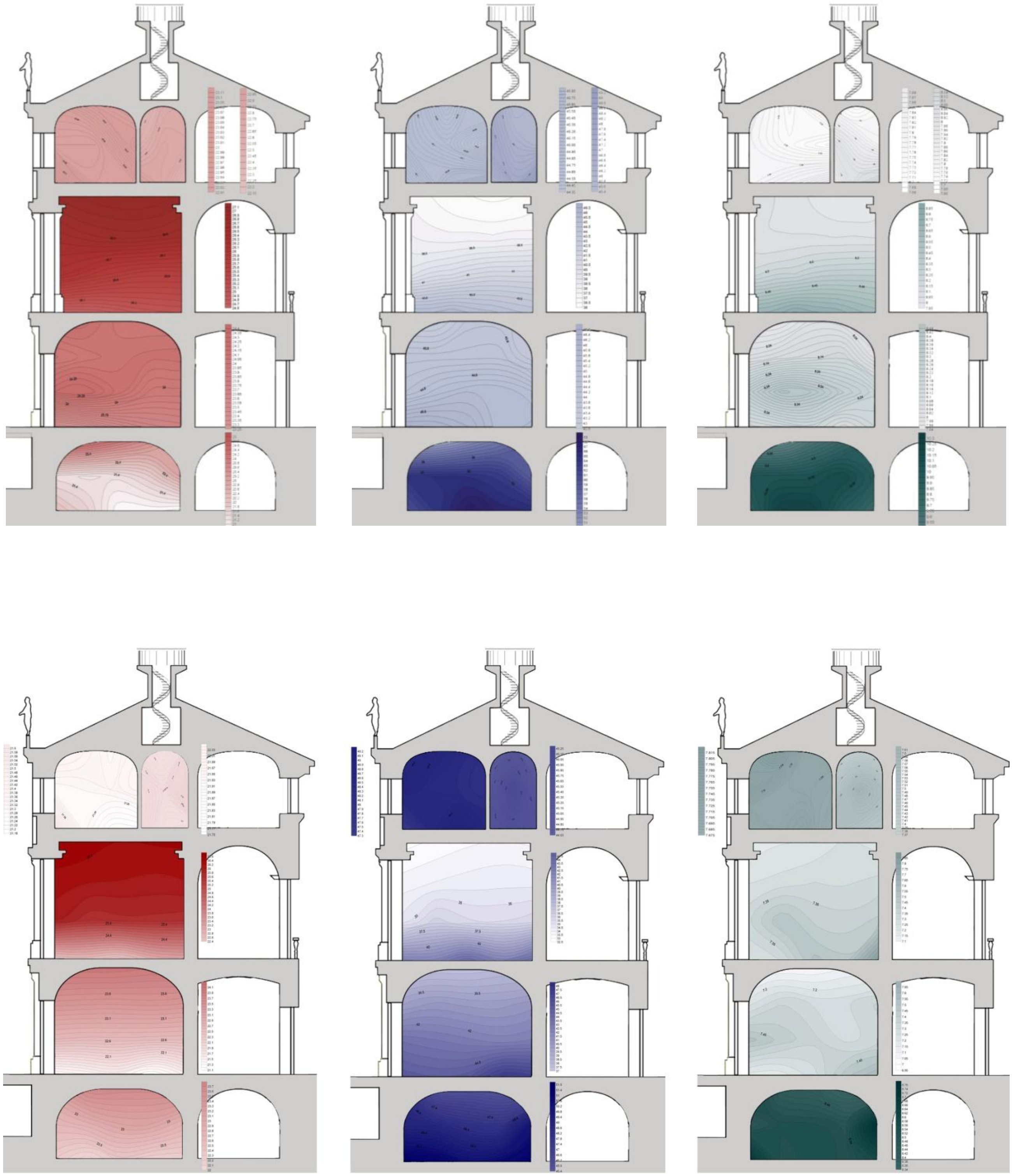


Fig. 4.13 – Comparison between the gradients of T, RH and MR along the main cross section.
Up: indoor conditions in April 2010 with the heating system off
(T 20,4-27,1°C, RH 36-69%, MR 7,6-10,3 g/kg);
Down: indoor conditions in November 2010 with the heating system on
(T 21,1-26,6°C, RH 32,5-51,8%, MR 6,9-8,8 g/kg).

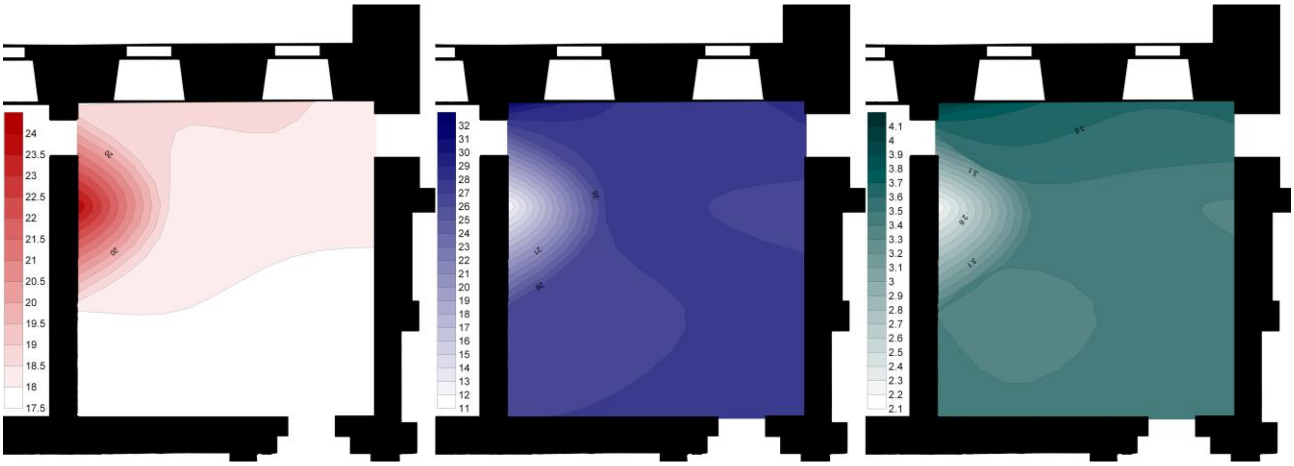


Fig. 4.14 – Gradients and levels of T, RH and MR generated in winter by an air inlet in Room VII. (17/02/2012 - Outdoor conditions: T 8,59°C - RH 45,7% - MR 3,13 g/kg)

In winter, when the heating system is on we can observe very high temperatures in the first floor room (T max: 27°C, ΔT max: 3°C) and a relevant difference between values here and those surveyed in the corresponding room downstairs, where temperature tends to be about 4-5°C lower (fig. 4.13, down). The lack of regulation of air flow and temperature could be one of the main causes of this situation: warm air naturally rises to the top of the ducts and, therefore, to the first floor room. Moreover, since there is no air extraction, except for leaking windows, the warmest air tend to accumulate in the upper part of the room.
The influence of air stratification still seems to be relevant in spring, when the heating system is off and the ballroom on the first floor is still the warmest one (fig. 4.13, up). In this season the greenhouse effect caused by the lack of effective solar shading has probably a more significant influence: the ballroom, facing the gardens, has five huge windows exposed to the solar radiation coming from southwest. On the other hand the room on the second floor is the warmest one in summer, due to the huge amount of heat transferred trough the roof.
The thermal level of the interiors of the Villa is in general higher than the outdoor level throughout the year. Extremely high temperatures were measured in summer, when temperatures inside the building can be constantly higher than outdoor temperatures for prolonged periods of time, especially in the rooms facing the gardens. This can mostly be explained as a consequence of the daily incomes of solar radiation accumulated by both the vertical and the horizontal solid components of the structure (Camuffo 1998, pp. 109-115).
The uncomfortable environment inside the Villa during summer, together with the great attention constantly paid to heating devices within the building throughout its history, could even confirm the hypothesis of a dwelling mainly intended for winter use.

Looking closer at the effects of the heating system on the microclimate, one of the main worries was that the heating system may cause dangerous variations in T and RH inside the same room. The psychrometric map in fig.4.14 shows how the sharpest gradients are concentrated near the air inlet, while the rest of the room maintains quite homogeneous values (ΔT=1,5° - ΔRH=2%).
Thermography was also used to analyse the effects of the heating system on the paintings (fig.4.15). Even before starting the analyses, one could expect just by common sense that hanging paintings close to the inlets would expose them to higher risks; the analyses confirmed it.
What was less clear was that the heating system is influencing the indoor environment of the museum not only by direct air draughts. In fact, the inner walls affect the indoor climate as well,

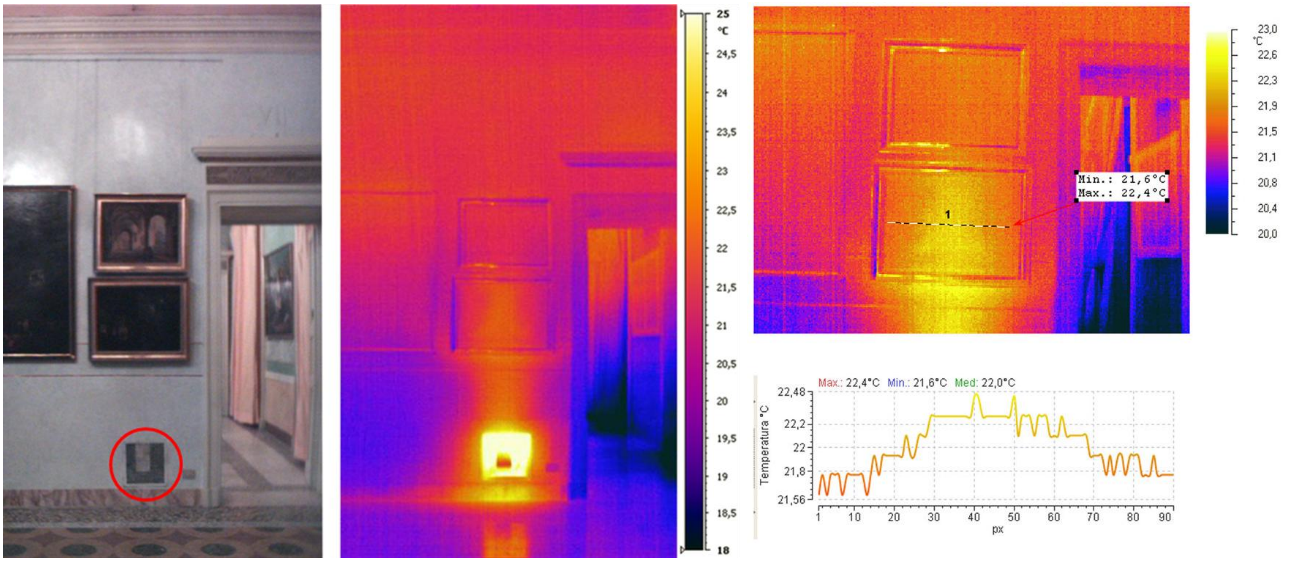


Fig. 4.15 – In Room VII thermography is used to analyse the effects of an air inlet on paintings and measure surface temperatures

since the ducts circulating air to the rooms are cut into the walls and not insulated. These ducts are thus not comparable to the air-ducts of modern air systems which are (or should be) well insulated and do not lose heat towards the environment. Here, on the contrary, heat is transferred firstly from warm air to the walls and then slowly released to the rooms. As a result the heating system works both through air convection and through radiation. This can be localized and roughly quantified with thermography (fig. 4.17).

Going back to the original thermal behaviour of the villa, it must be remembered that something similar must have happened with all the chimneys: six of them were probably for the underground stoves, some for the ovens in the kitchen and others for the fireplaces. That is why they were generally cut into inner walls rather than into outer ones. In the Villa the only exception is a duct of the air system located on the façade overlooking the gardens; Fig.4.16 shows the heat dispersion.

Nowadays, the ducts increase the heat radiation of the walls in wintertime while in summertime fresh air can rise from the basement to the rooms through them. (fig. 4.3).

This is just an example of how historic structures, exploiting their solid and massive masonry, can influence the indoor environment of this sort of buildings. Their behaviour is not only determined by the thermal inertia of the thick building envelope, which obviously in wintertime slows the heat loss from the interior to the exterior, while in summertime can help to keep the indoor cool.

The monitoring campaign was able to detect these peculiar phenomena but, at the moment, it was not possible to quantify accurately their influence.

As already said, Villa Reale has many rooms and various climate control systems are installed within the building. The yearly scatter graph in fig. 4.18 summarises and highlights the effect which different strategies for climate control produce in different rooms.

In the unheated storage (blue dots) RH is limited in the range 40-60% almost all year long, while T has the largest range. In the heated exhibition rooms (green dots, orange dots) T never falls under 15°C but during winter RH can drop to under 20%, especially in rooms with air inlets.

The performance of the unheated storage in the yearly scatter graph confirms how a passive strategy for climate control could be effective in limiting the RH yearly range and obtaining acceptable conservation conditions by enhancing the building envelope performance. The ASHRAE Class C is met in the storage in relation to RH and even a Class B could be reached

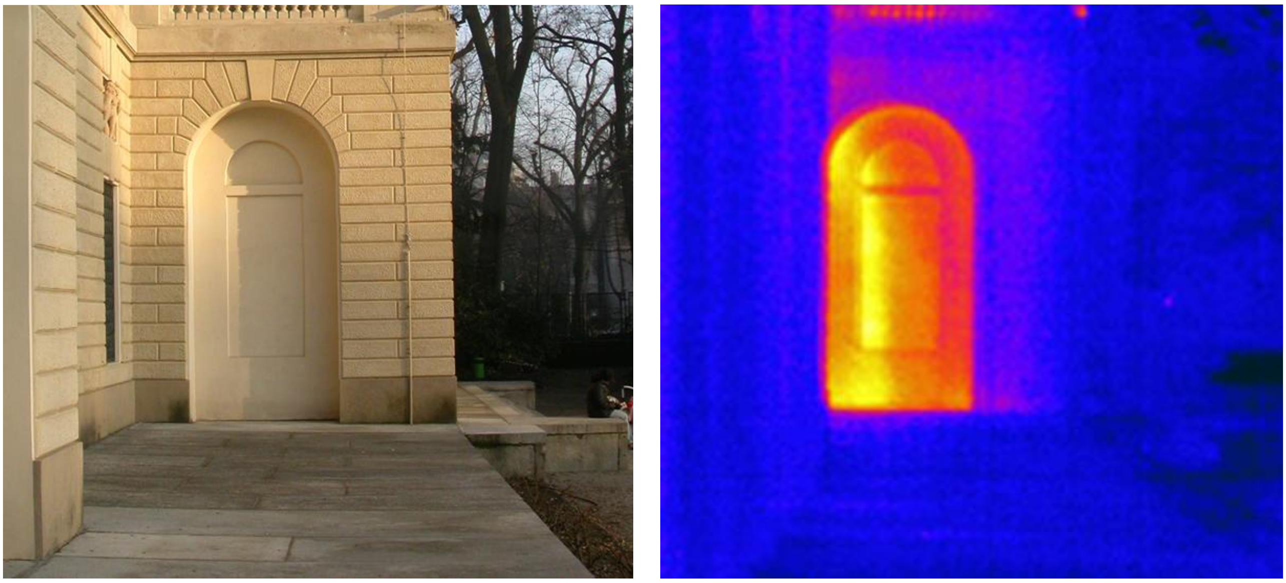


Fig. 4.16 – Heat dispersion from a duct cut into an external wall

Fig. 4.17 – Heat transmission from a duct cut into an inner wall

quite easily. Nevertheless, an indoor temperature falling down to 5°C in wintertime cannot evidently be acceptable for the rooms open to the public. Furthermore, the high summer temperatures, beside being uncomfortable for people, could induce chemical decay (the ASHRAE chapter for museums suggests to stay below 30°C).
On the other hand, exhibition rooms do not even meet the Class C due to the high T levels and the frequent RH fluctuations in summer and to the extreme low RH levels in winter.
A good compromise and a possible reference for a sound climate control strategy is represented by the small storage (dark red dots). Here the windows and their shutters are constantly shut as in the unheated storage but in winter a radiator is kept on to a minimum. As a result, temperature does not reach extremely low values but the yearly RH range (35-60%) is slightly larger than the unheated deposit. Short-term fluctuations and RH levels are quite satisfactory: they indicate a level of control near to Class B for relative humidity.

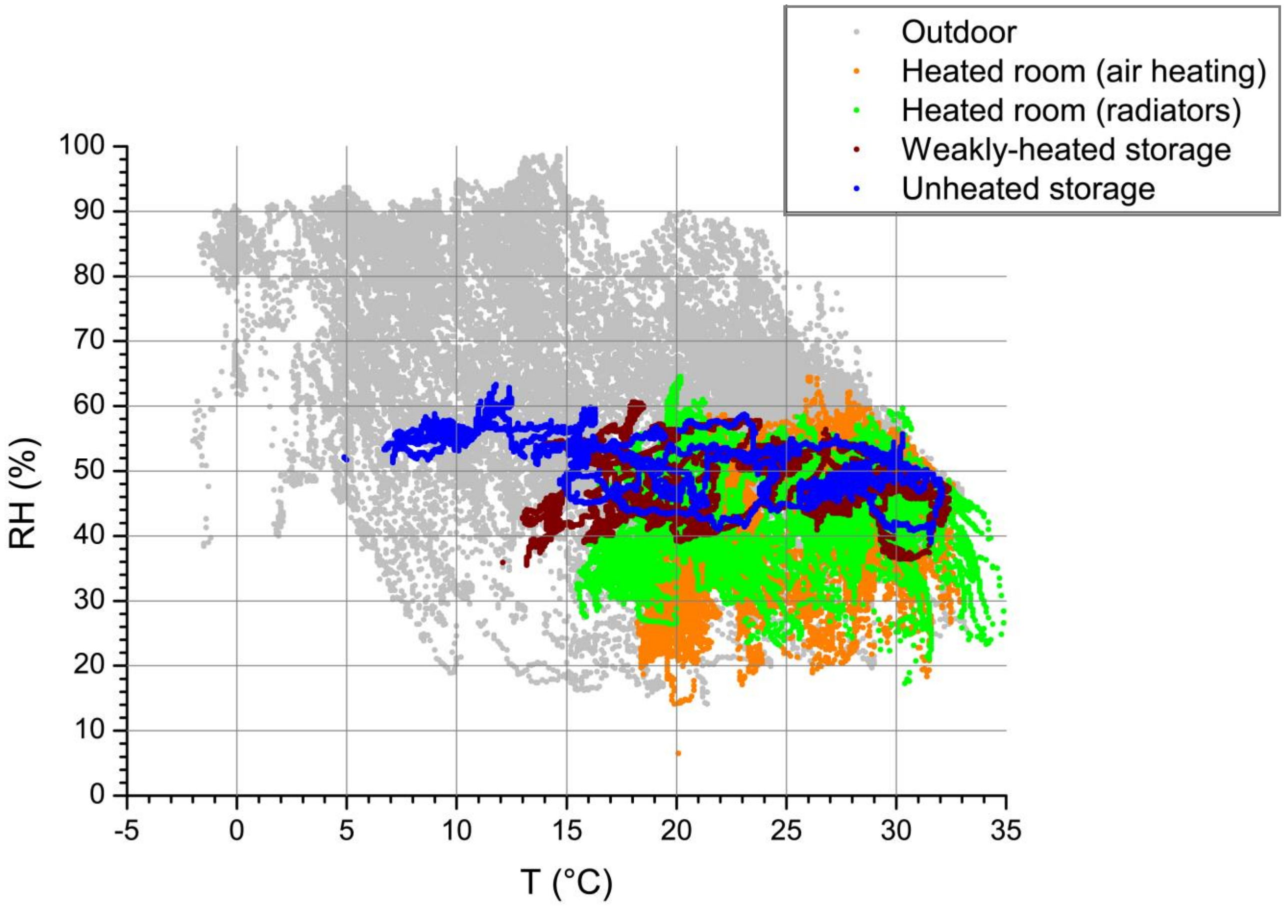


Fig. 4.18 – Yearly scatter graph of T and RH values in Room VII (orange), Room IV (green), large storage (blue), small storage (dark red) and outdoor (grey)

4.1.4 Final considerations on the case study

In spite of the difficulty of studying the indoor climate of such a huge and complex building with a little amount of data, focus was on the definition of the historical indoor climate, through the monitoring of the indoor parameters and through the analysis of the link between their imbalances and specific building features. An accurate description of the building, its construction and maintenance history (i.e. the heating systems, the shape of the interiors, the building structure and envelope...) has been developed and it will be helpful in order to set possible solutions.

The research confirms the effectiveness of the proposed integrated approach when dealing with historic buildings. The environmental behaviour of historic buildings follows schemes which are the result of old and established technical knowledge which nowadays are often gone forgotten, disregarded and/or misunderstood. An effective intervention has absolutely to consider them.

Villa Reale was built as a private dwelling and, as a consequence, with the objective of providing comfortable and hygienic conditions to people, rather than aiming at the preservation of the artworks. Recent refurbishments of the central heating system, the removal of doors and shading systems, the incorrect management of natural ventilation and the habit of keeping windows opened have worsen the indoor climate: nowadays data shows environmental conditions which fall quite a long way short of traditional museum standards and are hardly acceptable for a museum environment, especially in the exhibition rooms.

In relation to the decaying mechanisms observed by conservators on hygroscopic materials, the most evident problem is related to the low humidity levels. This can immediately be interpreted as a consequence of the air heating system, whose functioning is not balanced by a humidifier or controlled by a humidistat. Other risks are induced by sharp fluctuations of the hygrothermal values due to incorrect climate control strategies.

At the moment, data provides an analytical confirmation of what museum conservators had already empirically supposed during years about the risks related to a building progressively altered in its functioning and structural scheme, in its technical devices (e.g. the heating plants) and in some fundamental parts (e.g. the lack of the shutters). Results validate a conservation strategy in use at the museum: since exhibited paintings have shown a faster decay than paintings preserved in the storage, canvas paintings are moved into the unheated storage as they present environmental-related decay.
Obviously further developments are needed, especially an in-depth analysis focusing on the quantification of decaying risks induced to canvases by indoor climate conditions. The procedure recently proposed by Martens (2012) for the climate risk assessment in museums could be a useful reference for the future.
Another interesting point left unsolved is a comparative assessment of materials reaction to climate conditions: as an example it has been noticed that relined and transferred canvases show a quicker decay, when exposed in a heated room, compared to canvases treated with less invasive interventions (Fratelli 2010b).

The main objective of the research was to gather data and information to be used as a basis for the development of an integrated intervention on indoor climate control and management at Villa Reale. The monitoring and the analyses led to the identification of the rooms in the building that are nowadays characterised by the best environmental conditions (with regard to the mechanical decay of hygroscopic materials). The rooms passively controlled, with effective solar shading and higher air tightness (i.e. the attic storages), have better performances, since they enhance the thermal inertia and the humidity buffering provided by the building massive structure.
What emerged is that the building, if correctly used and managed, has the potential for offering suitable environmental conditions. This experience is thus showing that effective strategies for climate control in historic buildings should be based on a holistic analytical approach, aimed to identify which performances are obtainable from the building and, at the same time, how the peculiar features of a historic structure can be sustainably exploited.
Only this way a conscious design process will follow.

The same approach was followed to provide the museum conservators with operative indications and preliminary measures which could be easily and immediately applied as mitigation strategies until a more extended intervention will be possible.
These should surely include, when possible, a stricter control of the solar radiation and a sound management of the natural ventilation. The current lack of shading systems increases the frequency of extreme and dangerous conditions; their presence in the past is testified by numerous historic images and they could easily be re-installed.
The extremely low RH values caused by heating in exhibition rooms could require the installation of some kind of humidification. Nevertheless, introducing moisture in a heated historic building can be dangerous and it should be done very carefully. The hygrothermal mapping and the thermographic analyses performed in the interiors of the Villa (fig. 4.13, 4.14, 4.15, 4.17) have shown considerable space gradients in the air temperatures and surface temperatures. The water vapour spreading through the rooms could result in even steeper RH variations, which are dangerous for artworks. Moreover, increasing the moisture content of the air in winter is notoriously

controversial in historic buildings, which have no insulation or vapour-barriers: interstitial or surface condensation can occur in the coldest components, causing damage to outer walls or windows.
An alternative could be to reduce the temperature inside the rooms or to have the indoor thermal level following more closely the outdoor trends, but this could cause problems with human comfort.
Considering the existing layout, both the solutions would only be possible and effective if the heating system was divided into sections, so that each zone can be independent from the other and the adjustment easier and based on local conditions.
The natural convective flow observed in the ducts in summer could be exploited to obtain an energy-effective room cooling and ventilation. Nevertheless, the existing system should somehow be integrated and improved with air extraction and air filtering to improve air quality.

4.2 Assessment of an unheated conservation environment: Skokloster Castle in Sweden

Fig.4.19 - View of the castle

4.2.1 Introduction

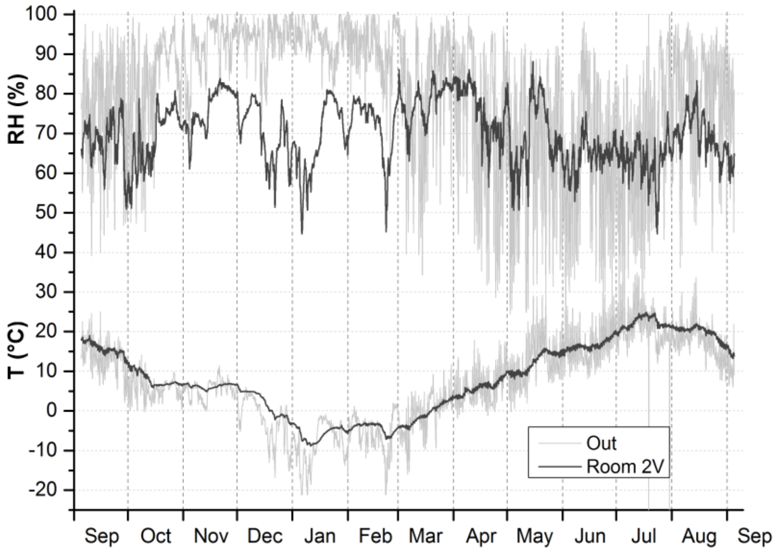
Skokloster castle, located north of Stockholm on Lake Mälaren, is a heavy stone and brick building hosting an important and heterogeneous collection of artworks. It was designed by Nicodemus Tessin the Elder for Carl Gustaf Wrangel. Construction work started in 1654 and was interrupted in 1676 as Wrangel died. The castle then passed into the hands of Brahe family until 1967 when it was sold to the Swedish State.

The building envelope is characterized by masonry walls and lead glass windows with limited air tightness. An inner corridor, which is in direct connection with outdoor air through the staircases, connects the rooms. The building is open to visitors from May to September

There is no active climate control system, with the exception of a few rooms on the bottom floor used for offices. The factors influencing the indoor climate of the castle are the heat and moisture transfer through the envelope, the hygrothermal inertia of the structure and of the interiors, solar radiation and wind.

Despite being cited as a good passive preservation environment, conservators are now observing decay to the collections related to the indoor climate that may call for a re-evaluation of the climate control strategy. This is mainly related to reoccurring mould growth in some rooms and mechanical damages to paintings believed to be associated with levels and variations of RH. Gotland University has been monitoring the indoor climate of the castle since 2009 in order to get a better understanding of the present indoor climate and what needs to be done about it.

A general survey of the environmental conditions of the castle was made by Brostrom and Leijonhufvud (2010). The results showed that RH variations detected inside the castle were



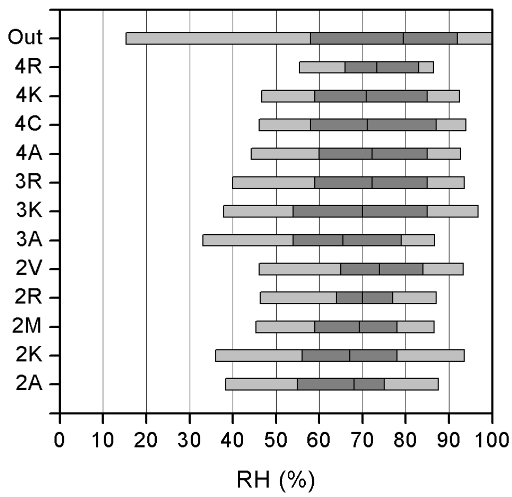


Fig. 4.20 –Yearly trends of RH (%) and T(°C) in Room 2V compared to outdoors

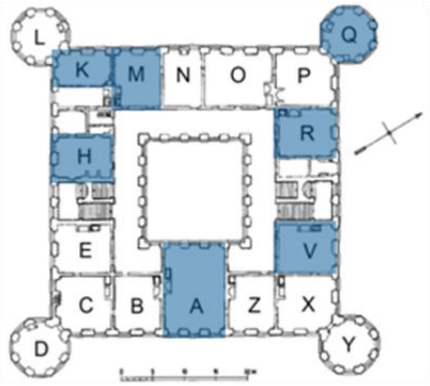
Fig. 4.21 – RH in twelve selected rooms: seasonal range (light grey) and range of 30-day moving average (dark grey). The line in the middle of each bar is the seasonal average

reduced when compared to the outdoor climate (fig. 4.20) but there were considerable differences among the rooms in terms of short term variations affecting hygroscopic materials (fig.4.21). Air exchange was identified as one of the main factors determining this situation. A reduction of the air exchange rate was suggested as a strategy to limit RH fluctuations.
On the other hand, one of the main problems affecting the collections is related to high indoor RH levels, leading to mould growth in some rooms, as described by Bjurman and Leijonhufvud (2012).
The general effect of air exchange on the hygrothermal parameters inside the building is here analysed, focusing on its influence on the stability of the indoor climate and trying to understand whether an improvement of the air tightness of the building envelope could be beneficial without increasing the mould risk.

4.2.2. Development of a procedure to evaluate the influence of air exchange on indoor climate fluctuations

The study is based on data collected in Skokloster Castle by previous research projects and analyses performed by Gotland University. The monitoring campaign was carried out from the 15th of June 2008 to the 9th of September 2010 in 25 different rooms outspread on different floors and in different directions. 45 data loggers of the type TinyTag plus2 were used during the campaign. Temperature (T) and relative humidity (RH) data for the whole year were obtained by the monitoring campaign. The corresponding mixing ratio (MR) was then calculated.

The air exchange rate is expressed as Air Changes per Hour (ACH). Measurements were made following the Nordtest Method standard NT VVS 188 (Nordtest 1997): homogeneous emission of tracer gas was used to measure the local mean age of air, utilising passive tracer gas sources and diffusive samplers. The measurement is based on the fact that the local steady concentration of a contaminant distributed with equal source strength in all parts of the space will attain a value which is proportional both to the local mean age of the air and the contaminant source strength per volume. The inverse of the local mean age of the air in a zone is defined as the “room-specific ventilation flow rate” or “local air change rate”. In naturally ventilated environments, this parameter,



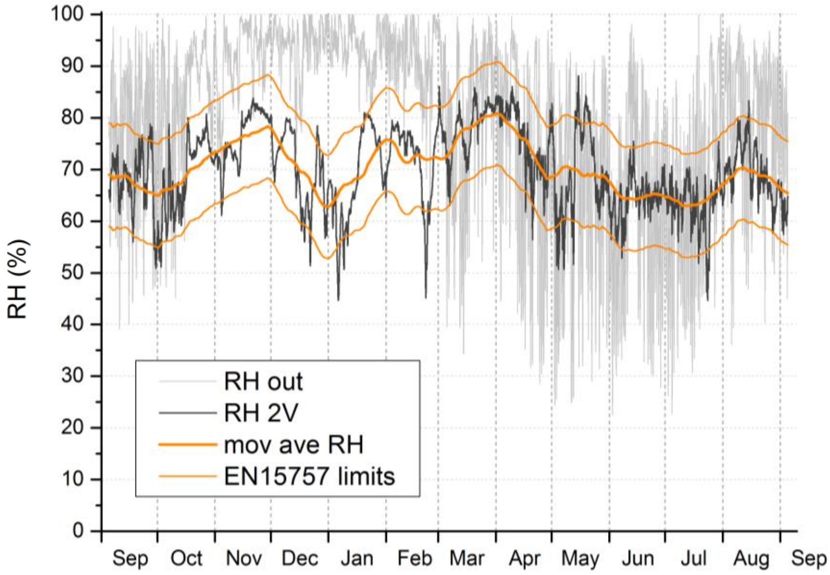


Fig.4.22 – Plan of the first floor of Skokloster Castle. The analysed rooms are highlighted.
Fig 4.23 – Yearly graph of RH in room 2V. RH safe range according to EN15757 standard is also included.

expressed as ACH, can be considered the equivalent of the specific ventilation flow rate, usually used for the ventilated system as a whole to express the flow rate of outside air entering into a ventilated system, divided by the volume of the ventilated system.
Measurements were made according to the following schedule.

Autumn: from 2009-10-10 to 2009-11-23 – 44 days.
Winter: from 2010-01-21 to 2010-03-04 – 42 days.
Spring: from 2010-04-21 to 2010-05-27 – 36 days.
Summer: from 2010-07-14 to 2010-08-23 – 40 days.

On the basis of the results obtained, seven rooms on the second level (first floor) of the castle were selected and investigated (fig.4.22).

In order to evaluate the effect of the air exchange rate, expressed as the average air changes per hour in the surveyed periods, it was necessary to find a comparable indicator for temperature, relative humidity and the mixing ratio in the same seasonal periods. The standard deviation (σ), was chosen as a proper indicator of the variations of the parameters in a given period of time. In the seven selected rooms, standard deviation of T, RH and MR was thus calculated for the same period for which the corresponding average ACH were determined.
Graphs comparing ACH and σ of T, RH and MR in the same seasonal periods were plotted to see if it was possible to find a correlation between those values, according to the following hypothesis:

(1) $$\sigma_{\mathrm{n}}(\mathrm{T}) = f_T(\mathrm{ACH_n})$$

(2) $$\sigma_{\mathrm{n}}(\mathrm{RH},) = f_{RH}(\mathrm{ACH_n})$$

(3) $$\sigma_{\mathrm{n}}(\mathrm{MR}) = f_{MR}(\mathrm{ACH_n})$$

n: amount of days on which both σ and average ACH are calculated

It was then decided to focus this analysis on mixing ratio, which is considered the best indicator to detect the effects of air exchange in indoor environments since it is not dependent on temperature

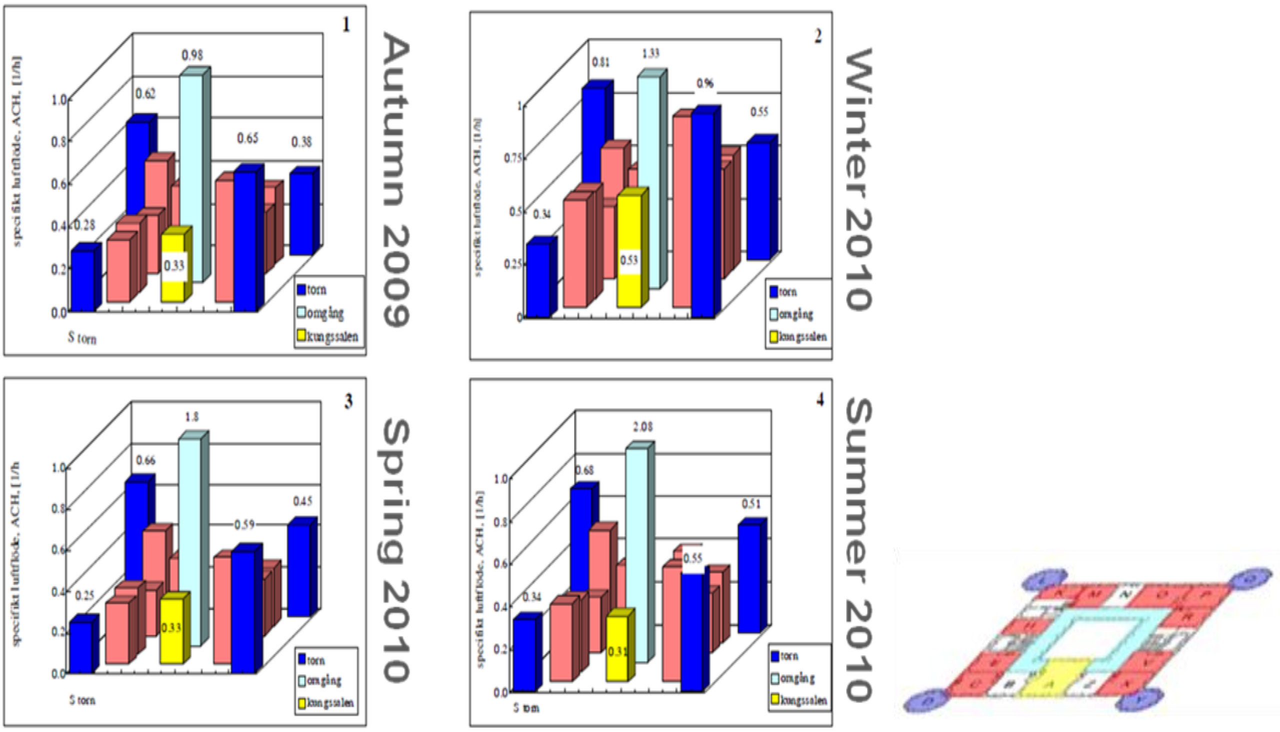


Fig 4.24 – Air exchange measurements expressed as ACH in first floor rooms in different seasons. The towers (blue) and the corridor (cyan) generally have the highest values.

and, compared to temperature and relative humidity, it is the parameter less influenced by solar radiation, heat gains or thermal properties of the walls (Camuffo 1998, pp. 48-53).

The next step was the choice of using the procedure specified by the EN 15757:2010 (fig. 4.23). Here it was adopted to distinguish seasonal variations from short-term fluctuations, which were supposed to be more related to air exchange. The difference between each surveyed value and the corresponding 30-day moving average (MA) value was calculated while standard deviation was calculated on the same period of days on which air exchange measurements were performed.
In order to show to what extent outdoor fluctuations were transmitted to and/or buffered in the indoor environment, a specific parameter was created. Henceforth it will be defined as Climate Fluctuations Transmittance (CFT). It expresses the ratio between the standard deviation of the indoor fluctuations and the standard deviation of the outdoor fluctuations:

(4) $$\mathrm{CFT}_{n_1} = \frac{\sigma_{n_1}\left(X_{in} - MA_{n_2}(X_{in})\right)}{\sigma_{n_1}\left(X_{out} - MA_{n_2}(X_{out})\right)}$$

σ : Standard Deviation
MA: Moving Average
X_{in}: indoor values (T or RH or MR)
X_{out}: outdoor values (T or RH or MR)
n_1 : number of days for which σ is calculated (36-44 days in ACH measurements)
n_2: number of days for which MA is calculated (30 days following EN15757 standard)

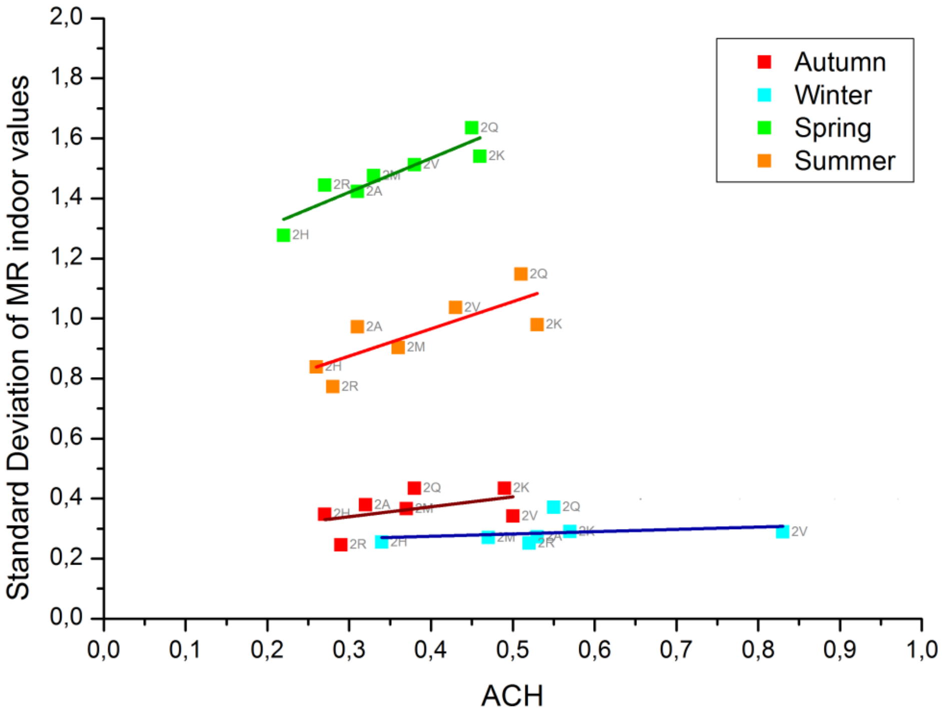


Fig. 4.25 – Standard deviation of indoor MR as a function of ACH in different seasons. Different seasonal patterns are highlighted. Air exchange seems to have an higher influence on MR variations in Spring and Summer (Pearson's r is 0,91 and 0.79 respectively) than in Autumn or Winter (Pearson's r 0,47 and 0.28 respectively)

As in the procedure to evaluate the general influence of air exchange rate on hygrothermal parameters, CFT was plotted with ACH in order to find a correlation:

(5) $\mathrm{CFT_n\,(T)} = f_T(\mathrm{ACH_n})$

(6) $\mathrm{CFT_n\,(RH,)} = f_{RH}(\mathrm{ACH_n})$

(7) $\mathrm{CFT_n\,(MR)} = f_{MR}(\mathrm{ACH_n})$

n: amount of days on which both average ACH and σ in the CFT formula are calculated

Given the importance of RH fluctuations for the conservation of hygroscopic materials, here CFT was calculated on relative humidity only, but the method (as well as the EN15757 procedure) can also be applied to the other parameters, i.e. temperature and mixing ratio.
Linear correlation was measured using the Pearson's correlation coefficient (r): the closer the value is to 1, the stronger is the correlation. Given the variables involved, it was assumed that a value under 0.5 would express a poor correlation.

4.2.3 Results and discussion

ACH values in analyzed rooms generally range from 0,2 to 0,9 ACH, depending on the location of the room and the time of the year (fig. 4.24). Higher values were detected in the corridor (1-2 ACH) and sometimes in the towers and corner rooms which are more exposed to outdoor climate. Nevertheless, it must be underlined that values detected do not represent exclusively air infiltration from outdoors but also air movements between the rooms.

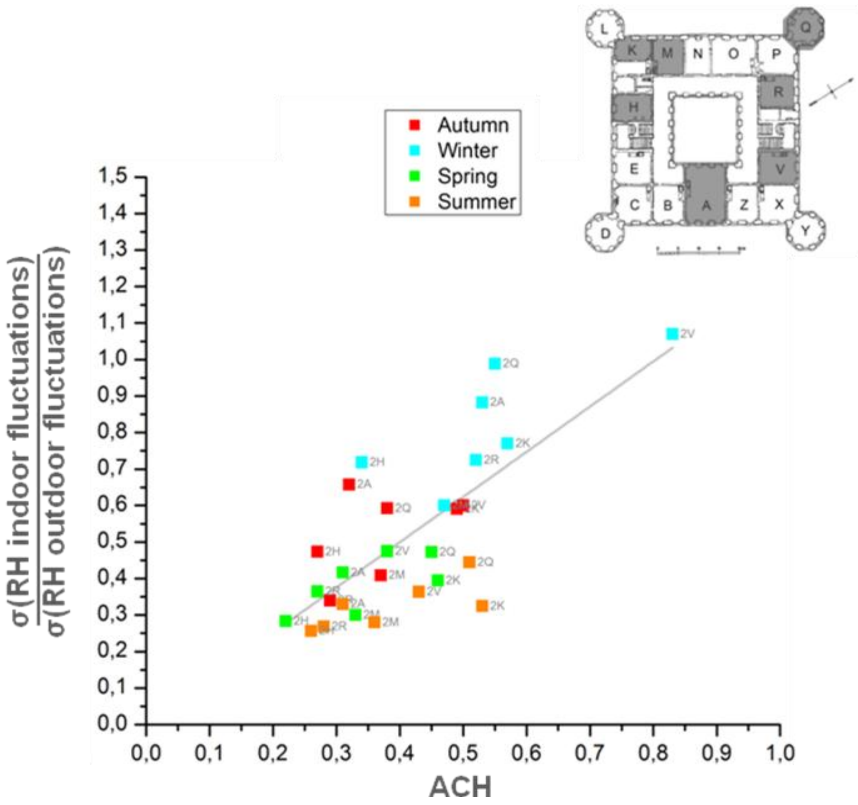


Fig.4.26 – Standard deviation of CFT as a function of ACH. Different seasons are highlighted. Linear regression is used to show the correlation coefficient considering all the values for the whole year (Pearson’s r is 0,73)

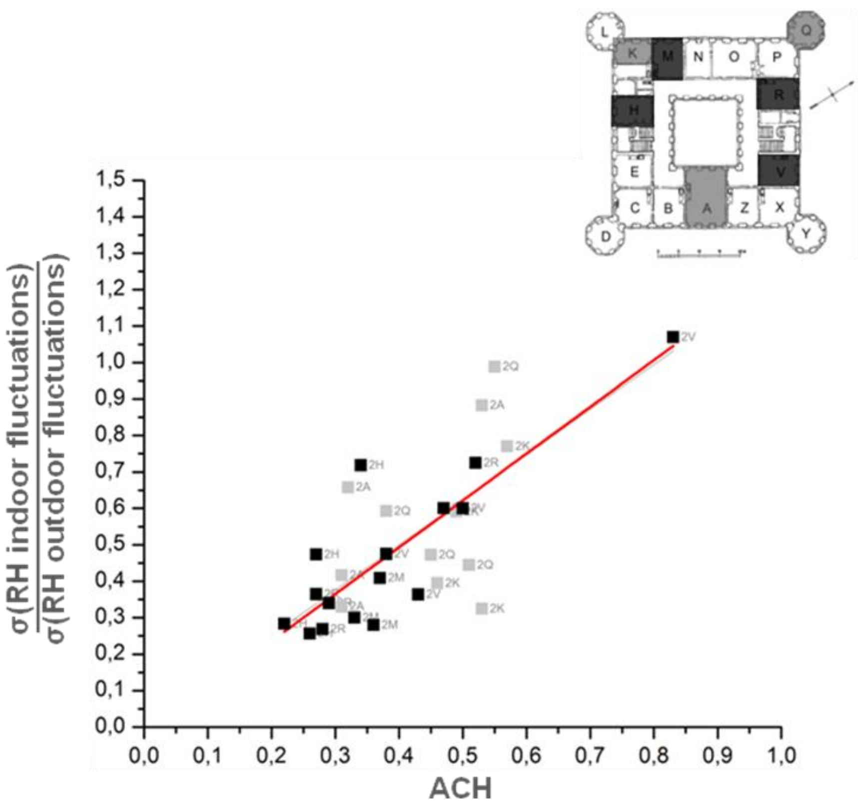


Fig.4.27 – Standard deviation of CFT as a function of ACH. Linear regression is used to show the correlation coefficient considering the values of the four most similar rooms for the whole year (Pearson’s r is 0,86)

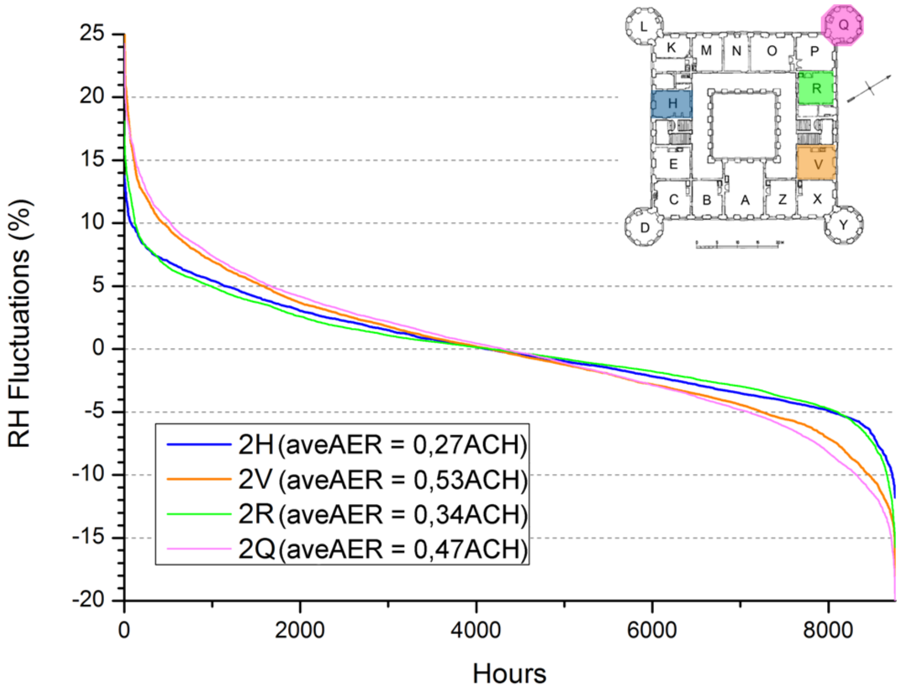


Fig.4.28 – The duration graph is a cumulative presentation of RH levels in rooms 2H, 2Q, 2R and 2V. A flatter curve indicates a more stable climate.

The graph comparing ACH values with MR variations, expressed as standard deviation, highlights different seasonal patterns (fig. 4.25). Autumn and winter values have flatter trends while similar ACH values correspond to larger variations in spring and summer. On the one hand this should be due to seasonal differences in the magnitude of MR. On the other hand the results could also be influenced by the fact that in spring and summer the castle is open to visitors and windows are more likely to be opened. As a consequence, the amount of infiltrated outdoor air on the total exchanged air should be higher and this could result in a stronger influence of air exchange on MR variations, although the range of ACH values are similar to autumn and winter values.

Encouraging results were obtained plotting the Climate Fluctuations Transmittance values.
A quite strong correlation (Pearson's correlation coefficient >0,7) can be found between the CFT of relative humidity values and air exchange rate, as shown in fig. 4.26. This indicates that in Skokloster Castle, regardless of seasonal behaviours and the position and orientation of the rooms, RH short term fluctuations are directly connected to air exchange. A higher air exchange rate is therefore expected to cause a higher level of fluctuations and, as a consequence, a higher risk for hygroscopic materials in the collections.
If we consider only the rooms with similar characteristics, such as shape, dimensions, ratio between volume and surface exposed outdoors (fig. 4.27) there is an even stronger correlation. Considering the values of all the seven analysed rooms during the four seasons, the Pearson correlation coefficient is 0.73. The same coefficient calculated on four more similar rooms is 0.86.
This would suggest that, despite other factors have an influence on RH fluctuations (e.g. T variations or moisture transfers), the Climate Fluctuations Transmittance can give good results if used as an indicator in order to evaluate the influence of air exchange on RH fluctuations in different indoor environments.

Results obtained are confirmed by duration curves, as shown in fig 4.28. Yearly indoor values of RH fluctuations in four rooms with different yearly average of ACH, different shape and different

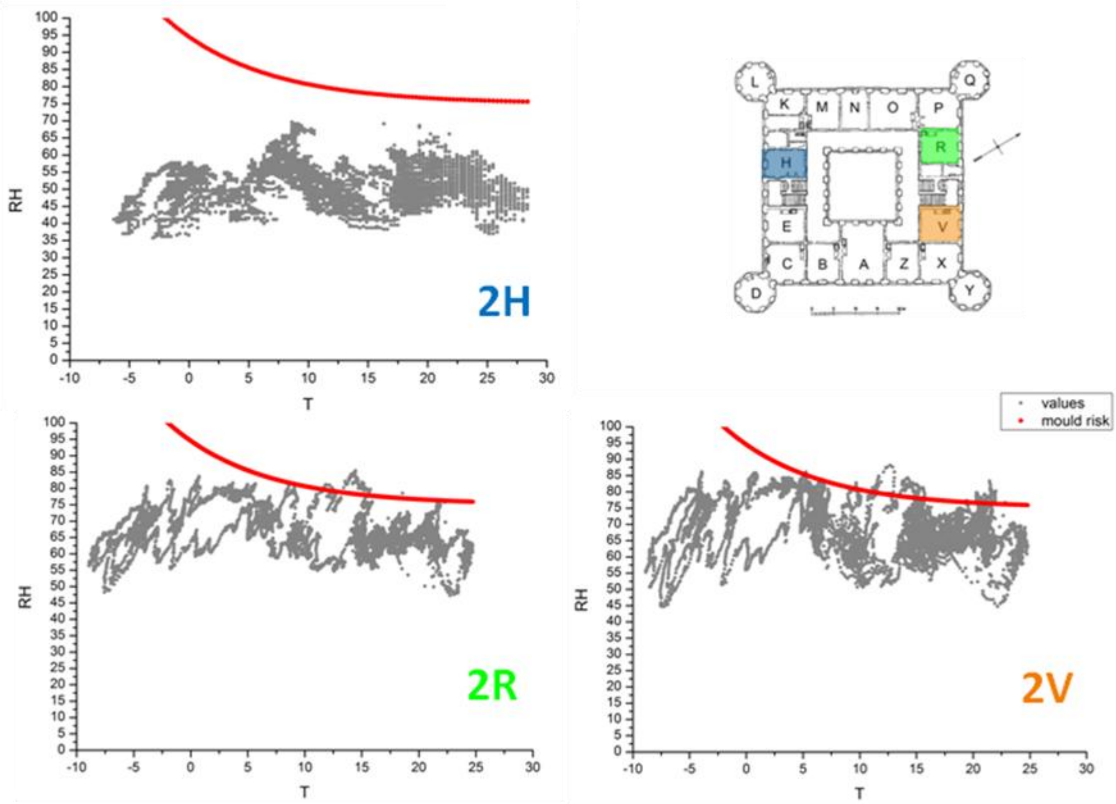


Fig. 4.29 – Mould growth risk evaluation in rooms 2H, 2R, 2V using Sedlbauer isopleths. Values above the red line should be considered risky.

orientation, were plotted in a cumulative graph. The two rooms with a lower ACH (i.e. 2H and 2R) show flatter curves and lower peaks if compared with the two rooms with higher ACH (i.e. 2V and 2Q), indicating a higher stability of RH levels.
With regard to the observed influence of strong wind in RH drops or peaks, wind speed was measured and its variations was compared with RH indoor trends in some rooms in order to find some connections, but results are still not significant and a deeper analysis is probably needed to obtain a better comprehension of this issue.

It is common to associate poor ventilation and low air exchange rates with moisture problems. However this is not necessarily so. In environments like the rooms of Skokloster castle, where there are no internal moisture sources, the difference between indoor and outdoor mixing ratio is generally small throughout the year. Thus mould risk would depend on differences in temperature and relative humidity over the short term. A previous study showed that a key factor for mould risk seemed to be the temperature levels in the rooms (Bjurman and Leijonhufvud 2012) . As a consequence, north rooms (2R, 2V) with less solar gain, have lower T and higher RH. This results in a higher mould growth risk and there have been mould problems indeed.
Sedlbauer isopleths (2002) were used to describe the mould risk in the rooms (fig.4.29). Values above the red line can result in mould growth if given time long enough. Room 2H has the lowest AER and has no mould growth risk, while room 2V has the highest AER and a significant mould growth risk. Room 2R has a low AER and at the same time quite a high risk. A correlation between AER and mould growth risk is thus not implied but it can be claimed that in analysed rooms a lower AER does not necessarily result in a higher mould growth risk.

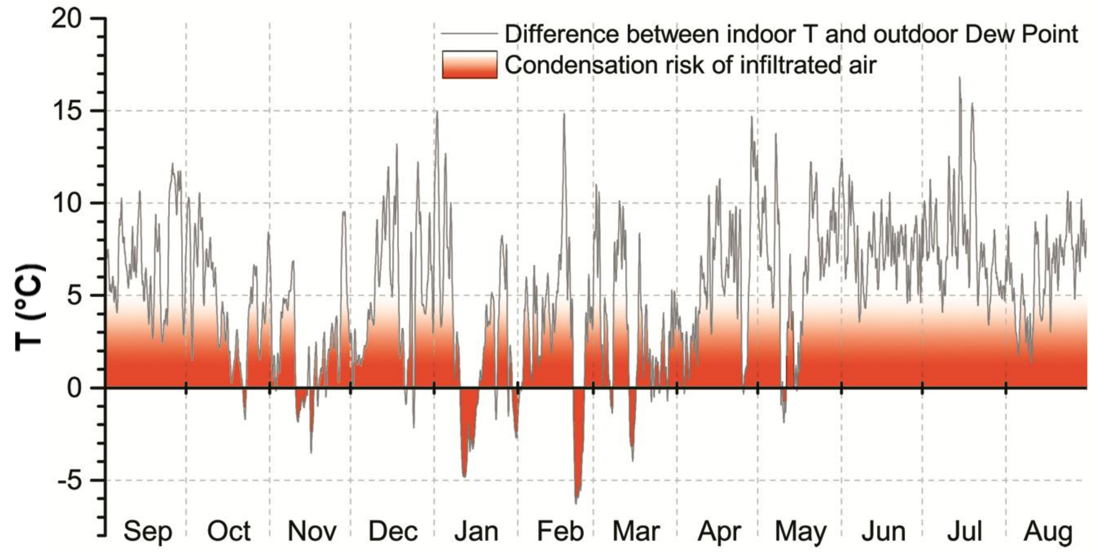


Fig.4.30 – Difference between outdoor dew point and indoor temperature in room 2V. Values close to or below 0°C have to be considered risky if outdoor air infiltrates into the room.

With high humidity levels outdoors and low temperatures indoors, the outdoor dew point can fall below the indoor temperature, which would mean a potential risk of condensation of outdoor air entering the rooms (since the rooms are unheated surface temperatures are generally in equilibrium with air temperatures). In such a situation, a lower AER would reduce the risk. Fig.4.30 shows the difference between the indoor T in room 2V and the outdoor dew point: when it is close to or below 0°C, it should be considered risky.

4.2.4 Conclusions on the case study

The study has assessed the effect of air exchange on the hygrothermal parameters inside the building focusing on its influence on the stability of the indoor climate and trying to understand whether an improvement of the air tightness of the building envelope could be beneficial without increasing the mould risk.

A specific method was developed and a new parameter, called Climate Fluctuations Transmittance, was proposed.

Based on measurements from Skokloster castle, the present investigation has shown that a reduction of the air exchange can provide a more stable indoor climate. A correlation between air exchange and RH short-term fluctuations was found, indicating that a reduction of the air exchange rate could be an effective strategy to lower the risk for mechanical damage on hygroscopic materials.

It is generally thought that an improvement of air tightness can cause a higher mould growth risk. On the contrary, this study shows that in a building like Skokloster Castle, with no internal moisture sources, this is not necessarily true. Nevertheless, this strategy is probably not enough to lower dangerous RH levels in rooms in the north part of the building and an active intervention (e.g. dehumidification, conservation heating or adaptive ventilation) would probably be necessary.

The Climate Fluctuations Transmittance has proved to be effective for the purposes of this study.

Results could be improved by a deliberately selected dataset, based on the most suitable rooms and on the most significant periods to be analysed. Having the same 30-day period of air exchange measurements for each season would make the data more coherent and fully corresponding with the calculated moving average

Another bias is introduced by the method chosen for the tracer gas tests: with the single-gas sampling technique, the ACH obtained express the measure not only of the air exchange between outdoor climate and indoor climate but also of the air exchange between the various rooms of the buildings (e.g. the round corridor). A double-sampling technique could be helpful in distinguishing the indoor air circulation from air leakage or infiltration through the envelope.

In conclusion, the method proposed in this study through the use of the Climate Fluctuations Transmittance parameter can be used as a general procedure to assess the influence of air exchange in unheated historic buildings.

Nevertheless further applications to other case studies are needed to validate the method.

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Chapter 5
A historical climate for historic buildings?
Discussion of the results

5.1 Learning from the history of conservation, learning from construction history

Looking into the field of conservation, the historical analysis characterising the first part of the thesis has shown how scientific progress and technical development are influenced by social and cultural history.
In recent times, authors looking back at the historical development of environmental standards for conservations have focused their criticism on the lack of scientific evidence that informed early specifications (Brown & Rose 1996, Erhardt et al. 2007). What was often called scientific was rather based on empirical approach, practical knowledge and professional habits which as time went by became a sort of dogma. The problems derived from the questionable application of strict environmental standards and from the consequent installations of modern air conditioning in historic buildings have repeatedly been highlighted throughout this thesis.
This would suggest a critical approach even to our present knowledge: if what was commonly accepted in the past can be not anymore valid today, how can we know that what we consider valid today will be accepted as well in the future? Absolute values, valid in every place and every time do not exist and that is why history is a powerful instrument for a critical analysis.
As a result of these reflections, one could assume that the strange and sometimes contradictory history of climate control strategies in museums and historic buildings could hardly be chosen as an example to demonstrate the usefulness of learning from the past.
Nevertheless, we have to take in mind that a good historical research is not a fruitless description of past events but a useful collection of past experiences that can be (re-)evaluated in the light of what we know today: suggestive influences and valuable information can be obtained even from a supposedly “wrong” history.

As an example, looking at the origins of these environmental standards we could claim that major problems were probably caused not so much by their empirical determination, but by the fact that specifications developed for specific collections in a specific environment within a specific climate zone were accepted as absolute values and applied worldwide in every context.
As described in Chapter 1, the notorious RH set point of 58% used in Manod Quarry for the collections of the National Gallery, was determined in the 1920s from the average equilibrium moisture content of wooden samples exposed for one year to the indoor climate of the museum in London. It was thus somehow derived from the stabilization of the existing environmental conditions to which the collections have been acclimatized.
With the benefit of hindsight, analogies with the procedures recently specified in the EN 15757 standard and in the ASHRAE handbook can be seen. Obviously the progress in scientific research on materials response to hygrothermal conditions has in the meantime managed to define the fundamental concepts of acclimatisation and response time, allowing a more accurate distinction between the risks derived from short term fluctuations and allowable seasonal trends.
In British wartime repositories an emphasis on precaution may have led to excessively restricted ranges, but it must be acknowledged that the climate control systems installed were an admirable example of adaptive approach and that the underground climate was used in a very clever and innovative way (see the heat pump installed in the British Museum repository, the first one in the United Kingdom). Moreover, due to the consequences of war and related threats, pioneering experiences on the transfer of artworks were made, while at the same time great attention was paid to risk assessment and energy saving.

A critical review of those times does not necessarily imply complete criticism and it would be a counterproductive mistake if negative opinions on the scientific evidence of those early specifications would be automatically extended to the climate control strategies then in use.
In many cases this technical knowledge was lost, or was simply forgotten, once the search for the ideal climate in museums determined the extensive use of air conditioning. To gather historical information and documentation on early climate control in museums and historic buildings is thus a basic task. Other authors had already underlined the link between historic environmental control systems and their consequences on preservation years ago (Beck & Koller 1980, Koller 1994); the first two chapters of this thesis and the research on Villa Reale (par 4.1.2), characterised by a method derived from construction history, have also dealt with this topic.
In view of what has later been found on materials properties and on the opportunity for more relaxed standards, many of those experiences should be recovered and revaluated.
This is particularly true with regard to installations in the 1930s: during that period full control of the conservation environments through air conditioning was still not feasible and those in charge of climate control, i.e. engineers and architects, focused on what was realistically achievable. The approach to climate control was thus based on what today we would call adaptive strategies and mitigation measures, as it has been shown in chapter 1.3. The solutions then adopted became obsolete since they could not provide the strict level of climate control later required, which was only achievable by a full air conditioning.
Today such a strict level of climate control can be justified in cases of very precious and fragile artworks preserved in important and rich institutions, but to extend it to the whole cultural heritage would be impossible. The problem would not be so much the sustainability on a global scale, due to the high consumption of energy sources; the real problem is that the costs involved are generally not affordable by most of the smaller institutions and even by some of the largest ones.
That is why studying those experiences and trying to figure out how to integrate and develop them with our technical knowledge can inspire innovative and energy-efficient approaches to climate control. A couple of cases are presented here.

The use of hygroscopic materials for buffering relative humidity in conservation environments was suggested by MacIntyre in his chapter on climate control in *Muséographie* (OIM 1935). That was not only meant for passive climate control, but it was also attempted in a somehow active way in the air conditioning system he installed in Hampton Court in 1934: common canvas hoses were put into the ventilation ducts to have air conditioned and dehumidified during humid summertime, an inspiring and cost-effective solution probably never attempted again.
MacIntyre also recommended a smart control of air exchange and recirculation based on the comparison between indoor and outdoor conditions of temperature and relative humidity. This had been proved to be very effective in those same years in Portland Art Museum, where the installation of refrigeration to limit high humidity levels in the warmest days of the year was still not feasible due to high installation and operating costs. Similar solutions are today implemented in complex high-efficiency air handling units; nevertheless this method would also confirm the validity of a simpler and less invasive solution for climate control in historic buildings, such as the adaptive ventilation recently proposed by Broström, Hagentoft and Wessberg (2011).
A very significant example of the application of this kind of approach to a large and important museum is the new climate control system installed at the Medieval & Renaissance Galleries of the Victoria & Albert Museum (fig. 5.1). Here "*The passive approach developed, exploits the massive nature of the building and uses sophisticated control techniques to minimise variations in humidity in the galleries but uses neither refrigeration nor humidification machinery to achieve its performance*. (...)*The design strategy developed for stabilising the RH environment involves*

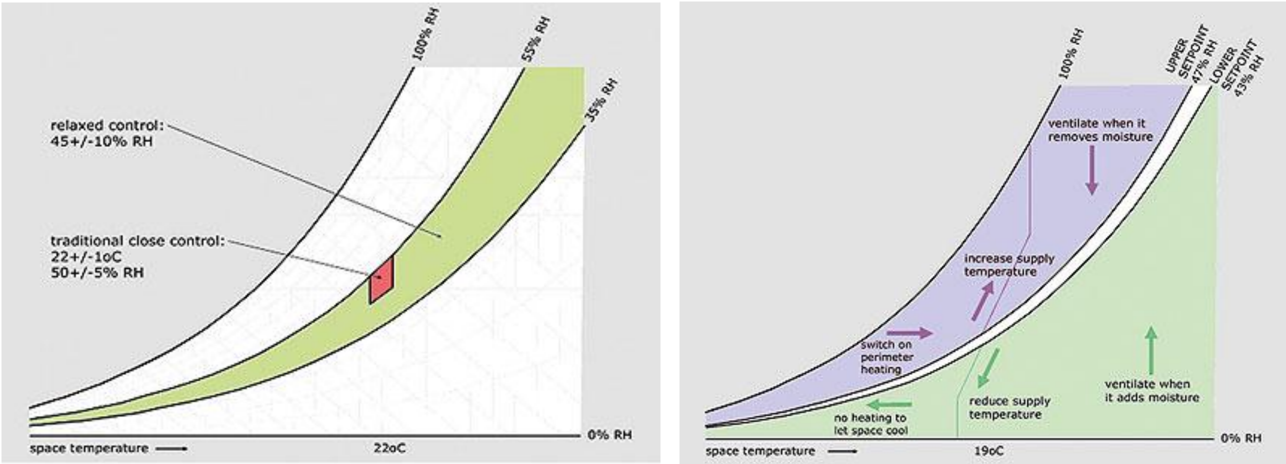

Fig.5.1 – Left: Target ranges of a traditional close control (red) and of a relaxed control based on relative humidity (green). Right: Stabilisation of RH by ventilation and heating (Bingham & Walker 2009)

exploiting the external air condition together with the ventilation and heating of the interior." (Bingham & Walker 2009, pp.13-14)
A comparison from the point of view of conservation conditions between the satisfying performances of the new system and those of the old air conditioning is provided by Pretzel (2009).

Forgetting and rediscovering useful knowledge is probably something that has not only characterised the strategies for environmental control but that could also affect some conservation practices in museums.
An example is provided by the research on Villa Reale: when thinking at operative and mitigation interventions to be provided for the museum conservator (see par. 4.1.4), I realised that almost all the identified risks and their possible remedies, had already been acknowledged in the 1940 *Manual on the conservation of paintings* (OIM 1940). They are reported here as a matter of interest:

"with heating by radiators, it is often not realised how difficult it is to keep uniform temperature in all parts of a room, especially when the premises include outside walls, the temperature of which on winter days is sometimes 3 to 6° lower than that of the premises inside. Consequently should a painting or a glass case be placed against such a wall, it will be exposed to serious risks of deterioration, as the relative humidity will be quite different at the back and at the front" (p.61);

"when heating is obtained by means of hot air, (...) care should be taken in the ordinary way to study the circulation of the hot air so as to avoid placing objects in the path of main currents, which, besides being harmful in themselves, always imply a certain amount of dust suspension" (p.75);

"danger spots can be located and remedies sought. Pending a new lay-out to eliminate draughts and should no remedy be found, the best thing to do is to take especially sensitive objects away from danger spots" (p.77)

“window ventilation – which means letting in air of a temperature and hygrometric condition appreciably different from those of the air in the room – is to be eschewed whenever the air can be renewed in other ways, e.g. doors, air-inlets, etc.” (p.76)

“no central heating system should be fitted without the indispensable corollary of a compensating system for moistening the air” (p.76)

It could be claimed that most of these are widely accepted common sense practices in a museum and that a basic management would be enough to solve those problems.
Nevertheless this quite surprising discovery made me think that maybe the correct question was not what can be learnt from history, but what should already have been learnt and maybe was forgotten and/or is undervalued. In this we also have to include all the knowledge that is removed because considered out-of-date or that is not transmitted because considered obvious.
This often happens without following a logical thread but simply under the influence of external circumstances which are partially or totally accidental.
Rediscovering some forgotten or removed knowledge, or just recovering practices left in the background for a long time, is probably one of the main results of this thesis.
It would probably be very interesting to carry out some research on the mechanisms and paths followed by these removing processes in the field of conservation. Climate control in conservation environments could probably offer several case studies, but this is not properly the object of this dissertation.

5.2 Completing the circle: outcomes in building conservation practice and research

Throughout this research period I have sometimes been asked why an architect specialised in building conservation is interested in these topics.
My cultural background and training in architecture and building conservation was indeed challenged by this research. I often found myself in the exciting and complicated position of being forced to cross disciplinary boundaries: physical and chemical decaying mechanisms had to be watched with the eye of a conservation scientist, technical installations understood with the mind of a building services engineer, sources analysed with historical methods, data gathered and processed with competence in mathematics and statistics.
Rather than leading to a holistic vision of the several questions arisen, crossing disciplinary boundaries can be frustrating and also dangerous and counterproductive for the research because dealing with fields of expertise in which one has no specific competence can lead to trivial and superficial conclusions.
Nevertheless, the contrary is also true: when teamwork is needed for decision making – a quite common situation with committees dealing with conservation questions – a very specific competence in one field of expertise without a basic knowledge on the other disciplines involved can be counterproductive and frustrating for a positive discussion of the problems.
That is why I consider the crossing of boundaries as a strength of my work and this experience enforced on me the belief in the absolute need of a multidisciplinary expertise for dealing with questions related to climate control and analysis in conservation environments.

Regarding the role that a building conservator can play in these questions, I refer to figure 5.2 since a picture is worth a thousand words: a heating duct from Villa Reale is presented as it was surveyed with endoscopic analysis, as it can be seen in a thermal image and referred to a historic treatise of building construction.
This suggestion is to confirm the importance of a multidisciplinary approach to building conservation practice, to demonstrate that building conservators need a wide-ranging but very specialised education and that their specific and complex field of expertise is absolutely required in the decision making process when dealing with climate control strategies in heritage buildings.
My current impression is that this fundamental contribution is often undervalued: strategic decisions for climate control in historic environments are generally a matter of compromise between object conservators and engineers. Leijonhufvud and Broström (2012) have discussed the dichotomy that derives from this conflict between a techno-economic vision and a cultural heritage oriented vision (fig. 5.3). My opinion is that a building conservator, especially if trained in architecture, could play a decisive role in mediating between these two paradigms, since this dichotomy should be implied in his whole field of expertise and multidisciplinary education.

On the other hand the pictures composing figure 5.2 show very well the significant results that can be obtained by coupling climate analysis with other analytical methods which are generally more related to building conservation practice.
Thermal imaging was used to confirm the results of the geometrical survey of the ducts, which required the use of an endoscopic probe; at the same time documentation from old treatises was used to better understand the reference scheme of the historic heating system and to support the assumptions on the behaviour of the system, based on convective flows and heat transfer from non-insulated ducts, that were suggested by thermographic analysis.

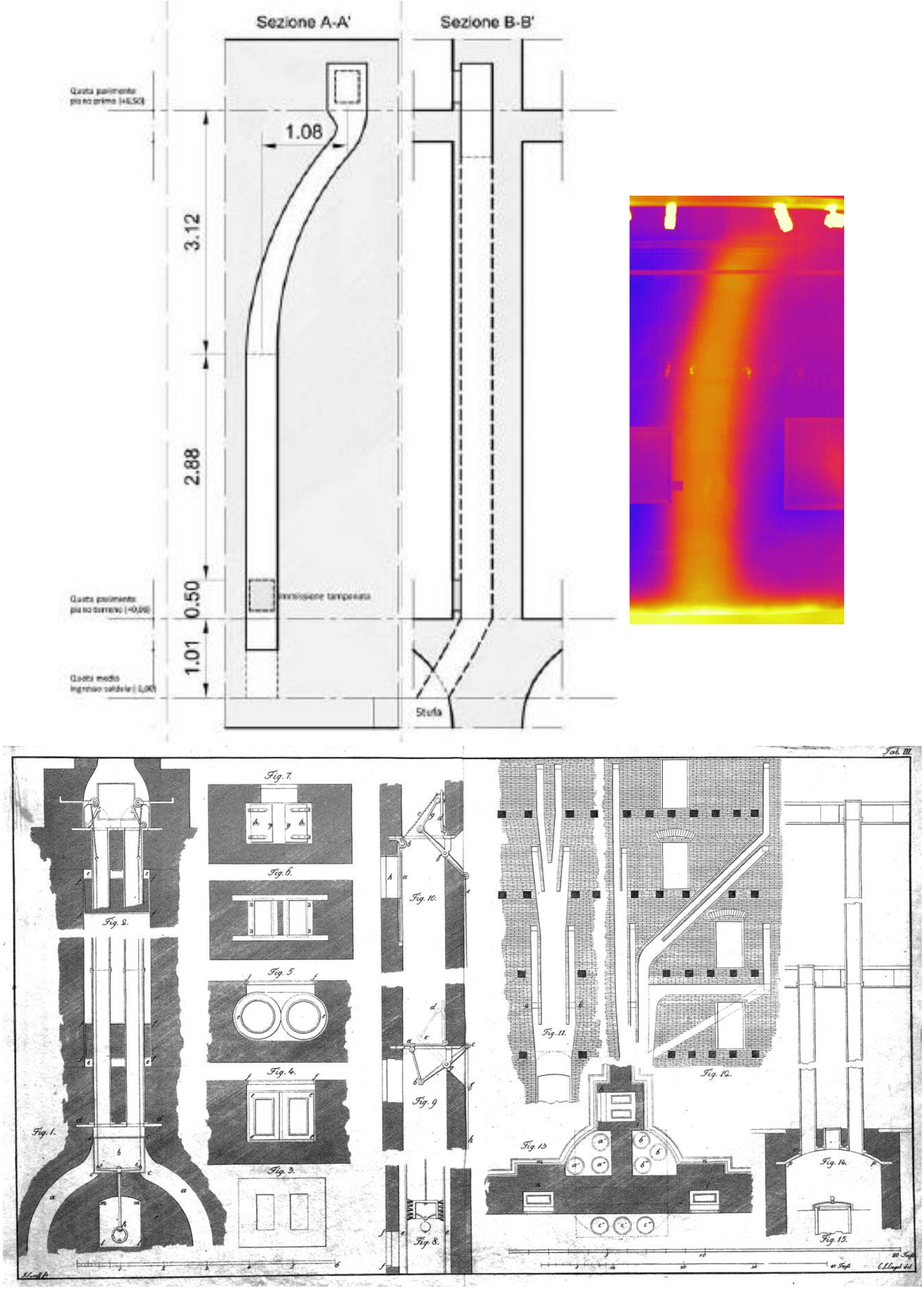

Fig. 5.2 – Comparison between the survey of a duct through endoscopy, its thermal image and an extract from a historical treatise of building construction (C.L. Engel 1830)

Keyword	Techno-economic paradigm	CHM paradigm
Mindset	Toolbox with standard solutions	Every object is unique
Approach	Systematic, linear	Dynamic, intuitive, traditional
Key question	Best solution to meet demand?	Preserve what, why and for whom?
Rationality	Optimization problem	Bounded in place and time
Objectives	Save energy & money	Changes with viewpoint, subjective
Criteria	Quantitative, measurable, probabilistic	Incommensurable, qualitative,difficult to measure, uncertain

Fig.5.3 – Decision making on climate control for conservation as exemplified in Merrit & Reilly (2010) and by Leijonhufvud and Broström (2012). CHM means Cultural Heritage Management

This integrated approach is clearly a very effective tool for studying and analysing the hygrothermal features of historic buildings.

Both the case studies suggest that the EN 15757 procedure can be helpful for the comparative assessment of different environments within complex historic buildings with many rooms.
In Villa Reale the procedure to determine target ranges was applied both to environments considered good for conservation and to rooms where climate-induced decay was observed and it was found that a higher frequency of out-of-range short term fluctuations was associated with more problematic rooms.
Out of range fluctuations were then further analysed in order to identify the factors causing the more risky and dangerous conditions and to assess the effects of different climate control

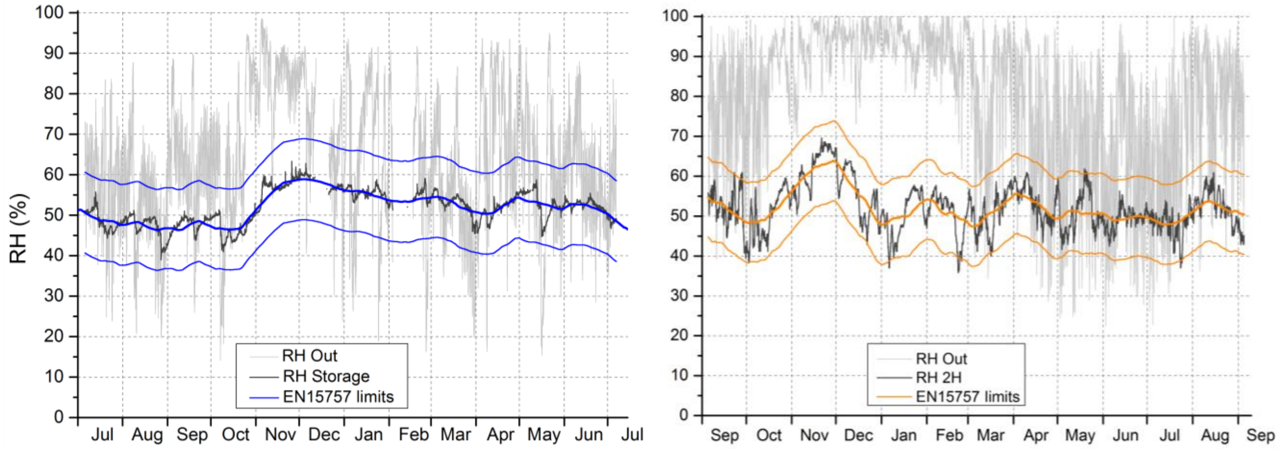

Fig. 5.4 – Yearly trends of RH in two unheated rooms compared with EN 15757:2010 target ranges. Left: the large storage in the attic of Villa Reale. Right: Room 2H in Skokloster Castle.

strategies on the indoor climate. In this way potential future interventions can be directed where they are more needed and effective.

Results suggest that passive strategies enhancing the hygrothermal inertia of historic buildings are more effective to obtain suitable conservation conditions. Anyway, this is nothing new: what here has been deducted by data and on-field analyses, was already written by Paribeni and Giovannoni in the 1930s (see par. 1.3) and it has been confirmed in practice by the recent case of the Victoria & Albert Museum mentioned above. The effectiveness of passive climate control for conservation has been also discussed by Padfield and others in different papers (Padfield 2007, Padfield et al. 2007). Passive strategies are obviously very energy efficient and sustainable and, compared to sophisticated HVAC systems for museums, they are less invasive and not exposed to failures or breakdowns.

The study on Skokloster Castle confirmed, in a historic building located in a completely different climate zone, the indications derived by the research on Villa Reale.

The passive behaviour of the building was further analysed: starting from the EN 15757 method, a specific procedure was developed for the assessment of the influence of air exchange on different unheated rooms of the castle.

A correlation was found between air tightness of the rooms and climate stability of their indoor climate. Moreover a new parameter was proposed, called Climate Fluctuations Transmittance: it is a rather simple and quick indicator to evaluate how outdoor climate fluctuations are buffered in historic interiors. If improved, it could be used in further applications for the assessment of the hygrothermal behaviour of historic buildings.

Figure 5.4 shows the yearly RH trends in the unheated storage of Villa Reale and in an unheated room with limited air exchange in Skokloster Castle. Together with the scatter graph in fig. 4.18, where yearly values from different rooms in Villa Reale are compared, it demonstrates that often nothing or only very small interventions are required in historic buildings to ensure good conservation conditions, if their potential is fully understood and exploited.

On this point we can quote once again some interesting words by Tim Padfield about the relation between sustainability and museums: "*Sustainability, in the museum context, is almost the same as durability. It means to devise a building that functions on its own. (...) Sustainability for me, a person who has had a lifetime's experience of air-conditioning that doesn't work, is building a*

museum in thick mud where the climate is appropriate—a museum in the middle of the hot desert where you want to keep the temperature down. In other words, sustainability is the idea of using cunning, looking at what people did in the past, adding that to modern physics, and generally designing things that you're proud of because you didn't drag in a whole lot of electricity and energy." (GCI 2007, pp.11-12). I think these words are very appropriate to describe the approach proposed by this thesis and can be applied not only to the environmental design of museums, but also to the low energy refurbishment of historic buildings in general.
In my opinion a further term should be introduced to describe the long-term benefits of passive climate control in historic buildings, which is resilience: the survival of so many artworks in relatively good conditions in unheated historic buildings, such as churches, castles and dwellings is probably the clearest evidence that massive historic structures generally have in themselves good capabilities to react to extreme climatic events and to buffer sharp hygrothermal variations.
Any intervention causing abrupt change on this hygrothermal behaviour and thus modifying the equilibrium historically established between a historic building and its environment should be avoided. When absolutely needed, an effective intervention has to be based on the preliminary and comparative analysis of the existing conditions, the requirements and the potential future uses.
A good example is the well-known refurbishment of the Neues Museum, where climate control systems were dimensioned on the basis of preliminary monitoring, the old systems partially exploited and display-cases were used to obtain a closer environmental control for the most delicate objects of the collection (Rahn, Friedrich & Riemenschneider 2009, Thiele 2009)

One of the main objection to a passive approach to environmental conservation is usually the lack in human comfort derived. Priority on RH stability is good for the preservation of the artworks but can result in uncomfortable conditions: temperature, which is more important to human comfort, will be regulated depending on relative humidity, if some climate control is installed, or it will follow closely the outdoor seasonal trends in a passive strategy. The graphs of Villa Reale in par. 4.1.3 show very well that in unheated rooms, temperature, though very stable in the short term due to the thermal inertia of the building, ranges from 5°C to over 30°C throughout a year.
Here the question is: is it right to force people to accept uncomfortable and unhealthy conditions to preserve a museum collection or a historic building?
In times of mass tourism and budget cuts, the attractiveness towards visitors is a requisite to which cultural institutions will hardly renounce and a comfortable indoor climate is fundamental to offer a pleasant and enjoyable visit. The instance of heritage enjoyment and use, together with the need for fundraising, would be in conflict with the instance of heritage conservation.
In my opinion this conflict could be eventually solved thanks to one of the main objectives of heritage, which is education. I mean that, instead of being proposed of an easy fruition of cultural heritage, the visitor could be involved as a positive actor in the conservation process by making him aware of his role and impact on the preservation of cultural heritage. Looking at climate control problems in this perspective, the visitor could be well disposed to accept a less comfortable visit if he knows that this will have a positive effect on conservation.
Different problems occur with workers, such as guardians or custodians. Here a valid answer could be to develop smart systems to provide them comfortable and healthy conditions with a low impact on the overall indoor climate, such as the friendly-heating systems recently proposed for churchgoers by Camuffo et al. (2006).

In conclusion, it can be affirmed that an informed and conscious empirical approach, implementing field analyses and measurements, coupled with experimental scientific research and a critical

historical revision of procedures developed throughout the time, has proved to be a very effective method for analysing unique and complex structures like historic buildings.
Thanks to this perspective it has been shown that the complex and multidisciplinary questions rising from the assessment of conservation environments and the development of climate control strategies can find satisfying answers with a limited impact on the preservation of our historic buildings and without affecting the possibility for a sound and sustainable use of our cultural heritage.

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Conclusions

Results and outcomes of the research have been discussed in Chapter 5. Conclusions are here firstly drawn as answers to the research questions presented in the introduction and then presented as general considerations on the possible future developments of this study and on further applications of the methodology proposed.

1) ***How have hygrothermal standards and specifications for environmental control been developed, spread and applied in the past? And how was climate controlled in museums before the introduction of modern air conditioning?***

The first part of the thesis has reconstructed the history of the development of hygrothermal standards and specifications from the introduction of central heating in museums to present days.
Even considering the limits declared in the introduction, the historical methodology used has proved to be effective in examining critically which climate control strategies were considered the most favourable to ensure suitable conservation conditions in conservation environments and in describing how they were promoted and spread in international publications.
Special focus was on construction history and on the development and application of climate control installations and devices in museums until the post-war period.
The result is a rather complete overview which highlights the link between technical development and evolution of museum specifications and shows how technical and scientific knowledge in the field of conservation has been decisively influenced by social and cultural history.
It may be used as reference or background for further research, more focused on a limited number of case studies.
The link between construction history, history of indoor climate and history of museums, which is at the basis of this study, is an innovative perspective which deserves to be further developed in the future.

2) ***Can a historical approach bring new knowledge and tools for the assessment of the present indoor climate in historic buildings?***

In the evolution of climate specifications for conservation throughout time, it can be observed a growing attention paid to the interactions between an object and its particular environment, since every object develops specific reactions to the climatic conditions in which it has been preserved for a long time. This has led to the concept of historical climate, with an emphasis on the existing conservation conditions rather than on ideal conditions.
A definition of historical climate was introduced by the EN 15757:2010 standard, while the EN 15759-1:2011 confirmed it as a priority in the decision making of climate control strategies to ensure good conservation conditions.
The direct link between a cultural object and its historical climate suggested that, when dealing with conservation environments in historic buildings, a further link could be established, i.e. how the influence of a historic building on its indoor climate has changed throughout time.
As a consequence, the thesis has proposed a second extended meaning for the concept of historical climate: the long-term history of conservation environments. This concept was then applied to museums and historic buildings through historical methodology.

In the second part of the thesis it was proposed an integrated approach which, by merging the two above-mentioned concepts of historical climate, allows both a potential reconstruction of the

conditions to which collections have been exposed throughout their history and a comprehensive assessment of the existing indoor climate within a particular historic building.
The proposed method was successfully applied to two case studies, a museum in Italy and a castle in Sweden. Analyses and results were presented and discussed in Chapter 4.
It was shown that a historical perspective in indoor climate analysis is very effective for identifying and assessing peculiar constructive features and environmental mechanisms which historic buildings can present. Case studies also demonstrated the good potential of historic structures for passive climate control strategies which exploit their hygrothermal inertia.

3) Which potential consequences does the concept of historical climate have on building conservation practice?

The proposed integrated approach, derived from the concept of historical climate, can find interesting application in the field of building conservation: it could be a useful support to face important questions like the compatibility between the conservation of buildings and the conservation of artworks or actual issues like the implementation of sustainable and energy efficient climate control strategies in historic buildings.
Case studies have shown the importance of extensive indoor climate analyses in historic buildings to make informed choices regarding climate control and the improvement of conservation environments from the point how view of climate-induced decay.
The decisive role that the building conservator should have in decision making processes related to climate control issues in historic buildings has been underlined in Chapter 5.
It was also shown that useful indications can derive from the rediscovery of practical solutions for climate control applied in the past to conservation environments. Today those solutions could inspire valid and less invasive alternatives to air conditioning, favouring the material conservations of historic structures.
Finally, the results obtained from the application of this new approach to climate analyses confirm that the development of a conscious and critical process of knowledge and the implementation of focused analytical procedures are the first and fundamental components to design an effective long-term conservation strategy for historic buildings.

The field of application of this study is somehow quite limited. The method proposed was applied to a restricted part of the historic buildings, those exposing artworks or cultural objects and thus generally used as museums.
Since they have the function of protecting valuable objects from environmental decay, these buildings required particular conditions and were thus studied and analysed in deep throughout the history.

Nevertheless the methodology presented in this thesis could be also applied to the larger context of historic buildings in general, which are used for other different functions involving the presence of people.
In this case, an assessment of the application to historic buildings of current standards and requirements regarding hygiene, health and comfort, sometimes quite restrictive, may be needed. A similar application of the historical method could be useful for tracing a comparative history of the specifications for human comfort. Though it was not the main topic of this study, the increasing trend in recommended comfortable temperatures can be clearly seen comparing the evolution of

museum standards throughout time. It has been incidentally shown in the text that an indoor temperature of about 12°C was considered satisfying at the beginning of 19th century in England (see paragraph 1.1) and that one hundred years later 15°C in Europe and 21°C in North America were indicated as generally accepted temperatures for humans (paragraph 1.3).
As in the case of conservation standards, it would be interesting to analyse the influence of social and cultural factors in the development of so different indications: the consequences of the application of these standards to historic buildings and the potential conflict between comfort and sustainability could be analysed from a different perspective.

The traditional solutions applied in the past to obtain comfortable conditions could also be studied through a comparative assessment. Several of these interesting constructive details are still existing in historic buildings, many others used to be discussed in books and manuals, further more can be found in documents and sources describing everyday life.
It could be interesting to study how the indoor climate was influenced by the habit of planking or panelling the inner side of stone walls in private dwellings. The same could be done for a less known practice, which was the use to cover inner walls during the winter season with thick woven coatings, that were then removed in summer.
Specific solutions were also developed for windows, which are very delicate components in historic buildings from the point of view of climate control. A deep analysis of the interrelations between the edges of the walls and the frame of the windows was probably involved in complex technical details, such as the use of internal wooden shutters in splayed windows which, when opened, fitted perfectly the oblique edges of the walls. It was a smart solution for increasing the income of light and insulating the colder part of the wall at the same time.
Another common practice in Northern Italy was the substitution of the external shutters used in summer as solar shading with glass panels to obtain more insulating double glazed windows for the cold season.
Just a few examples were given above to show that all these traditional practices are likely to have a good potential in environmental control, which by now can only be foreseen. Targeted studies are needed to give a quantitative assessment of their effectiveness and efficiency, not so much as single components but in their combined effect as a complex integrated system.

The traditional technical knowledge and many practical applications could be recovered and re-used today, with positive outcomes from the point of view of energy efficiency not only in historic buildings but also in new ones.
This is also the case of the models currently in use to calculate the energy performances of modern buildings, which seem not to work so well with the historic structures. These, as it has been shown, mainly rely on the inertia of massive walls which smoothes and buffers the wide and sudden variations of the outdoor climate.
Nevertheless, the same concept of hygrothermal inertia deserves to be further studied and specified: research is nowadays focusing on the moisture dynamics inside old masonry walls, which probably plays a key role in the interactions between outdoor and indoor environment and in the perception of comfort by building users.
Studying these issues in very complex cases like historic buildings could help to develop very accurate analytical procedures and tools that could be even applied to modern buildings.

Current research in the field of conservation of objects and buildings is already acquiring growing influence in the more general sector of construction industry. The collaborative and multidisciplinary European project *Climate for Culture*, for example, is carrying on valuable and

groundbreaking research on indoor climate modelling and hygrothermal building simulation and on the development of mitigation strategies to counteract the impact of climate change on historic buildings and on the built environment.
In this perspective, the 1930s experiences could be once again inspirational to us: even in a rather difficult historical period, research based on international cooperation and multidisciplinary collaboration succeeded in favouring a remarkable progress in the field of heritage conservation. Today, the key for progressing in cultural heritage research is probably still the same.

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