Annex 2

Report

Physical response of polychrome wood to fluctuations of environmental parameters

Dr. Łukasz Bratasz

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1. CURRICULUM VITAE

Name:	Łukasz Bratasz
Date of birth:	29th January 1972
Place of birth:	Kraków
Primary employment:	The Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences ul. Niezapominajek 8, 30-239 Kraków
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2. Scientific degrees

1996 – MS in physics:	Department of Mathematics, Physics and Computer Science, Jagiellonian University
2002 – PhD in physics:	Department of Mathematics, Physics and Computer Science, Jagiellonian University Title of the PhD dissertation: „Investigation of atomic constants by using four wave mixing in arc plasma”

3. Research

Research areas:	*Physics* – atomic spectroscopy, plasma sources, laser diagnostic of plasma, nonlinear optics, laser design. *Cultural heritage research* – physical methods of non-invasive testing and monitoring of museum objects, modelling stresses and strains induced in materials by impact of environmental factors, environment in museums and historic buildings, impact of global climate change on cultural heritage, application of physical methods in practical protection of cultural heritage.
Main experimental techniques:	four wave mixing, atomic spectrometry, water vapour sorption, mercury porosimetry, acoustic emission, laser vibrometry, speckle interferometry, in-situ monitoring of microclimate parameters and material response in historic buildings, optical fibre techniques, x-ray fluorescence, x-ray imaging, computed tomography, water transport imaging by NMR technique.

4. INFORMATION ON THE PROFESSIONAL DEVELOPMENT SO FAR

1996-1997	assistant in the Department of Atomic Optics, Institute of Physics, Jagiellonian University
1997 - 2002	PhD studies at the Institute of Physics, Jagiellonian University
1999	six-month research fellowship at the National Institute of Standards and Technology, Gaithersburg, USA
2002-2011	research fellow in the Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences
since 2011	researcher in the Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences
since 2007	senior researcher in the National Museum in Krakow
since 2013	head of physical and chemical laboratory in the National Museum in Krakow

5. Discussion of a single-topic series of publications on which the habilitation is based

5.1. List of publications on which the habilitation is based together with the bibliometric analysis

No.	Publication	IF (five-year mean)	Contribution [%]
1	S. Jakieła, Ł. Bratasz, R. Kozłowski, „Acoustic emission for tracing the evolution of damage in wooden objects”, Studies in Conservation, 52, 101-109, 2007.	0.456	50%
2	Ł. Bratasz, R. Kozłowski, D. Camuffo, E. Pagan, „Impact of indoor heating on painted wood: monitoring the altarpiece in the church of Santa Maria Maddalena in Rocca Pietore, Italy”, Studies in Conservation, 52, 199-210, 2007.	0.456	70%
3	S. Jakieła, Ł. Bratasz, R. Kozłowski, „Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions”, Wood Science and Technology, 42, 21-37, 2008.	1.817	50%
4	S. Jakieła, Ł. Bratasz, R. Kozłowski, „Acoustic emission for tracing fracture intensity in lime wood due to climatic variations”, Wood Science and Technology, 42, 269-279, 2008.	1.817	50%
5	Ł. Bratasz, „Acceptable and non-acceptable microclimate variability: the case of wood”, in: Basic Environmental Mechanisms Affecting Cultural Heritage, Nardini Editore, Florence, 49-58, 2010.	chapter in a book	100%
6	R. Kozłowski, Ł. Bratasz, Ł. Lasyk, M. Łukomski, „Allowable microclimatic variations for painted wood: direct tracing of damage development”, Postprints of Symposium “Facing the Challenges of	paper in peer reviewed conference	60%

	Panel Paintings Conservation: Trends, Treatments and Training", eds. A.S. Chui, A. Phenix, Getty Conservation Institute, Los Angeles, 158-164, 2011.	materials*	
7	Ł. Bratasz, A. Kozłowska, R. Kozłowski, „Analysis of water adsorption by wood using the Guggenheim-Andersen-de Boer equation", European Journal of Wood Products, 70, 445-451, 2012.	0.630	70%
8	B. Rachwał, Ł. Bratasz, M. Łukomski, R. Kozłowski, „Response of wood supports in panel paintings subjected to changing climate conditions", Strain, 48, 366-374, 2012.	1.473	60%
9	B. Rachwał, Ł. Bratasz, L. Krzemień, M. Łukomski, R. Kozłowski, „Fatigue damage of the gesso layer in panel paintings subjected to changing climate conditions", Strain, 48, 474-481, 2012.	1.473	60%
10	Ł. Bratasz, I. Harris, Ł. Lasyk, M. Łukomski, R. Kozłowski, „Future climate-induced pressures on painted wood", Journal of Cultural Heritage, 13, 365-370, 2012.	1.366	60%
11	Ł. Bratasz, „Allowable microclimatic variations for painted wood", Studies in Conservation, 58, 65-79, 2013.	0.456	100%

Summary Impact Factor, mean of 2007-2011 (all publications) 18.17

Summary Impact Factor, mean of 2007-2011 (publications in the habilitation series) 9.94

Summary number of citations of May 20, 2013 (all publications) 75.

Hirsch Index 5.

Relatively low Impact Factors of journals publishing results of scientific research supporting the protection of cultural heritage are outcome of much lower research potential and low funding in this area, compared to classical fields of physics, chemistry, or material science. It is enough to say that only two journals covering this research field are listed in the Journal Citation Reports of Thomson Reuters: *Studies in Conservation* (IF 0.456) and *Journal of Cultural Heritage* (IF 1.366), and their relatively low Impact Factors result from low editions of the journals. However, *Studies in Conservation* issued for 50 years represent a very high standard, all papers are rigorously peer reviewed and edited, and journal's impact on standards and policies in the cultural heritage protection is significant. Low impact factors result also from the fact that papers are targeted at conservators whose career path is focused on artistic achievements with little emphasis on publishing in scientific journals.

*/ Peer reviewed and thoroughly edited proceedings of conferences of the Conservation Committee of International Council of Museums ICOM, the International Institute for Conservation in London and the Getty Conservation Institute in Los Angeles are a very important communication tool of scientists with the conservation community, frequently more so than purely scientific publications. I have published in the proceedings of all three conferences (see my publication list) and I have included one publication of this type in the series of publications on which the habilitation is based [**H6**].

5.2. Discussion of research objectives of studies covered by the habilitation, results and their application

5.2.1. Introduction

My research work has concerned the use of methods and techniques of applied physics to solving one of the most important interdisciplinary issues in the cultural heritage field – establishing critical environmental fluctuations inducing cracking of polychrome wood, which remains unsolved on an international scale.

Polychrome wooden objects are complex multi-layer structures composed of humidity-sensitive materials – wood, animal glue, gesso and paints. They respond dimensionally to variations in relative humidity (RH) and temperature in their environment: they swell when they adsorb water vapour and shrink when they desorb water vapour. A notable effect is, however, that each material responds differently to the adsorption or desorption of water vapour. The difference in the response of gesso, used as a preparatory layer on wood, and of unrestrained response of wood substrate, especially in the most responsive tangential direction of the wood, has been identified as the worst case condition for fracturing of the pictorial layer: upon desiccation, the shrinkage of wood overrides that of the less responsive gesso layer which experiences compression, whereas upon wood swelling the gesso layer experiences tension. If the strain of a wood support goes beyond the critical level, the gesso can crack or delaminate.

Stresses induced due to the changes in RH are not limited to the pictorial layer only. The wood substrate may also experience stress due to a restraint on its dimensional response resulting from the excessively rigid construction restricting movement, or by assembling wood elements with different mutual orientation of their anatomical directions. The constraint of wood from free movement can cause deformation and cracking of the material, and subsequent cracking and flaking of the pictorial layer.

The concept that a stable climate reduces risk of cracking in painted wood – widely spread in the museum community - has been derived from practical observations. However, only relatively recently were two key issues – the dimensional response of the objects to changes in temperature and RH, and the critical levels of strain at which materials begin to deform plastically or fail physically – systematically examined (Mecklenburg, Tumosa and Erhardt, 1998).

The researchers proposed to accept yield strain of wood or gesso as a 'failure criterion', that is, allowable RH variations should not cause strains exceeding yield strains of wood or the gesso layer so that the response of the materials should at all times stay in the elastic (reversible) region. The failure criterion thus defined has allowed critical variations to be derived which take into account their magnitude and starting RH level.

An alternative concept used to establish the criteria for environmental control has been that of the 'acclimatisation' of polychrome wooden objects to the environmental conditions within which they have been preserved for a long time. Michalski (2009) coined the term 'proofed fluctuation' defined as the pattern of largest RH or temperature fluctuations to which the object has been exposed in the past. It was assumed that the risk of physical damage beyond that already accumulated in the past from present environmental fluctuations which do not go beyond the 'proofed fluctuations' is extremely low. The proofed fluctuation concept eliminates any need to elaborate mechanical response calculations and offers a risk assessment based just on historical environmental records. The acclimatisation concept was explicitly expressed in the international standards on the control of indoor environmental conditions favouring the conservation of sensitive historic materials (UNI 10969, 2002, PN-EN 15757, 2012). It should be stressed that the harmlessness of the pre-existing environmental conditions has been a key assumption in the approach. The assumption has to be carefully checked in each case, as physical damage can be cumulative/fatigue rather than catastrophic, therefore fluctuations, even if not exceeding the historic levels, can involve risk of damage.

5.2.2. Research aims of the present work

My research work accomplished over last 10 years aimed at getting deeper insight into the physical response of polychrome wood, as a complex, multilayer system, to fluctuations of environmental parameters, and establishing magnitudes of critical fluctuations that lead to object damage. The investigations have comprised:

- time-dependent analysis of the polychrome wood response to variations of RH and temperature, an aspect so far completely neglected, carried out by modelling water vapour transport processes and resulting strain and stress fields across wooden polychrome elements, with the use of the finite element computational technique
- experimental determination of properties of the materials comprised in polychrome wood: sorption of water vapour, moisture related swelling and shrinkage, water vapour diffusion and surface emission coefficients, tensile stress-strain relationships, required for the modelling of accurate 'real time' response of objects
- refining the failure criterion by analysing the response of a composite and mechanically coupled system - wood support coated with a multilayer material structure forming the pictorial layer, rather than simplistic analysis of responses of individual layers building up the structure which has been used so far.
- taking into account vulnerability of the pictorial layer to fatigue fracture – a consequence of the cumulative strain effects – as the continuous accumulation of slight changes, rather than infrequent serious damaging events, accounts for much of the deterioration of the investigated system.

The analyses carried out were based on physical methods and theories encompassing:

- the Guggenheim-Andersen-de Boer three-parameter sorption equation
- the similarity-hypothesis by Peralta and Bangi to describe the hysteresis of sorption
- diffusion equations with the diffusion coefficient related to water content, temperature and wood density, discretized using the weighted residual method following Galerkin's approach. The equations were solved using the Newton-Raphson method
- adjustment to the water vapour pressure resulting from a relationship between water content in wood and temperature changes, assuming an isochoric change in a cell of wood
- elastic regime of the mechanical interactions with the assumption of wood's moisture-related dimensional response in the form of a three-parameter Hill function

- algorithms for the image correlation of speckle interferograms to determine critical fatigue strains for the pictorial layer in the mechanical testing.

In turn, I have applied acoustic emission measurement as a method of direct, experimental monitoring of physical damage development induced by instability of environmental parameters. The method is based on continuous monitoring of energy released as ultrasound waves during fracture processes in materials. The acoustic emission method is non-invasive and capable of operating in real-world display conditions of objects. The methodology developed has allowed classical measurements of environmental parameters which affect the object to be replaced by direct and continuous recording and wavelet frequency analysis of signals related to damage which can be adopted as damage indicators. The use of the acoustic emission method has opened new perspective in science-based control of safety of polychrome wooden objects in museums and historic buildings.

To illustrate the principal achievements of my research work, I have selected a single-topic series of publications "Physical response of polychrome wood to fluctuations of environmental parameters" which encompasses 11 most representative publications from my entire publishing record. The results, concepts and their application are briefly described below.

5.2.3. Determination of material properties required for modelling of water vapour transport and spatial distribution of strain and stress in polychrome wood

Investigations of material properties required for the modelling encompassed: sorption of water vapour, moisture related swelling and shrinkage, water vapour diffusion coefficients, coefficients of the surface emission of water vapour, as well as mechanical properties: stress-strain relationships, elasticity moduli and Poisson's ratios, and fatigue functions. Detailed information on measuring methods and the parameters measured are comprised in publications **H3, H6-H9.** Working in the field of applied research I had to take into account a considerable diversity of materials present in objects of cultural heritage (for example of wood species) as well as diversity of environmental conditions (temperature, relative humidity, air flow velocity) which may occur in the environment of modelled objects.

A good example of complexity of the investigations was determining water sorption isotherms for a representative number of wood species present in objects of cultural heritage. I pioneered the evaluation of water vapour sorption for 21 historically important wood species used in the past for panel paintings and woodcarving [**H7**]. For the range between 0% and 90% RH, the relationships between the amount of adsorbed water and RH are described by a sigmoid shape of the type II isotherm in the IUPAC 1985 classification. It indicates the monolayer-multilayer physisorption in which an adsorbed surface layer progressively thickens as the vapour pressure is increased up to saturation pressure. The Guggenheim-Andersen-de Boer three-parameter sorption equation was used to interpret the physisorption of water on wood as it is capable of describing the full shape of type II isotherm and yields meaningful physical parameters as monolayer capacity and energy constant related to the net molar heat of adsorption. The same equation was used to derive average adsorption and desorption isotherms from the entire set of sorption data measured for 21 wood species (Fig. 1).

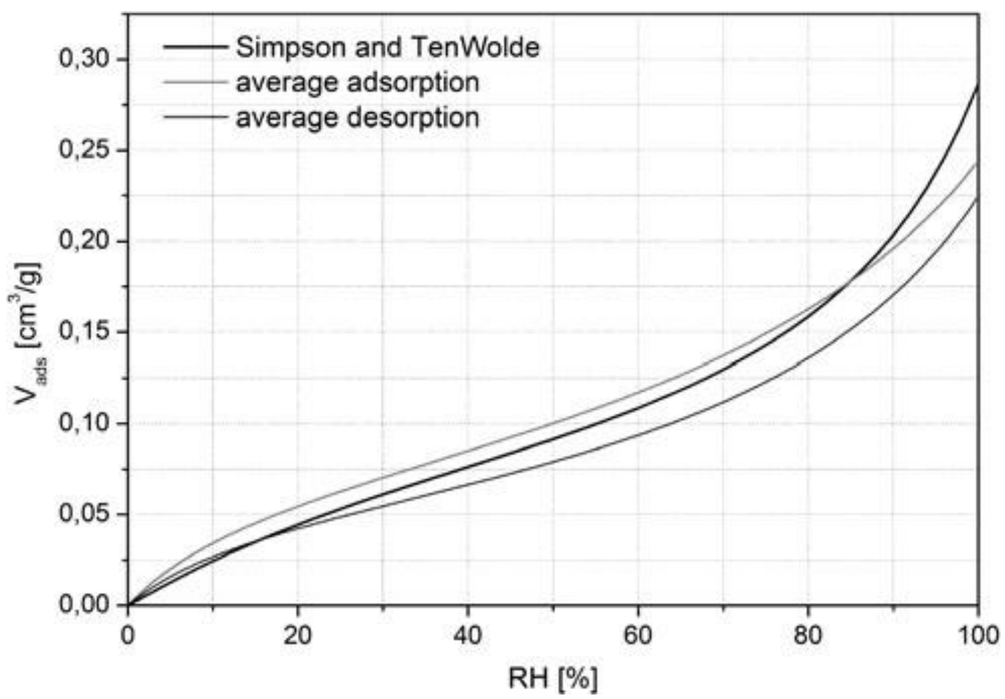

Figure 1. Average adsorption and desorption isotherms of water vapour calculated from the GAB equation using constants obtained by fitting the entire sets of adsorption and desorption data for 21 wood species important for cultural heritage. A 'general' adsorption curve by Simpson and Ten-Wolde (1999), widely used in wood science, is plotted for comparison.

Moisture sorption was found to be relatively invariant between various wood species reflecting similar chemistry of wood composition. For most practical purposes, moisture sorption by wood may be approximated by average sorption isotherm (adsorption and desorption) which would apply as a first approximation to any wood species constituting heritage objects.

Fatigue curve of gesso, used as a preparation layer on wood, is, in turn, an example of a key mechanical parameter established in my research which describes the cracking risk of the pictorial layer [**H6**]. Gesso is made by mixing animal glue with either gypsum or chalk. The volume ratio of inert solids to glue has a pronounced influence on the mechanical properties and dimensional response of the gesso. At high concentrations of inert used in the past, mechanically resistant but soft gessoes of little dimensional response to ambient humidity were obtained. Therefore, as mentioned in the introduction, the difference in the response of gesso and the free response of wood substrate is the worst case condition for fracturing of the pictorial layer.

Mecklenburg, Tumosa & Erhard (1998) proposed that, similarly to wood, the yield strain – established by testing at 0.002 - is the 'failure criterion' for the gesso. It should be recalled that the yield strain is determined in a single cycle loading test as the limit of the elastic range at which non-recoverable plastic deformation begins. In my research, the failure criterion was refined by taking into account fatigue failure from multiple strain cycles. Wood specimens coated with a gesso layer were subjected to repeated cycles of mechanical stretching to imitate repetitive dimensional changes of unrestrained panel paintings induced by RH fluctuations. Owing to very small size of the cracks formed, in the micrometric range, recording the crack development required highly sensitive and suitably repeatable method. A speckle interferometer was designed and built to this end which monitored the formation and development of cracks in the gesso layer, operating in the speckle image correlation mode. The results obtained allowed plotting an S-N curve where S is the strain leading to fracture and N is the number of cycles causing the fracture at that strain (Fig. 2). It is worthwhile adding that the developed algorithm of signal processing for the designed interferometer coupled with generators of sound waves exciting surface vibrations was subject of a publication not included in this procedure. It allows also delamination of the paint layer – typical damage of paintings – to be mapped and its development to be monitored both in the laboratory and in real-world display conditions of objects in a museum or a historic interior.

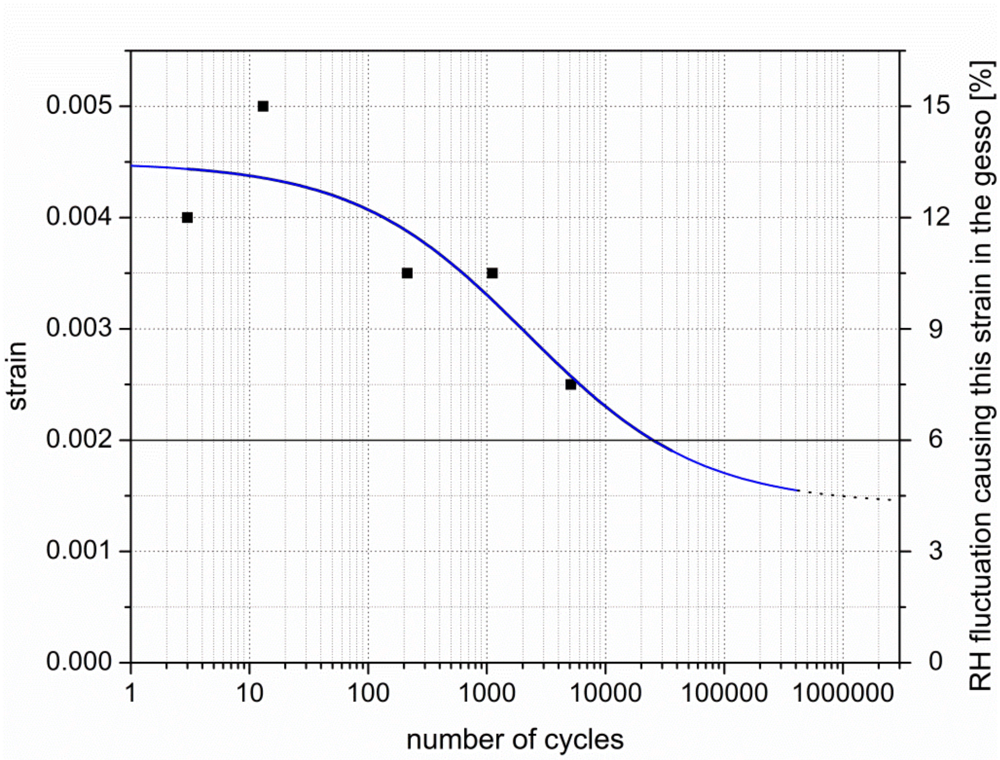

Figure 2 Strain, and corresponding amplitude of RH variation, leading to fracture in gesso versus number of cycles to cause fracture at that strain. The most responsive tangential direction in wood was considered and each RH variation was assumed to cause a full response of an unrestrained wood substrate. The amplitude of RH variation was calculated assuming a starting point of 50% RH.

The general shape of the fatigue curve is sigmoid, starting from the strain for fracture in a single cycle or a few cycles, and dropping to a plateau where cyclic strain can be tolerated indefinitely. The strain of 0.002 was accepted to be close to that value for any practical assessment of the risk of damage, as no fracture in the gesso appeared at that strain after a very large number of 30,000 cycles applied, equivalent to approximately 100 years of diurnal strain cycles. The fatigue fracture criterion established experimentally agrees with the single-cycle yield strain criterion. The result agrees with theoretical predictions as accumulation of damage is not possible without some plastic yield at least locally.

A further particular achievement of the material research was a measurement of the Poisson's ratio for the gesso, not available earlier in the literature [**H9**]. The measurement was carried out using the speckle interferometer for a wide RH range between 25 and 65%. The gesso specimens were compressed in strain steps of 0.0015 and the transverse strain was determined from the interferographic patterns. The Poisson's ratio was determined to be 0.2 in the entire RH range investigated.

5.2.4. Time-dependent analysis of response of model objects of polychrome wood to variations of environmental parameters

Water vapour movement and sorption induced by fluctuations of environmental parameters – temperature and relative humidity, as well as spatial distributions of strain and stress resulting from these fluctuations were carried out for two typical model objects:

- **object of cylindrical symmetry** as a model system imitating bulky wooden elements like sculptures. Such elements can be regarded as reflecting structure of a tree trunk with the element surfaces loosely following the tangential planes parallel to the trunk axis. The stress development in such objects is the result of slow water vapour diffusion in response to a change in ambient RH which results in evolution of the moisture content gradient across wood. The gradient gives rise to stress due to a gradient in the dimensional change of the material. The engendered stress decreases very slowly as the moisture gradient gradually vanishes and the cylinder reaches the new equilibrium moisture content through its cross section.
- **flat freely responding objects with a pictorial layer** imitating panel paintings. As it was mentioned above, stress and damage development in the pictorial layer in such system is outcome of a difference between a significant moisture-related response of wood substrate, especially in the tangential direction of wood, and a negligible response of ground gesso layer.

Modelling of water vapour transport processes and spatial distributions of strain and stress in the structure of polychrome wood was done by solving the diffusion equations with the diffusion coefficient related to water content, temperature and wood density, using the Newton-Raphson method, discretized using the weighted residual method following Galerkin's approach, and applying the elastic model of mechanical interactions, using as well the finite element calculation technique. The governing equations and computing procedures used are described in detail in publications **H3** and **H9.** All simulations started from stationary state of the system defined by the initial temperature and RH of the environment. The equilibrium moisture content in the materials corresponding to each stationary state was calculated from the history of environmental parameters changes and experimentally determined hysteresis of the adsorption and desorption isotherms. In the next step of the simulation, the differential equation of water vapour diffusion was solved using the two-dimensional discretisation of objects: for the cross-section of a cylinder (water vapour diffusion along the radial direction) and for the cross-section of a panel (water vapour diffusion perpendicular to the face). As the thermal diffusion coefficient is 4-5 orders of magnitude higher than that of water vapour, the response of the investigated system to temperature changes was considered instantaneous. Under such assumption, the effect of temperature changes on the spatial distribution of water content was calculated in each time step assuming an isochoric gas change in a wood cell filled with the matter in 25%. From the water content distribution, the distributions of the moisture-related strain and of the stress resulting from the restraint of the response were determined.

The modelling carried out for a **cylinder [H3]** produced maps of maximal stress engendered in wood by water content gradients across the material, producing its differential dimensional change. Magnitudes of the gradients, and thus of the stresses, depend on magnitude of an RH change in the environment, rate of this change and the starting RH level of the variation. Examples of stress maps calculated for a wooden cylinder of 130 mm in diameter for two different time scales of the RH changes – instantaneous and lasting 24 h – are shown in Fig. 3.

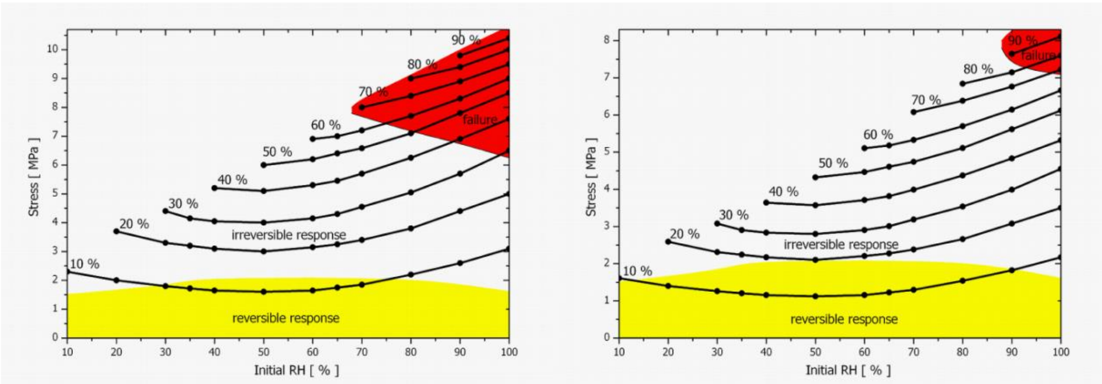

Figure 3. Stress induced in a wooden cylinder of a diameter of 130 mm by RH changes between 10% and 90%, instantaneous (left) and lasting 24 h (right), plotted as a function of the initial RH level from which the variation starts. Domains of RH variations producing reversible (yellow domain) or irreversible response (white domain), as well as leading to wood's failure (red domain) are marked.

Introducing the yield criterion, described in the introduction, on the stress maps derived from the modelling allowed the allowable RH variations below which the risk of mechanical damage is very small to be established as a function of the amplitude, time period and the starting RH level of the variation (yellow domain in Fig. 3). In turn, introducing the wood's tensile strength as the failure criterion on the stress maps allowed the domain in which wood is endangered by failure to be determined (marked in red in Fig. 3).

The research results showed that middle RH region is optimal from the standpoint of reducing risk of stress in a wooden cylinder. For the worst-case abrupt RH variations, wood can endure variation amplitude of up to 15% in this region but the allowable domain narrows when RH levels shift from the middle range. The allowable amplitude of the variations increases when time allowed for the change increases. However, stress field does not vanish even for slow, quasi-static changes in RH due to structural internal restraint resulting from the anisotropy in the moisture-related dimensional change.

Similar modelling of the time-dependent **free response of a panel covered with a pictorial level** [**H8, H9**] allowed the critical amplitude of the RH variations below which gesso remains undamaged to be established. During the first phase of calculations [**H8**], the criterion of gesso's yield (strain of 0.002) was used as well as the worst case of wood's free response in the tangential direction was assumed. If RH variations last much longer than the response time of a panel, the critical RH variations can be determined by reading the change in RH from the isotherms of moisture related swelling that will cause a difference of 0.002 between the responses of gesso and wood in the tangential direction. The allowable RH fluctuations thus derived are shown in the right axis of the plot in Fig. 2.

The simple calculation of critical magnitudes of RH variations was refined by taking into account the time required for the water vapour diffusion into a panel so that the dynamics of the process i.e. impact of RH variations lasting less than the response time of a panel is properly assessed. The behaviour of a wooden panel subjected to a simple step RH variation from the initial dry conditions to the final humid ones is illustrated in Fig. 4 which plots the relationship between the panel thickness and the time it takes for a panel to reach $(1 - 1/e)*100\% \approx 63.2\%$ of its final (asymptotic) strain. The parameter analysed can be termed the time constant of a panel response. The relationships are plotted for two situations: a symmetric diffusion through both the faces of a panel and an asymmetric diffusion through one of the two faces - simulating the extreme effect of completely blocked water vapour flow through the face covered with a pictorial layer.

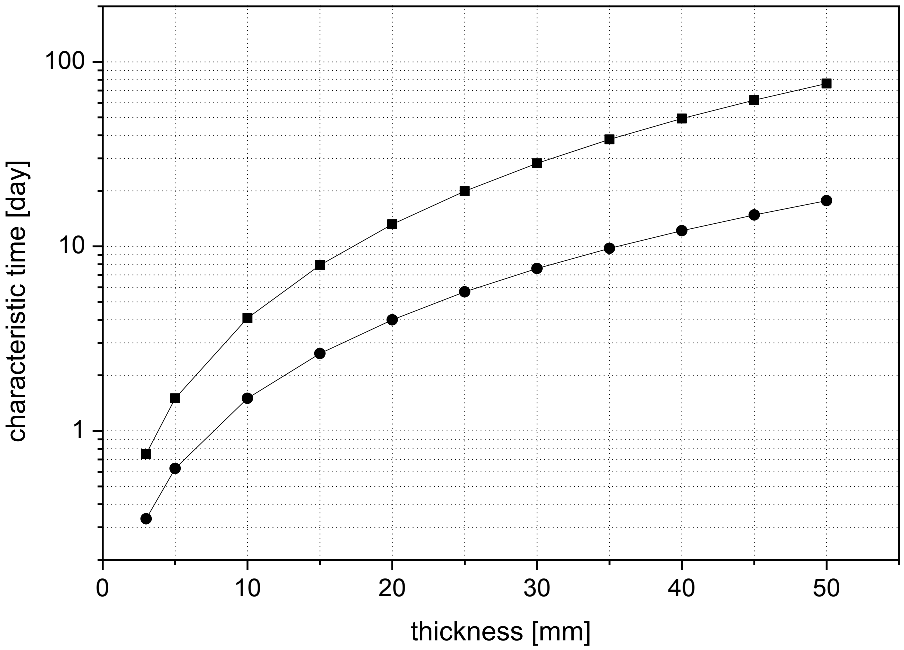

Figure 4. Response time of a wooden panel with one face (■) and both faces (●) diffusively opened subjected to a step RH change, as a function of panel thickness.

The step changes illustrated above occur sporadically in the environment of objects, yet cyclically repeated RH fluctuations account for much of the deterioration of polychrome wood. Cyclic RH fluctuations were represented in numerical simulations by a sine function. Although real-world climate fluctuations are the ergodic process, constant cycles were considered to grasp the general pattern of the panel's response. Each RH cycle of given amplitude and duration causes two consecutive swelling and shrinkage strains in a panel. The strain magnitude depends, as analysed earlier, on the panel thickness and the configuration of diffusion. The amplitude of cyclic sinusoidal RH fluctuations causing the strain of 0.002 in the most responsive tangential direction of the wood, assumed to load the decorative layer up to its yield point, was derived for the mid-RH range as a function of cycle duration, panel thickness and diffusion configuration (Fig. 5).

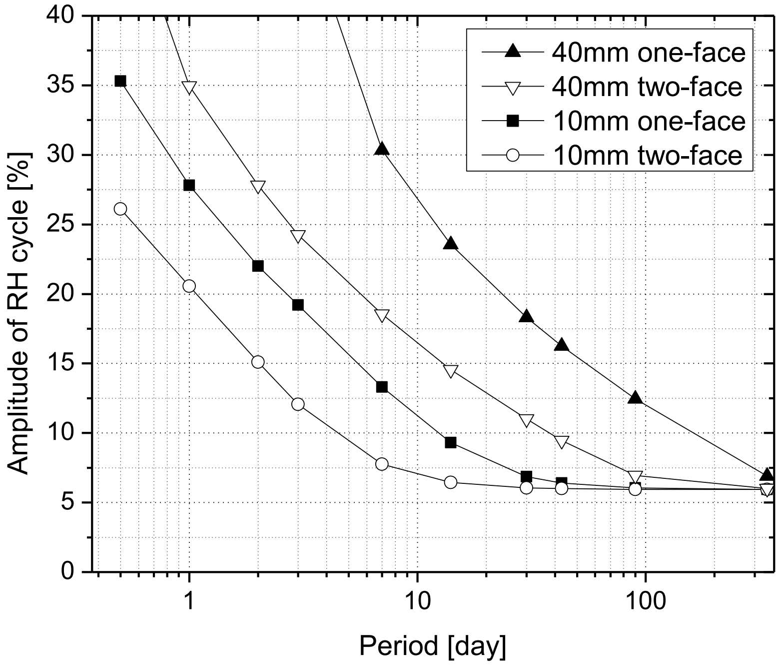

Figure 5. Amplitude of sinusoidal RH cycles at 20^{o}C causing the critical strain of 0.002 in the tangential direction of wood as a function of the cycle duration for two panel thicknesses of 10 and 40 mm and for a symmetric and asymmetric diffusion.

The analysis of free response of a panel covered with a pictorial layer to RH variations described above was further refined by taking into account two important factors [**H9**]. Firstly, coupling of wood support with a rigid gesso layer was considered. The object formed is non-homogenous in its material structure but mechanically and diffusively coherent. Material properties of gesso were measured experimentally, and then used to assess the RH response of gesso itself and to predict the restraint of the applied gesso layer on the free movement of the wood support. Secondly, vulnerability of the pictorial layer to fatigue processes was taken into account by considering a relationship between the critical strain and the number of cycles at that strain, described above.

To calculate the amplitude of RH variations allowable for panel paintings, the variations were again approximated by a sine function. The allowable amplitude of an RH cycle for a given panel was calculated as a value causing cyclically the critical difference between the coupled responses of the wood substrate and the gesso layer leading to the first fracture of this layer after 100 years of cycle occurrence. 100 years were selected as a time span typical of museum protection strategies over which the permanent changes accumulating in the object would produce a 'perceptible damage', in this case considered the first fracture on the undamaged gesso. The results of the calculations are showed in Fig. 6.

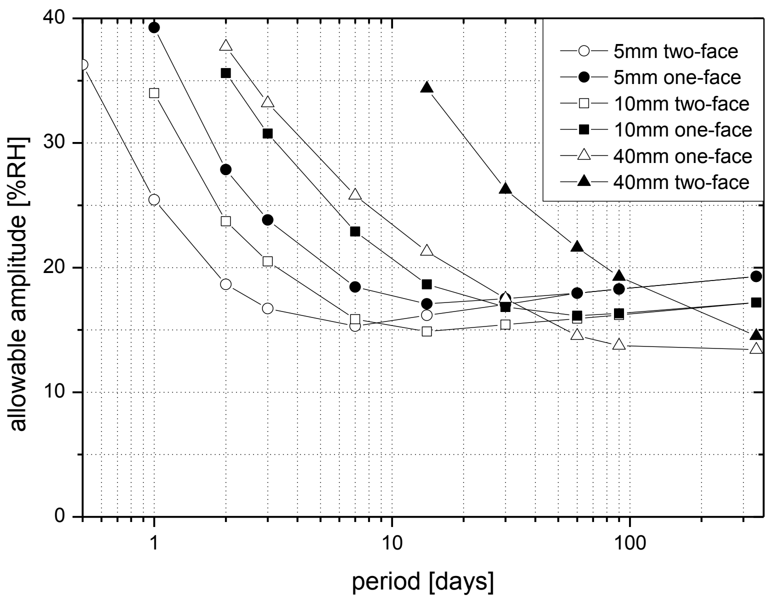

Figure 6. Allowable amplitude of the sinusoidal RH cycles as a function of the cycle duration for panels of thickness between 5 and 40 mm, gesso thickness of 0.5 mm and the water vapour flow through one or both faces at 20 ^{o}C.

The panels respond dimensionally less and less significantly when the fluctuation period decreases, which is reflected in an increasing allowable amplitude of the fluctuations. Also, when the duration of a cycle goes beyond the time of full response of the panel, its allowable amplitude increases as fewer cycles would occur in the period of 100 years considered. Moreover, the dimensional response of thin painted panels decreases due to restraint placed on the free response of the substrate by the gesso layer. It was established that the situation of wood substrate 10 mm thick, with two faces open to the water vapour diffusion, subjected to fluctuation cycles lasting 14 days represents 'the worst case' of the study performed and the allowable amplitude of an RH cycle for this case is only ±14%.

The refined physical model of the structural response of polychrome wood yielded a more than two-fold increase of the allowable amplitude for the worst-case RH cycles to ±14% when compared with merely ±6% derived for the simplified criterion of single-cycle yield strain and without considering the coupling of the gesso layer with the wood support.

5.2.5. Experimental verification of the structural response of polychrome wood objects to variations of environmental parameters

Acoustic emission method, consisting in monitoring of elastic energy released in the form of ultrasound waves during fracturing processes in materials, was adapted, developed and applied – for the first time globally in research on the physical damage processes in heritage objects – to the experimental verification of results of the modelling [**H1, H4**]. Investigations of cylindrical wood specimens demonstrated that high-frequency components produced during wood fracturing could be extracted from the recorded signals using the wavelet transforms. Energy extracted in this frequency range is precisely correlated with crack size, and that in turn with the amplitude and rate of an RH variation. The research confirmed accuracy of the numerical modeling by showing that the AE activity generated in a wooden cylinder becomes negligible when RH variations are below the allowable magnitude predicted by the modelling, or when the time interval of the RH variation is long enough (Fig. 7).

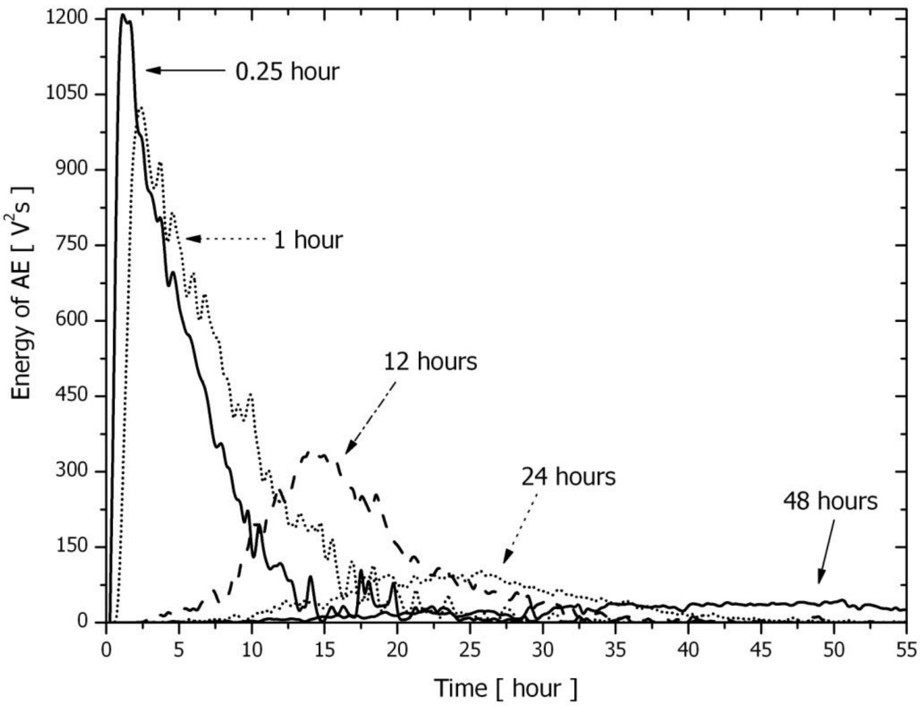

Figure 7. Energy of AE events per 15-minute time interval during a drop of RH from 70 to 30%. The different plots show the effect of altering the time over which this RH change occurs.

On-site AE monitoring of a wooden altarpiece in an historic church further confirmed the usefulness of the method in tracing stress development in wood induced by instability of the environmental parameters [**H1**]. Moreover, the research results confirmed the possibility of tracing a gradual development of micro-damage areas, which are precursors of macroscopic, from the perspective of a conservator or a curator, wood damage.

A further validation of the modelling of structural response of a wooden cylinder to fluctuations of environmental parameters was offered by measurements of dimensional response of elements of historic wooden sculptures during continuous in-situ monitoring of the main altarpiece in the church of Santa Maria Maddalena in Rocca Pietore in Italy, which ran for two years. The elements of the altarpiece responded to the variability of indoor temperature and RH [**H2**]. The responses varied considerably with the thickness of the elements monitored. A fine wooden element, 5 mm thick, expanded and contracted quickly and completely even during short-term RH changes. On the other hand, the overall dimensional reaction of a massive wooden element, 150 mm in diameter, was much slower, as the adsorption or desorption of water vapour was too slow to produce uniform moisture content throughout the wood. Further, variations in the width of a large slit (crack) propagating along the radial direction in the wood was recorded during the monitoring with the use of a sensor based on the measurement of Eddy currents.

The monitoring confirmed the findings of the modelling work that only the external layer of wood, several millimetres thick, is strongly affected by any, even rapid, change in RH. Radial gradients in water content developed engender stress in the tangential direction of wood, resulting from restrained dimensional change. The slit width increased or decreased, respectively, on a decrease or increase of RH, due to swelling or shrinkage of the external layer of wood leading to increases of tensile or compressive stresses. The expansion and contraction of the crack was rapid and followed even short fluctuations of the environmental parameters. The simulations carried out demonstrated that the existing crack reduced by 25% the tangential stress calculated for the full restraint of the external layer. Therefore, cracking brings about an ‘acclimatisation’ of the elements to the fluctuations of the environmental parameters and, in consequence, the magnitude of allowable fluctuations of these parameters increases above the critical values determined by the modelling. The described observation confirms that these critical values provide a cautious ‘baseline’ in the environmental standards for safe display and storage of sensitive objects as they are based on the extremes of conservative criterion of the elastic deformation of wood and assumptions of worst case response of fully restrained wood in the tangential direction.

Experimental validation of the results of numerical simulations by measurements of deflection of a wooden panel coated with a layer of gesso exposed in real-world conditions in the National Museum in Krakow is also worth noticing [**H9**, Fig. 8]. As the primary solution of the modeling are displacements, the observed agreement between the calculated and measured deflection provided assurance that all of the mechanical and diffusion parameters had been adequately determined and, therefore, the environment-induced strains calculated by the model could be deemed reasonably accurate.

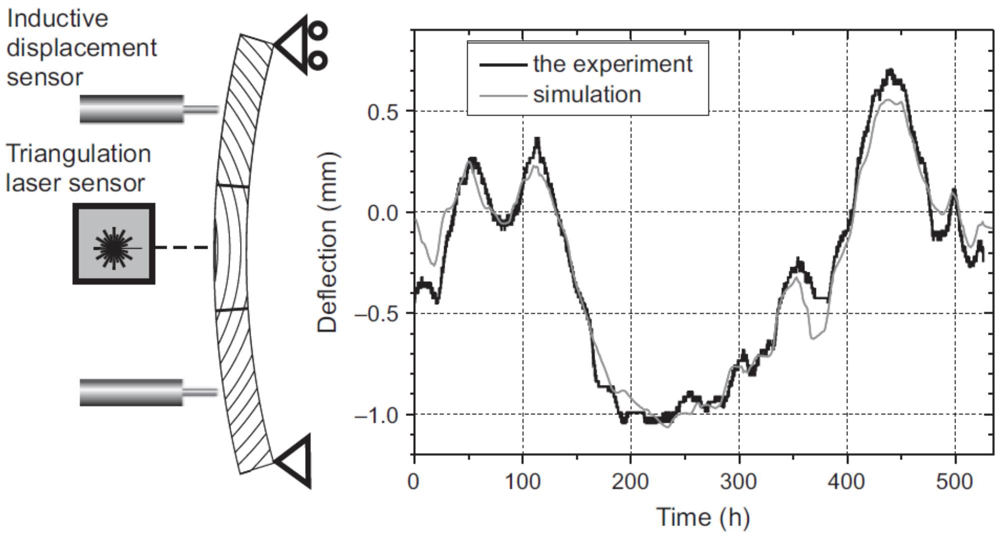

Figure 8. Set-up to monitor the deflection of the experimental panel (left) and changes in deflection in response to changes in ambient RH: measured and calculated (right)

5.2.6. Application of the research results covered by the habilitation

The insight into the structural response of polychrome wood to fluctuations of environmental parameters and related damage potential opened path to development of a synthetic risk index to assess environmental stability, which can be a tool supporting long-term policy and strategy of protection of cultural heritage objects.

The proposed index can be defined as a yearly ‘dose’ of accumulated fatigue damage of the pictorial layer from the real-world fluctuations of environmental parameters, according to the equation:

$$C = \left(\sum_{i=1}^{k} \frac{n_i}{N_i} + \sum_{j=1}^{l} n_j \frac{A_j}{A_0} \right) \times \frac{1}{a}$$

where k is number of RH ranges smaller than A_0, a threshold range for fracture of the design layer in a single cycle - each contributing n_i cycles and N_i being number of cycles to failure for a given RH range; j is number of RH ranges greater than A_0, each contributing n_j cycles of range A_j. a is number of years over which the RH cycles are counted from the real non-periodic RH-versus-time variations. The first component in the brackets, known in the materials science as Miner's rule, assesses the combined damaging effect of the below-threshold RH cycles on the design layer. The second component assesses the combined damaging of the above-thresholds RH cycles, the damaging impact of each cycle range being weighted by the ratio of a given range A_j to the threshold range A_0.

The proposed index was used to asses impact of global climate change on vulnerable to RH variations object stored indoors. Climate predictions for the future have been extracted from the output of two widely used models from the Hadley Centre, UK: HadCM3 and HadRM3. HadCM3 is a coupled ocean-atmosphere global circulation model with a grid resolution of 2.5 × 3.75° i.e. 278 × 295 km^2 at 45°N latitude. HadRM3 is a regional climate model, which encompasses Europe at a higher resolution (a grid of equal-area cells, 50 × 50 km^2) but spans only the years 2070 to 2099.

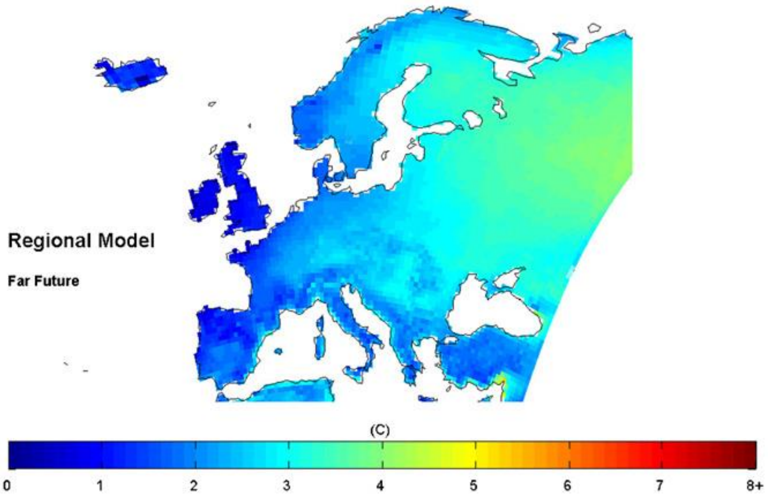

Figure 9. Climatological risk index to painted wood mapped over Europe for 2070–2099 derived from HadRM3 output under the A2 scenario.

Correlation functions between indoor climatic parameters and outdoor climate were derived from measurements of real conditions in unheated historic buildings. Then, the obtained predicted indoor RH versus time histories were subjected to a mathematical process of filtering in which they were reduced into simple cycles of various amplitudes using the Rainflow Counting protocol. In result, a European climate risk map was obtained (Fig. 9) as well as a map of differences in the risk indices for the near and far future, taking years 1961-1990 as the baseline (Fig. 10).

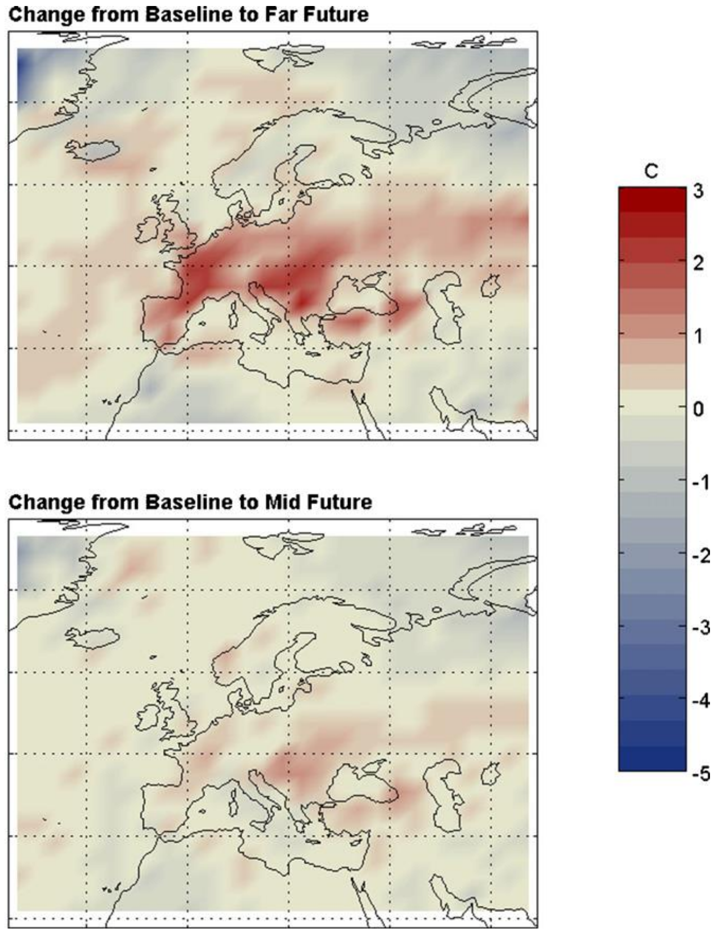

Figure 11. Difference maps from baseline (1961–1990) to near future (2010–2039) and far future (2070–2099) representing the changes in the climatological risk index to painted wood derived from HadCM3 output under the A2 scenario.

The presented methodology is not limited to forecasting the damaging impact of future outdoor climate change on polychrome wood. It can be also used to assess stability of environment in a more precise way than offered by general climate quality classes contained in the environmental standards (for example ASHRAE, 2007). The analysis can be applied both to buildings of natural microclimate with no active climate-control systems and to buildings with controlled climate in which active systems operate to control air temperature (heating), air temperature and humidity (air-conditioning), or ventilation rate. Another potential application of the risk indices is evaluation of the harmlessness, or otherwise, of various strategies for reducing the environmental control needed to ensure good preservation of the objects, using less and simpler equipment and lowering investment, maintenance and energy costs.

5.2.7. Synthetic review of the current state of knowledge on allowable fluctuations of environmental parameters for polychrome wood

Scientific understanding of mechanism of the effect of variations in environmental conditions on polychrome wood requires by very nature of the task an interdisciplinary approach. In my work, I have been exploring the research area where several scientific disciplines overlap - material science - in particular physical chemistry of interfacial phenomena such as adsorption and diffusion of water vapour, wood science, physics of the transport processes, experimental mechanics, and physical methods of tracing damage. In turn, the outcome of my research has been highly relevant to practical protection and management of cultural heritage resources and should be adequately communicated to the heritage protection community.

As my research programme developed, I wanted more and more to ensure that my scientific achievements reached the conservation practitioners and decision makers in the cultural heritage protection in Poland and globally. Therefore, I published two one-author review articles synthesising the scientific state-of-the-art in this field: a chapter in a book [**H5**] *'Basic environmental mechanisms affecting cultural heritage'*, and a paper [**H11**] in *Studies in Conservation* – the premier international journal for the conservation of historic and artistic works. In these reviews, I have brought together all diverse aspects of my research and offered a systematic progression through multi-fold aspects of the physical response of polychrome wood as a complex, multilayer system to fluctuations of environmental parameters, and discussed the consequences for the practice of heritage protection.

The most general conclusion from the synthesis accomplished is that the research increasingly has undermined the fundamentalist concept of the strict control of environmental parameters in museums, which has led to more relaxed environmental specifications and individual long-term targets for specific collections, seasonal changes and broader ranges of short-term fluctuations.

Each polychrome wood object with its individual original structure and conservation history, acclimatised to a particular environment in which it has been exposed, needs individual levels and ranges of temperature and RH. However, the body of scientific evidence indicates that moderate variations within the approximate range 50 ± 15% do not endanger heritage objects; temperature is a secondary parameter when the heritage protection is concerned.

The range provides a cautious ‘baseline’ for the environmental standards for safe display of polychrome wood. This baseline can be re-defined with advances in research on the mechanism of physical fracture in polychrome wood, in particular when the determination of critical strain levels is refined. I am convinced that the direct monitoring of polychrome wood by acoustic methods to trace micro-damage induced by instability of environmental parameters will become an additional, important tool for safety control of wooden heritage objects.

In publication **H11**, I also undertook a review of existing environmental specifications and standards. The recent European standard PN-EN 15757:2012 is especially valuable - I substantially contributed to its development and the translation into Polish as member CEN Technical Committee 346 and chairman of PKN Technical Committee 311.

I am convinced that all the publications presented have reached the heritage professionals in the broadest sense of the term: practising conservators, heritage and museum scientists, collection and conservation managers, teachers and students of conservation and academic researchers in the subject area of my research. I am also convinced that, in this way, the research brought together for my habilitation has provided synthetic scientific base to the current debate on the improvement of the environmental standards for cultural heritage collections, in terms of reducing energy consumption and carbon emissions while maintaining high level of the collection care (IIC2008, IIC2010).

5.2.8. References

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UNI 10969. 2002. *Cultural Heritage - Environmental conditions for conservation. General principles for the choice and the control of the indoor environmental parameters. Part 1 Microclimate.*

6. Discussion of other research and organisational achievements.

6.1. Research work before PhD

I was employed as an assistant in the Institute of Physics, Jagiellonian University, immediately after accomplishing my Master thesis, devoted to the determination of electromachining plasma discharge, in the Department of Atomic Optics of the Institute. The work was continued during my PhD studies in the group of Professor Karol Musioł which produced two publications in a journal listed in the Thomson Reuters Report:

1. A. Miernikiewicz, Ł. Bratasz, S. Pellerin, N. Pellerin, K. Musioł, and J. Chapelle, "New interesting results on the Electro-Discharge Machining", High Temp. Material Processes, 3, 193-211, 1999.

2. N. Pellerin, S. Pellerin, Ł. Bratasz, K. Musioł, K. Dzierzęga, A. Miernikiewicz, and J. Chapelle, "Analysis of some Electrical-Discharge Machining Mechanism", High Temp. Material Processes, 5, 423-437, 2001.

Then, the research interest of my group focused on the determination of structure of atoms and ions of silicon, germanium, krypton, xenon, neon and argon - elements important for the electronic industry as well as astrophysics. The results obtained led to a collaboration with the National Institute of Standards and Technology, Gaithersburg, USA, and allowed me to obtain a six-month internship there. During my stay, I was involved in calibration of a unique Fourier spectrometer working in a range from deep ultraviolet (180nm) to far visible (780nm) and its application in the investigation of atomic structures.

Results of this work were published in three papers in journals listed in the Thomson Reuters Report:

1. S. Zielinska, Ł. Bratasz and K. Dzierzega, "Absolute Transition Rates for transition from $5p^4$ (^3P) 6p $^4P^o_{5/2}$, $^4P^o_{3/2}$, $^4D^o_{7/2}$ and $^2D^o_{5/2}$ levels of Xe II", Physica Scripta, 66 (6), 454-457, 2002.
2. K. Dzierżęga, Ł. Bratasz, U. Griesmann, G. Nave, "Absolute transitions rates for transitions from 5p levels in Kr II", Physica Scripta, 63 (3), 209-218, 2001.
3. Ł. Bratasz, K. Musioł, "Branching Ratio measurements for Ge I and Ge II", Acta Physica Polonica, 98 (4), 345-351, 2000.

and one paper in peer reviewed conference materials:

U. Griesmann, R. Kling, JH. Burnett; Ł. Bratasz, "The NIST FT700 Vacuum Ultraviolet Fourier Transform Spectrometer: applications in ultraviolet spectrometry and radiometry", Proceedings of the Society of Photo-optical Instrumentation Engineers (SPIE), Denver, 3818, 180-188, 1999.

After return to my mother institution, I took part in the implementation of a national research project focusing on measurement and determination of Stark parameters (width, shift and asymmetry) and their dependence on distribution and density of electrons in arc plasma by means of a method of nonlinear optics – the degenerate four wave mixing method.

The development and application of the degenerate four wave mixing method to the plasma research allowed solving fundamental problems of the classical spectroscopy: non-local character of the measurement related to the integration of the signal over the entire optical path, and assumption of temporal stability of the plasma discharge. The obtained results were published in a journal listed in the Thomson Reuters Report:

K. Dzierzęga , Ł. Bratasz, S. Pellerin, B. Pokrzywka and K. Musioł, "Stark Width and Shift Measurement for the 696,543nm ArI line using degenerate four wave mixing (DFWM) Spectroscopy", Physica Scripta, 67, 1-7, 2003, and constituted also the core of my doctoral thesis developed under the supervision of Professor Karol Musioł – I obtained the PhD degree in 2002.

6.2. RESEARCH WORK AFTER PHD

After receiving the PhD degree, I decided to continue my scientific career in the Cultural Heritage Research Group led by Professor Roman Kozłowski at the Jerzy Haber Institute of Catalysis and Surface Chemistry of the Polish Academy of Sciences. My first task in this exciting and completely new for me area of research, combining methods of chemistry and physics, involved implementation of project FRIENDLY HEATING funded by the European Commission within the 5th Framework Programme (2002-2005). The project was focused on the investigation of impact of heat, moisture and particulate matter transport, induced by heating of historic churches, on historic materials and objects, especially on polychrome wood. Within the project, I developed together with the emerging research group, three novel research tools:

- system of triangulation laser sensors and displacement sensors based on Eddy current measurements for continuous in situ monitoring of dimensional changes of wooden historic objects, such as sculptures or panel paintings, in response to temperature and humidity fluctuations in their environment
- numerical modelling of water vapour and heat transport in wooden objects allowing to predict moisture content gradients in the cross-sections of the materials resulting in the internal stress fields; the modelling was based on a broad programme of the laboratory measurements of critical material parameters – water vapour sorption isotherms and expansion coefficients, diffusion and surface diffusion coefficients as well as mechanical properties
- monitoring and analysis of acoustic emission defined as elastic energy released during crack development, material deformation or fatigue processes.

The application of the above research tools allowed achieving new scientific outcome: determination of a multidimensional map of variations of temperature and relative humidity critical to wooden elements plotted as a function of their amplitude, duration and initial level. When the critical variations are exceeded, risk of deformation or mechanical damage of wooden historic objects becomes significant.

The obtained results were published in 6 publications targeted at professionals in the subject area of applied chemistry and material science as well as at conservators and conservation scientists. Next to 3 publications included in this habilitation, other 3 publications were published:

1. Ł. Bratasz, S. Jakieła, R. Kozłowski, "Allowable thresholds in dynamic changes of microclimate for wooden cultural objects: monitoring in situ and modeling", *ICOM Committee for Conservation, 14th Triennial Meeting, The Hague: Preprints*, ed. I. Verger, James & James, London, 582-589, 2005.

2. Ł. Bratasz, R. Kozłowski, "Laser sensors for continuous monitoring of dimensional response of wooden objects *in situ"*, *Studies in Conservation*, 50, 307-315, 2005.

3. Ł. Bratasz, R. Kozłowski, A. Kozłowska, S. Rivers, "Conservation of the Mazarin Chest: structural response of Japanese lacquer to variations in relative humidity", *ICOM Committee for Conservation, 15th Triennial Conference, New Delhi: Preprints*, ed. I. Verger, 2, 933-940, 2008.

In the application aspect, the gathered knowledge allowed for precise assessment of damaging impact of heating systems, which disturb temperature and humidity in historic churches. Thus, the classification of the heating systems in terms of their suitability for the use in historic churches was made possible. An engineering work within the project led to the development of a new system providing localised heat in areas where people are, which in turn induced minimal disturbance of the microclimate in the rest of the church where historic objects and furnishings are located. A continuation of the undertaken practical measures was possible in the framework of two new projects granted to the group: „Proper heating of historic wooden churches – characterization of airflows, air particulate deposition and strains in the wood" – Polish-Flemish bilateral project, and project IGNIS „Heating systems for conservation of historic churches", which was coordinated by me within the Structural Operational Program. Project IGNIS allowed for the development of a novel heating control system offering optimal comfort for churchgoers and at the same time protection of historic objects vulnerable to climate variations. The production of the developed control system was started by company TermoTechnika from Świdnica.

The obtained results related to the area of cultural heritage protection in historic churches, were published in a publication included in this habilitation, as well as in a book of which I was a co-author and in a further journal publication:

1. *Church Heating and the Preservation of the Cultural Heritage. Guide to the Analysis of the Pros and Cons of Various Heating Systems*, Electa, Mediolan, 2006.

2. L. Samek, A. De Maeyer-Worobiec, Z. Spolnik, L. Bencs, V. Kontozova , Ł. Bratasz, R. Kozłowski, R. Van Grieken, "The impact of electric overhead radiant heating on the indoor environment of historic churches", *Journal of Cultural Heritage,* 8, 361-369, 2007.

The results were also presented at many international conferences on preventive conservation. At present, the research related to the impact of church heating on the state of preservation of historic interiors is continued within a national project focusing on monitoring, analysis and conservation assessment of re-suspension and deposition of particulate matter on architectural surfaces during heating episodes:

„Impact of historic church heating on transport and deposition of particulate matter" - national research project no. UMO-2011/01/D/HS2/02604, 2011-2014.

The acoustic emission method for non-invasive tracing and analysis of damage development at micro level, based on recording elastic waves generated during fracturing, was further developed within research project SENSORGAN (2006-2008) funded by the European Commission's 6th Framework Programme. The Institute was a research partner to the project and I was leader of Institute's project team. The main objective of the project was to develop a sensor toolkit for comprehensive monitoring of degradation processes in historic organs caused by the environmental factors. Successful implementation of the project allowed designing a simple and economic acoustic emission sensor for direct in situ tracing of cracking in the historic organs and other wooden objects. The sensor based on the know-how gained during the project has been produced by Hanwell Ltd. which signed a license agreement with the Institute http://www.the-imcgroup.com/product/item/woodwatch The sensor is now integrated into Hanwell's general radio monitoring system of environmental conditions in historic interiors. Additionally, the research results were published in:

C.J. Bergsten, M. Odlyha, S. Jakiela, J. Slater, A. Cavicchioli, D.L.A. de Faria, A. Niklasson, J.-E. Svensson, L. Bratasz, D. Camuffo, A. della Valle, F. Baldini, R. Falciai, A. Mencaglia, F. Senesi, C. Theodorakopoulos „Sensor System for Detection of Harmful Environments for Pipe Organs (SENSORGAN)", *e-Preservation*, 7, 116-125, 2010.

Further development of this very useful and promising method has been continued within several research projects:

- SMOOHS, 7th Framework Programme of the European Union, 2008-2011;
- „Acoustic Emission for museum object monitoring as a universal method of preventive conservation" – national research project of which I was a coordinator, 2009-2012.
- „Development of micro-damage monitoring method in mineral materials constituting historic architecture and sculptures", national research project, 2009-2013.

Another research topic, started during the FRIENDLY HEATING project and continued later, was development and application of numerical modelling of the water vapour movement and resulting stress fields in vulnerable historic materials, in response to variations in ambient temperature and RH. The modelling was used to assess the impact of global climate change on wooden objects and mineral materials containing clay within a further research project of the 6th Framework Programme NOAH'S ARK (2005-2007).

The research carried out was summarized in an atlas of the impact of global climate change on the European cultural heritage, a publication addressed to policy and decision makers:

> C. Sabioni, A. Bonazza P. Messina, M. Cassar, P. Biddulph, N. Blades, P. Brimblecombe, C. Grossi, I. Harris, J. Tidblad, R. Kozłowski, Ł. Bratasz, S. Jakieła, M. Drdacky, J. Blaha, I. Herle. J. Lesak, D. Masin, S. Pospisil, Z. Slizokwa, C. Saiz-Jimenez, T. Grontoft, G. Svenningsen, I. Wainwright, C. Hawkins, A. Gomez-Bolea, X. Arino Vila, E. Llop, „*The atlas of climate change impact on European cultural heritage*", Anthem Press, 2010.

The publication was awarded the European Union Prize for Cultural Heritage / Europa Nostra Award in the area of research.

Furthermore, the research carried out led to one publication which is included in this habilitation.

The analysis of stress fields generated by water sorption and transport in objects comprising hygroscopic materials as described above, continues to be one of my main fields of scientific activity. I have broadened research to issues of damage mechanisms in layered structures typical of most works of art. Understanding such complex multi-layer structures composed of humidity-sensitive materials - of which polychrome wood is an important category - is one of the most important challenges for cultural heritage research, both in the fundamental aspects and in the development of practical methods of object protection. I have continued research in this field within several projects:

- „ Establishing standards for allowable microclimatic variations for polychrome wood", a project supported by the European Economic Area Financial Mechanism, (2007-2010),
- „Management of the museum collections based on computer modelling of the impact of the microclimatic fluctuations on historic objects", national research project, (2009-2011),

- „Mechanism of panel paintings damage taking into account the growth ring structure and real climate fluctuations", national research project, (2011-2014), of which I am coordinator.

Research on the fatigue damage in historic materials due to large number of repeated cycles of climate variations, which is typical of environments in many museums and historic buildings, has been especially innovative at the international level.

Undertaking research on this challenging issue required the development of a new tool for measuring damage progress based on the use of interferometric methods, which could be applied both in the laboratory as well as in real-world conditions of historic objects. By combining two techniques, acoustic vibrometry and digital speckle pattern interferometry, it was possible to develop a method which was very useful in the measurements of very minute fatigue damage development. The research has led at the same time to new solutions in optical engineering. These new achievements were published in a journal listed in Thomson Reuters Report:

Ł. Lasyk, M. Łukomski, Ł. Bratasz, „Simple DSPI for Investigation of Art Objects", *Optica Applicata*, XLI, No. 3, 687-700, 2011.

A very different area of my scientific research, in the last several years, was determination of parameters and procedures of application of so-called Roman cements – natural hydraulic binders widely used for the façade decoration in 19th and at the beginning of 20th century. The production and use of this material declined after 1914, due to the development and mass production of the newer Portland cement. A thorough physico-chemical study of the reactions leading to the synthesis of calcium aluminates and calcium silicates during firing of the raw materials as well as taking place on hydration of the cements were made possible through the implementation of two European Union projects within the 5th and 7th Framework Programmes: ROCEM (2003-2006) and ROCARE (2009-2012).

My research was focused on two issues: optimisation of material properties to limit risk of damage of the historic material when repaired with the new Roman Cement – that is the issue of compatibility of new repair materials with the historic substrate - and on optimization of the hydration process to limit cracking of Roman cement mortars on drying. The research carried out was closely related to the application techniques important for the practical conservation of architectural heritage. A part of the obtained results has been already published:

G. Adamski, L. Bratasz, N. Mayr, D. Mucha, R. Kozlowski, M. Stilhammerova and J. Weber, „Roman Cement – key historic material to cover the exteriors of buildings", Technical Report of the RILEM Technical Committee „*Historic mortars*", 2-1, 2009.

In the framework of research carried out and the international projects, I have collaborated permanently with many centres of established position in the area of heritage science and protection. The key institutions comprise:

- Institute of Atmospheric Science and Climate CNR, Padua, Italy
- The Smithsonian Institution, Washington, USA
- Victoria and Albert Museum, London, UK
- Institute for Cultural Heritage Research NIKU, Oslo, Norway

6.3. Development of Laboratory of Analysis and Non-destructive Investigation of Heritage Objects of the National Museum in Krakow

My research and educational activity led to a collaboration with the Laboratory of Analysis and Non-destructive Investigation of Heritage Objects in the National Museum in Krakow of which I am presently the head. My activities in the Laboratory have led to the implementation of eight national and European Commission research projects, focused on the development of new scientific analytical and investigation methods or techniques for the protection and conservation of cultural heritage:

- „Improved protection of paintings during exhibition, storage and transit", 6th Framework Programme, 2008-2010.
- „Safe exposition of museums objects vulnerable to photodegradation"- national research project, 2008-2010.
- „Direct monitoring of strain for the protection of historic textiles and paintings on canvas" European Economic Area Financial Mechanism research project, 2008-2011.
- „The protection of the cultural heritage: new instruments for the monitoring of the impact of pollutants on surfaces", 7th Framework Programme, 2008-2011, of which I was a leader.
- „Wooden historic objects impregnated with polymers: structural changes, risk assessment, protection strategy" national research project, 2009-2011, of which I was a coordinator.
- „Development of micro-damage monitoring method in mineral materials constituting historic architecture and sculptures", national research project, 2009-2013.

- „Management of the museum collection based on computer modelling of the impact of the microclimatic fluctuations on historic objects”, national research project, 2009-2011,
- „Nicolaus Haberschrack - pictor de Cracovia”, national research project, 2010-2013.

The projects implemented and the related funding obtained (5 mln zloty), allowed for an increased employment of researchers in the group lead by me, which is illustrated in the table below:

	2007	2008	2009	2010	2011	2012
chemist with PhD degree	-	1	1	1	2	2
chemist with MS degree	-	-	1	2	1	1
physicist with PhD degree	-	1	1	1	1	1
physicist with MS degree	1	1	1	1	1	1
conservators	1	1	1	1	2	2
managers	-	1	1	1	1	1

Further, the obtained funding allowed for acquiring modern instrumental equipment unique in Polish museums: system for hyperspectral imaging, SEM microscope, system for radio monitoring of the environmental conditions, wireless digital x-ray imaging system, X-ray µ-fluorescence spectrometer, Raman spectrometer, spectrophotometer, 3D scanner, acoustic emission system, microfedometer, FTIR spectrometer with a set of fibre optics cables for non-invasive investigations of art objects.

A permanent collaboration was set up with the following institutions of international reputation in the field of natural and engineering sciences applied to cultural heritage: the Getty Institute, the Smithsonian Institution, English Heritage, Canadian Conservation Institute, the Victoria and Albert Museum, Tate Gallery and the Rathgen Laboratory.

Furthermore, I have undertaken efforts for granting status of a research institution to the Museum by the Ministry of Science and Higher Education. In 2009, the Museum obtained such status as the first and so far only museum in Poland, and has been obtaining yearly statutory funding for research from the Ministry. In 2012, the Scientific Board was set up in the museum to coordinate its research activities. I have become member of this board.

The National Museum in Krakow was invited to represent the country in the European Union NET-HERITAGE project (2008-2011) on behalf of the Ministry of Culture and

National Heritage. I have become leader of the project team. NET-HERITAGE was an Era-Net project aiming at coordination of policy of 15 UE countries in the field of cultural heritage research. The main focus of the project was to define research priorities and develop organizational framework for future common call for research projects in area related to protection of tangible cultural heritage, and to propose coherent framework for advanced education in the field of conservation science. I was a leader of a Work Package focusing on advance education issues.

Within the NET-HERITAGE project, I was nominated by the minister to a position of the chairman of Panel of Experts of the Ministry of Culture and National Heritage defining national research priorities in the area of protection of cultural heritage. The panel developed a report http://www.mkidn.gov.pl/pages/posts/net-heritage-1591.php, which has provided basis for activities described in paragraph 6.4.

6.4. Activities for enhancement of cultural heritage research area in Poland

Measures to enhance cultural heritage research, especially in the area of heritage protection, were a further result of the collaboration with the Ministry of Culture and National Heritage. They have led to:

- introducing relevant provisions on the priority role of the research on protection of tangible cultural heritage to the National Research Programme (KPB) in the strategic area „ Social and economic development of Poland in conditions of globalizing markets”
- access of Poland to the Joint Programming Initiative of the Council of Europe in the area of cultural heritage research. In 2009, the Council of Europe launched a review of joint research policy of the member states of the European Union to select the priority areas. Of 17 proposed areas, only three gained acceptance of the Council of Europe in the first round: „health”, „food” and „cultural heritage”.

6.5. Standardisation activities

In 2005, I was nominated as an expert of Working Group 4 “Environment” Technical Committee 346, of the European Committee of Standardisation CEN. As a member of the group I co-authored four officially adopted standards related to measurements methods in the field of cultural heritage and specification of optimal conditions for object storage and exhibition:

- European Standard EN 15758:2010, Conservation of cultural property - procedures and instruments for measuring temperatures of the air and the surfaces of objects.
- European Standard EN 15757:2010, Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced damage in organic hygroscopic materials.
- European Standard EN 15759:2011, Conservation of Cultural Property - Indoor Climate - Part 1: Guidelines for heating churches, chapels and other places of worship.
- European Standard EN 16242:2012 Conservation of cultural property - Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property.

Two further standards are being developed. In 2010, I initiated setting up a Technical Committee of the Polish Standardisation Committee focusing on conservation. Technical Committee 311, „Conservation of Cultural Heritage was set up in 2011 and I was elected its chairman.

6.6. Membership of expert groups and scientific associations

I have been nominated as member of several prestigious expert groups. My election to twelve-person Scientific Committee of Council of Europe Joint Programming Initiative on Cultural Heritage and Global Change: a new challenge for Europe” was particularly satisfactory. I was elected in a bottom up selection procedure from among hundreds of candidates. This nomination is especially important for me as I am the only representative of countries from Central and Eastern Europe.

I have been also honoured to be nominated to the Panel of Experts of the Art and Humanities Research Council, UK, the agency responsible, among other, for natural and engineering research in the cultural heritage field.

Moreover, I am member of two expert bodies:

- Scientific Board of the National Museum in Krakow
- Conservation Committee of International Council of Museum - ICOM, Working Group “Preventive Conservation”

During the research work on Roman cements, I was member of the Technical Association RILEM, Technical Committee „ Repair Mortars for Historic Masonry”, 2005-2007.

7. Detailed list of achievements

7.1. List of publications (after PhD)

In international journals listed in the Journal Citations Reports Thomson Reuters

1. Ł. Bratasz, „Allowable microclimatic variations for painted wood", Studies in Conservation, 58, 65-79, 2013, applicant contribution 100%.
2. W. Zawadzki, M. Bartosik, K. Dzierżęga, Ł. Bratasz, M. Łukomski, E. Peacock "Application of fiber Bragg gratings for strain measurement in historic textiles and paintings on canvas", Optica Applicata, Vol. XLII, 3, 503-517, 2012, applicant contribution 20%.
3. Ł. Bratasz, I. Harris, Ł. Lasyk, M. Łukomski, R. Kozłowski, „Future climate-induced pressures on painted wood", Journal of Cultural Heritage, 13, 365–370, 2012, applicant contribution 60%.
4. B. Rachwał, Ł. Bratasz, L. Krzemień, M. Łukomski, R. Kozłowski, „Fatigue damage of the gesso layer in panel paintings subjected to changing climate conditions", Strain, 48, 474-481, 2012, applicant contribution 60%.
5. Ł. Bratasz, A. Kozłowska, R. Kozłowski, „Analysis of water adsorption by wood using the Guggenheim-Andersen-de Boer equation", Eur. J. Wood Prod. 70, 445-451, 2012, applicant contribution 70%.
6. B. Rachwał, Ł. Bratasz, M. Łukomski, R. Kozłowski, „Response of wood supports in panel paintings subjected to changing climate conditions", Strain, 48, 357–444, 2012, applicant contribution 60%.
7. Ł. Lasyk, M. Łukomski, Ł. Bratasz, „Simple DSPI for Investigation of Art Objects", Optica applicata, XLI, 3, 687-700, 2011, applicant contribution 30%.
8. D. Camuffo, E. Pagan, S. Rissanen, Ł. Bratasz, R. Kozłowski, M. Camuffo, A. della Valle, „An advanced church heating system favourable to artworks: A contribution to European standardisation", Journal of Cultural Heritage, 11, 205–219, 2010, applicant contribution 30%.
9. S. Jakieła, Ł. Bratasz, R. Kozłowski, „Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions", Wood Science and Technology, 42, 21-37, 2008, applicant contribution 50%.

10. S. Jakieła, Ł. Bratasz, R. Kozłowski, „Acoustic emission for tracing fracture intensity in lime wood due to climatic variations", Wood Science and Technology, 42, 269-279, 2008, applicant contribution 50%.

11. Ł. Bratasz, R. Kozłowski, D. Camuffo, E. Pagan, „Impact of indoor heating on painted wood: monitoring the altarpiece in the church of Santa Maria Maddalena in Rocca Pietore, Italy", Studies in Conservation, 52, 199-210, 2007, applicant contribution 70%.

12. S. Jakieła, Ł. Bratasz, R. Kozłowski, „Acoustic emission for tracing the evolution of damage in wooden objects", Studies in Conservation, 52, 101-109, 2007, applicant contribution 60%.

13. L. Samek, A. De Maeyer-Worobiec, Z. Spolnik, L. Bencs, V. Kontozova, Ł. Bratasz, R. Kozłowski, R. Van Grieken, „The impact of electric overhead radiant heating on the indoor environment of historic churches", Journal of Cultural Heritage, 8, 361-369, 2007, applicant contribution 30%.

14. Ł. Bratasz, R. Kozłowski, „Laser sensors for continuous monitoring of dimensional response of wooden objects in situ", Studies in Conservation, 50, 307-315, 2005, applicant contribution 80%.

15. K. Dzierzęga , Ł. Bratasz, S. Pellerin, B. Pokrzywka and K. Musioł, „Stark Width and Shift Measurement for the 696,543nm ArI line using degenerate four wave mixing (DFWM) Spectroscopy", Physica Scripta 67, 1-7, 2003, applicant contribution 40%.

16. S. Zielinska, L. Bratasz and K. Dzierzega, „Absolute Transition Rates for transition from $5p^4$ (^3P) 6p $^4P^o_{5/2}$, $^4P^o_{3/2}$, $^4D^o_{7/2}$ and $^2D^o_{5/2}$ levels of Xe II", Physica Scripta, 66 (6), 454-457, 2002, applicant contribution 30%.

Publications in other international and Polish journals

1. D. Wilk, Ł. Bratasz, P. Frączek, M. Obarzanowski, A. Klisińska-Kopacz, J. Czop, „Konstrukcja i zastosowanie ram mikroklimatycznych w Muzeum Narodowym w Krakowie", Wiadomości Konserwatorskie, 30, 154-167, 2011, applicant contribution 30%.

2. C.J. Bergsten, M. Odlyha, S. Jakiela, J. Slater, A. Cavicchioli, D.L.A. de Faria, A. Niklasson, J.-E. Svensson, L. Bratasz, D. Camuffo, A. della Valle, F. Baldini, R. Falciai, A. Mencaglia, F. Senesi, C. Theodorakopoulos „Sensor System for Detection of

Harmful Environmenrts for Pipe Organs (SENSORGAN)”, e-Preservation 7, 116-125, 2010, applicant contribution 20%.

3. D. Wilk, Ł. Bratasz „Skuteczne zabezpieczenie obrazów przed niekorzystnymi wpływami środowiska muzealnego poprzez zastosowanie ram mikroklimatycznych”, Ochrona Zabytków, 3, 47-58, 2009, applicant contribution 50%.

4. Ł. Bratasz, J. Weber, K. Sterflinger, Raumklimatische Untersuchungen. „Die Wandmalereien in der so genannten Paulusgrotte von Ephesos“, Anzeiger der philosophisch-historischen Klasse der Oesterreichischen Akademie der Wissenschaften, 143, 107-116, 2009, applicant contribution 60%.

5. G. Adamski, L. Bratasz, N. Mayr, D. Mucha, R. Kozlowski, M. Stilhammerova and J. Weber, „Roman Cement – key historic material to cover the exteriors of buildings”, Technical Report of the RILEM”s Technical Committee „Historic mortars” e-ISBN 978-2-35158-083-7, 2-1, 2009, applicant contribution 20%.

Chapters in books

1. C. Sabioni, A. Bonazza P. Messina, M. Cassar, P. Biddulph, N. Blades, P. Brimblecombe, C. Grossi, I. Harris, J. Tidblad, R. Kozłowski, Ł. Bratasz, S. Jakieła, M. Drdacky, J. Blaha, I. Herle. J. Lesak, D. Masin, S. Pospisil, Z. Slizokwa, C. Saiz-Jimenez, T. Grontoft, G. Svenningsen, I. Wainwright, C. Hawkins, A. Gomez-Bolea, X. Arino Vila, E. Llop, „The atlas of climate change impact on European cultural heritage”, Anthem Press, 2010, applicant contribution 5%.

2. Ł. Bratasz, „Acceptable and non-acceptable microclimate variability: the case of wood”, Basic Environmental Mechanisms Affecting Cultural Heritage, Nardini Editore, Florence, 49-58, 2010, applicant contribution 100%.

3. R. Kozłowski, Ł. Bratasz „Church Heating and the Preservation of the Cultural Heritage. Guide to the Analysis of the Pros and Cons of Various Heating Systems”, Electa, Milan, 2006, applicant contribution 60%.

Publication in peer reviewed conference materials

1. Ł. Bratasz, „Allowable microclimatic variations in museums and historic buildings”, Climate for Collections: Standards and Uncertainties, Munich, Germany, 2012, applicant contribution 100%.

2. M. Łukomski, J. Czop, M. Strojecki, Ł. Bratasz, „Acoustic Emission monitoring: on the path to rational strategies for collection care", Climate for Collections: Standards and Uncertainties, Munich, Germany, 2012, applicant contribution 30%.

3. M. Strojecki, Ł. Bratasz, M. Łukomski, „Acoustic Emission for Tracing Damage in Wooden Artworks", Proceedings of World Conference on Acoustic Emission – 2011 Beijing, China, 256-261, 2011, applicant contribution 30%.

4. Ł. Bratasz, M. Strojecki, A. Klisińska-kopacz, M. Łukomski, „AE and works of art", Proceedings of World Conference on Acoustic Emission – 2011 Beijing, China, 581-586, 2011, applicant contribution 40%.

5. M. Strojecki, C. Colla, M. Łukomski, E. Gabrielli, Ł. Bratasz, „The Kaiser effect in wood- does historic wood have stress memory?", Proceedings of the European Workshop on Cultural Heritage Preservation EWCHP-2011, Berlin, ed. M. Krüger, Fraunhofer IRB Verlag ISBN 978-3-8167-8560-6, 171-176, 2011, applicant contribution 10%.

6. D. Wilk, Ł. Bratasz, R. Kozłowski, „Acoustic emission for monitoring crack formation in Roman cement mortars", Proceedings of the European Workshop on Cultural Heritage Preservation EWCHP-2011 Berlin, M. Krüger, Ed., Fraunhofer IRB Verlag, [ISBN 978-3-8167-8560-6], pp. 177-181, 2011, applicant contribution 30%.

7. Ł. Bratasz, R. Kozłowski, Ł. Lasyk, M. Łukomski, B. Rachwał, „Allowable microclimatic variations for painted wood: numerical modelling and direct tracing of damage", ICOM Committee for Conservation, 16th Triennial Conference, Lisbon, 2011, applicant contribution 40%.

8. R. Kozłowski, Ł. Bratasz, Ł. Lasyk, M. Łukomski „Allowable microclimatic variations for painted wood: direct tracing of damage development", Postprints of Symposium „Facing the Challenges of Panel Paintings Conservation: Trends, Treatments and Training", eds. A.S. Chui, A. Phenix, Getty Conservation Institute, Los Angeles, 158-164, 2011, applicant contribution 50%.

9. D. Wilk, Ł. Bratasz, R. Kozłowski, "Reducing shrinkage cracks in Roman cement renders", RILEM Proceedings PRO 78, 2nd Historic Mortars Conference & RILEM TC 203-RHM Repair Mortars for Historic Masonry Final Workshop, eds. J. Valek, C. Groot, J.J. Hughes, e-ISBN: 978-2-35158-112, 2010, applicant contribution 20%.

10. Ł. Lasyk, M. Łukomski, Ł. Bratasz, R. Kozłowski, „Vibration as a hazard during the transportation of canvas paintings", Conservation and Access: Contributions to the London Congress, eds. D. Saunders, J. H. Townsend, S. Woodcock, The

International Institute of Conservation of Historic and Artistic Works, London, 1, 64-68, 2008, applicant contribution 20%.

11. Ł. Bratasz, R. Kozłowski, A. Kozłowska, S. Rivers, „Conservation of the Mazarin Chest: structural response of Japanese lacquer to variations in relative humidity”, ICOM Committee for Conservation, 15th Triennial Conference, New Delhi: Preprints, ed. I. Verger, 2, 933-940, 2008, applicant contribution 60%.

12. Ł. Bratasz, S. Jakieła, Ł. Lasyk, R. Kozłowski, „Direct monitoring of damage in clay-containing sandstones by acoustic emission”, Proceedings of 11th International Congress on Deterioration and Conservation of Stone, eds. J. W. Łukaszewicz, P. Niemcewicz, Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika, 2, 349-356, 2008, applicant contribution 40%.

13. Ł. Bratasz, R. Kozłowski, D. Camuffo, „Target microclimate for preservation derived from past indoor conditions”, Contributions to the Museum Microclimates Conference, The National Museum of Denmark, Copenhagen, 129-134, 2007, applicant contribution 60%.

14. Ł. Bratasz, S. Jakieła, R. Kozłowski, „Allowable thresholds in dynamic changes of microclimate for wooden cultural objects: monitoring in situ and modeling”, 14th Triennial Meeting of ICOM Committee for Conservation, the Hague, 12-16 September 2005: Preprints, James & James, London, 2, 582-589, 2005, applicant contribution 60%.

Publications in other conference materials

1. Ł. Bratasz, „Allowable microclimatic variations in museums and historic buildings”, Climate for Collections: Standards and Uncertainties, Munich, Germany, 2012, applicant contribution 100%.

2. Ł. Bratasz, B. Rachwał, Ł. Lasyk, M. Łukomski, R. Kozłowski, „Analysis of Fatigue Process in Painted Wood”, Proceedings of the wood culture and science Kyoto 2011, the 177th Symposium on Sustainable Humanosphere, Kioto, Japan, 137-141, 2011, applicant contribution 40%.

3. M. Łukomski, Ł. Bratasz, M. Strojecki, „Understanding the Response of Painted Wood to the Environmental Impacts – a path to rational strategies for the collection care”, Proceedings of the wood culture and science Kyoto 2011, the 177th Symposium on Sustainable Humanosphere, Kioto, Japan, 142-147, 2011, applicant contribution 50%.

4. R. Kozłowski, Ł. Bratasz „Target microclimates for preservation of wooden object: an attempt at standardization", Proceedings of the international conference held by COST action IE0601, ed. Luca Uzielli, Firenze University Press, 127-132, 2010, applicant contribution 50%.

5. Ł. Łukasz, M. Łukomski, Ł. Bratasz, „Simple Electronic Speckle Pattern Interferometer (ESPI) for the Investigation of Wooden Art Objects", „Wood Science for Conservation of Cultural Heritage – Braga 2008: Proceedings of the International Conference held by COST Action IE0601, Braga (Portugal), 5-7 November 2008", ed. J. Gril, Firenze University Press, ISBN 978-88-6453-157-1, 11-16, 2010, applicant contribution 10%.

6. Ł. Bratasz, R. Kozłowski, ‚Entwicklung der neuen EU-Normen – The CEN TC346 draft standard on heating historic churches: minimising disturbance to the indoor climate", Klimagestaltung im Spannungsfeld zwischen Kulturguschutz und Nutzerwünschen, Tagungsblatt des 1. Konservierungswissenschaftlichen Kolloqiums, Berlin, 24-31, 2007, applicant contribution 80%.

7. R. Kozłowski, Ł. Bratasz, "Środowisko w muzeach i obiektach zabytkowych. Kierunki standaryzacji przyjęte przez Europejski Komitet Normalizacyjny", Konserwacja zapobiegawcza w muzeach, red. D. Folga-Januszewska, Krajowy Ośrodek Badań i Dokumentacji Zabytków, Warsaw, 155-164, 2007, applicant contribution 50%.

8. Ł. Bratasz, S. Jakieła, R. Kozłowski, "Szok mikroklimatyczny przy przenoszeniu obiektów drewnianych", Konserwacja zapobiegawcza w muzeach, red. D. Folga-Januszewska, Krajowy Ośrodek Badań i Dokumentacji Zabytków, Warszaw, 233-240, 2007, applicant contribution 40%.

In all publications on which the habilitation is based, my contribution consisted in formulation of the scientific problem, development of the research programme, coordination of calculations and experiments performed, partially also on carrying out experiments in the laboratory and *in situ*, analysis and interpretation of the results as well as on participation in manuscript development. In paper H11 of the series, I carried out creative synthesis of existing data and concepts, which allowed a consistent view of the issue to be developed.

In remaining papers, my contribution consisted in analysis of a scientific problem, participation in planning of the research programme, development of research methodology, partially also on carrying out experiments in the laboratory and in situ, analysis of the results and their interpretation.

7.2. Participation in research projects

1. „Comfortable to people and compatible with conservation of art works preserved in churches" – research project no. EVK4-2001-00007 „FRIENDLY HEATING", 5th Framework Programme of European Commission, 2002 – 2005.

2. „Roman cement to restore built heritage effectively" - research project no. EVK4-2001-00159 „ROCEM", 5th Framework Programme of European Commission, 2003-2006.

3. „Proper heating of historic wooden churches – characterization of airflows, air particulate deposition and strains in the wood" - Polish-Flemish bilateral research project, 2004-2006.

4. „Global climate change impact on built heritage and cultural landscapes" – research project no. SSP1-CT-2003-501837 „NOAH"S ARK", 6th Framework Programme of European Commission, 2004-2007.

5. „Implementation of Roman Cement technology in practical conservation of historic buildings" – „TECHKON", national research project no. WKP_1/1.4.1/1/2005/8/8/222/2005/U, 2005-2008.

6. „Sensor system for detection of harmful environments for pipe organs" – research project no. SSPI CT- 2005-022695 „SENSORGAN", 6th Framework Programme of European Commission, 2006-2008, **– coordination of the project on behalf of the Institute.**

7. „Chemical Interactions between Cultural Artefacts and Indoor Environment" – COST ACTION D42, 2006-2010.

8. „Establishing standards for allowable microclimatic variations for polychrome wood" – research project no. PL0086 „Wood", European Economic Area Financial Mechanism, 2007-2010.

9. „Heating systems for conservation of historic churches" – „IGNIS", national research project no. WKP_1/1.4.1/1/2006/93/93/648/2007/U, 2006-2008, **– coordination of the project.**

10. „Wood science for conservation of cultural heritage" - COST ACTION IE0601, 2007-2011.

11. „Improved protection of paintings during exhibition, storage and transit", research project no. SSP-CT-2007-044254 „ProPaint", 6th Framework Programme of European Commission, 2008-2010.

12. „Smart monitoring of historic structures", research project no. ENV-2007-212939, „SMOOHS", 7th Framework Programme of European Commission, 2008-2011.

13. „Safe exposition of objects vulnerable to photodegradation in museums"-national research project no. 193/N-COST/2008/0, „Anoksja", 2008-2010.

14. „Direct monitoring of strains in textiles for protection of historic tapestries and canvases" research project no. PL0267 „Fiber", European Economic Area Financial Mechanism, 2008-2011.

15. „Damage assessment, diagnosis and monitoring for the preventive conservation and maintenance of cultural heritage" research project no. ENV-2007-212458 „TeACH", 7th Framework Programme of European Commission, 2008-2011 **– coordination of the project on behalf of the museum.**

16. „Historic wooden objects impregnated with polymers: structural changes, risk assessment preventive strategy" research project no. 519/N-COST/2009/0, „Polimery", 2009-2011 **– coordination of the project.**

17. „European network on research programme applied to the protection of tangible cultural heritage" research project no. ENV-2007- 219301, 7. Framework Programme of European Commission „NET-HERITAGE", 2008-2011 **– coordination of the project on behalf of Ministry of Culture and National Heritage.**

18. „Acoustic emission for monitoring of museum objects as universal preventive conservation method" – national research project no. N N105 278536, 2009-2012 **– coordination of the project.**

19. „Roman cements for architectural restoration to new high standards", research project no. ENV-2007- 226898, 7th Framework Programme of European Commission, 2009-2012.

20. „Development of micro-damage monitoring method in mineral materials constituting historic architecture and sculptures", research project no. N N105 112938 Ministerstwa Nauki i Szkolnictwa Wyższego, 2009-2012.

21. „Museum collection management based on computer modelling of microclimate variation impact on heritage objects" national research project no. 538/N-COST/2009/0, „Envicontrol", 2009-2011.

22. „Nicolaus Haberschrack - pictor de Cracovia", national research project no. N N105 292139, 2010-2013.

23. „Impact of historic church heating on transport and deposition of particulate matter" national research project no. UMO-2011/01/D/HS2/02604, 2011-2014.

24. „Mechanism of panel paintings damage taking into account growth ring structure and real climate fluctuations”, national research project no. UMO-2001/01/B/HS2/02586, 2011-2014 **– coordination of the project.**

7.3. ORAL CONFERENCE PRESENTATIONS

1. Invited lecture Ł. Bratasz “Reviewing the guidelines: allowable microclimatic variations in museums and historic buildings", International Scientific Workshop “Heritage Science and Sustainable Development for the Preservation of Art and Cultural Assets On the Way to the GREEN Museum”, Rathgen Labor Berlin, Germany, 2013.

2. Ł. Bratasz, „Allowable microclimatic variations in museums and historic buildings”, Climate for Collections: Standards and Uncertainties, Munich, Germany, 2012.

3. M. Łukomski, J. Czop, M. Strojecki, Ł. Bratasz, „Acoustic Emission monitoring: on the path to rational strategies for collection care”, Climate for Collections: Standards and Uncertainties, Munich, Germany, 2012.

4. M. Łukomski, M. Strojecki, Ł. Bratasz “Emisja Akustyczna jako narzędzie do planowania strategii zarządzania klimatem w muzeum” Konferencja „Analiza Chemiczna w Ochronie zabytków”, Warsaw, 2012.

5. Ł. Bratasz "Międzynarodowe normy i zalecenia dotyczące oświetlenia obiektów zabytkowych", International conference „Light in the museum - necessity or threat”, Kraków 2012.

6. J. del Hoyo Meléndez, Ł. Bratasz, M. Włodarczak, A. Klisińska-Kopacz, "Micro X-ray fluorescence analysis (μXRF) of silver denarii from medieval Poland", 2nd International Congress Chemistry for Cultural Heritage, Istanbul, Turkey, 2012.

7. A. Klisińska-Kopacz, J. M. del Hoyo-Meléndez, M. Włodarczak, Ł. Bratasz “Micro X-ray fluorescence analysis (μXRF) of silver denarii of Bolesław Chrobry” 11. conference „Analytical Chemistry in Cultural Heritage Protection”, Warsaw, 2011.

8. Ł. Bratasz, J. Czop, R. Kozłowski, M. Łukomski, „Zarządzanie mikroklimatem w obiekcie zabytkowym: zielone muzeum /otwarty scenariusz”, conference "Muzeum a zabytek. Konflikt czy harmonia?", Kraków, 2011.

9. Ł. Bratasz, B. Rachwał, Ł. Lasyk, M. Łukomski, R. Kozłowski, “Analysis of Fatigue Process in Painted Wood”, the 177th Symposium on Sustainable Humanosphere, Kyoto, Japan, 2011.

10. M. Łukomski, Ł. Bratasz, M. Strojecki, “Understanding the Response of Painted Wood to the Environmental Impacts – a path to rational strategies for the collection care”, the 177th Symposium on Sustainable Humanosphere, Kyoto, Japan 2011.

11. M. Strojecki, Ł. Bratasz, M. Łukomski, “Acoustic Emission for Tracing Damage in Wooden Artworks”, World Conference on Acoustic Emission – 2011 Beijing, China, 2011.

12. Ł. Bratasz, M. Strojecki, A. Klisińska-kopacz, M. Łukomski, “AE and works of art”, World Conference on Acoustic Emission – 2011 Beijing, China, 2011.

13. Ł. Bratasz, R. Kozłowski, Ł. Lasyk, M. Łukomski, and B. Rachwał, „Allowable microclimatic variations for painted wood: numerical modelling and direct tracing of the fatigue damage”, ICOM Committee for Conservation, 16th Triennial Conference, Lisbon, Portugal, 2011.

14. M. Strojecki, C. Colla, M. Łukomski, E. Gabrielli, Ł. Bratasz, “The Kaiser effect in wood- does historic wood have stress memory?”, European Workshop on Cultural Heritage Preservation EWCHP 2011, Berlin, Germany, 2011.

15. M. Łukomski, B. Rachwał, Ł. Bratasz, R. Kozłowski, “In situ monitoring of the impact of microclimatic fluctuations on polychrome wood: a path to rational strategy for the collection care”, Joint Final Conference of COST Actions IE0601 and MP0601, Paris, France, 2011.

16. D. Wilk, Ł. Bratasz, „Spękania w zabytkowych zaprawach romańskich – wyjaśnienie mechanizmu ich powstawania za pomocą metod fizykochemicznych” 11. conference „Analytical Chemistry in Cultural Heritage Protection”, Warsaw, 2011.

17. Ł. Bratasz, A. Sadłowska-Sałęga, K. Wąs, J. Radoń „Symulacje zużycia energii dla różnych scenariuszy kontroli mikroklimatu”, Envicontrol Workshop, Kraków, 2011.

18. Ł. Bratasz, M. Strojecki, M. Łukomski, “Acoustic emission for tracing damage directly in works of art”, 39th conference of American Institute for Conservation, Philadelphia, USA, 2011.

19. Ł. Bratasz, „Risk of physical damage of textile objects due to environmental variations”. Workshop “Wpływ środowiska na stan zachowania zabytkowych tkanin”, Kraków, 2011.

20. Ł. Bratasz, „The NET-HERITAGE project to foster the science-based conservation in Europe". Workshop „Heritage science education in a changing world", Warsaw, 2011.

21. Ł. Bratasz, D. Wilk, „Fizykochemiczna analiza powstawania spękań w zaprawach zabytkowych" 10. conference „Analytical Chemistry in Cultural Heritage Protection", Warsaw, 2011.

22. Ł. Bratasz, M. Łukomski, W. Zawadzki, A. Klisińska-Kopacz, J. Sobczyk, M. Włodarczak, M. Bartosik, A. Wolak, A. Prokopowicz, K. Dzierżęga, „Monitoring of museums objects using optical fiber sensors", International Conference „Technologia i Technika w Badaniach Dzieł Sztuki", Toruń, 2011.

23. Ł. Bratasz, B. Rachwał, Ł. Lasyk, M. Łukomski, R. Kozłowski „Fatigue fracture of painted wood due to repeated humidity variations", workshop COST 0601, Izmir, Turkey, 2010.

24. D. Wilk, Ł. Bratasz, R. Kozłowski 'Damage of R. cement mortars due to drying shrinkage", Historic Mortar Conference, Prague, Czech Republic, 2010.

25. M. Łukomski, Ł. Lasyk, Ł. Bratasz „Digital Speckle Pattern Interferometry (DSPI) in analysis of the climate-induced damage of painted wood surfaces", 14th International Conference on Laser Optics, St.Petersburg, Russia, 2010.

26. P. Frączek, J. Sobczyk, Ł. Bratasz, J. Czop „Portable digital X-ray radiography system for studies of historical objects", 3rd Meeting X-Ray techniques in investigations of the objects of cultural heritage, Kraków, 2010.

27. J. Thomas, A. Klisińska-Kopacz, J. Sobczyk, Ł.Bratasz, T. Łojewski „Characterisation of fading behaviour of coloured papers during simulated display in anoxia", 9th Indoor Air Quality in museums and archives, Chalon-sur-Saône, France, 2010.

28. Ł. Bratasz „Acceptable and non-acceptable microclimate variability: the case of wood", workshop of COST D42, Cean, France, 2010.

29. Ł. Bratasz, B. Rachwał „Czy istnieją bezpieczne fluktuacje wilgotności względnej?" warsztat „Ochrona drewna polichromowanego: zarządzanie klimatem w budowlach zabytkowych i muzeach", Warsaw, 2010.

30. Ł. Bratasz, B. Rachwał „Computer modelling of dimensional response and stress fields in wooden artworks" workshop of COST 0601, Oslo, Norway, 2010.

31. R. Kozłowski, Ł. Bratasz, Ł. Lasyk, M. Łukomski, „Allowable microclimatic variations for painted wood: direct tracing of damage development" – plenary

lecture during Symposium „Facing the Challenges of Panel Paintings Conservation: Trends, Treatments and Training”, Getty Conservation Institute, Los Angeles, USA, 2009.

32. Ł. Bratasz, „Allowable microclimatic variations for painted wood and lacquer”, workshop of COST IE0601, Cambridge, UK, 2009.

33. Ł. Bratasz, S. Jakieła „Acoustic Emission Sensor for Direct Tracing of Physical Damage in Organs”, The pipe organ; the secular journey at the service for liturgy, conference of Italian Office of Ecclesiastical historic Buildings., Vatican, 2008.

34. C.J. Bergsten, M. Odlyha, S. Jakiela, J. Slater, A. Cavicchioli, D.L.A. de Faria, A. Niklasson, J-E Svensson, L. Bratasz, D. Camuffo, A. della Valle, F. Baldini, R. Falciai, A. Mencaglia, F. Senesi, „Sensor system for detection of harmful environments for pipe organs (SENSORGAN)” 8. Conference of European Union „Conservation and Enhancement of Cultural Heritage”, Ljubljana, Slovenia, 2008.

35. Ł. Bratasz, R. Kozłowski, S. Jakieła, „Sorption of moisture and dimensional change of wood species used in historic objects”, Workshop of COST IE0601, Braga, Portugal, 2008.

36. Ł. Lasyk, M. Łukomski, Ł. Bratasz, „Simple Electronic Speckle Pattern Interferometer (ESPI) for the investigation of wooden art objects”, Workshop of COST IE0601, Braga, Portugal, 2008.

37. Ł. Lasyk, M. Łukomski, Ł. Bratasz, R. Kozłowski, „Vibration as a hazard during the transportation of canvas paintings”, w: *Conservation and Access: Contributions to the London Congress of t*he International Institute of Conservation of Historic and Artistic Works, London, 2008.

38. Ł. Bratasz, R. Kozłowski, A. Kozłowska, S. Rivers, „Conservation of the Mazarin Chest: structural response of Japanese lacquer to variations in relative humidity”, w: *ICOM Committee for Conservation, 15th Triennial Conference,* New Delhi, India, 2008.

39. M. Łukomski, Ł. Lasyk, Ł. Bratasz, R. Kozłowski, „Electronic Speckle Pattern Interferometry (ESPI) in analysis of the climate-induced damage of painted wood surfaces”, Optical Coherence Tomography for Examination of ART Workshop, Toruń, 2008.

40. Ł. Bratasz, S. Jakieła, Ł. Lasyk, R. Kozłowski, „Direct monitoring of damage in clay-containing sandstones by acoustic emission”, Toruń, 2008.

41. Ł. Bratasz, S. Jakieła, M. Łukomski, R. Kozłowski, „Acoustic emission sensor for direct tracing of damage in historic objects", 9th International Conference Art2008, Non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage, Jerusalem, Israel, 2008.

42. M. Łukomski, Ł. Lasyk, Ł. Bratasz, R. Kozłowski, „Climate-induced response of painted wood surfaces: monitoring by laser techniques", 9th International Conference Art2008, Non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage, Jerusalem, Israel, 2008.

43. Ł. Bratasz, R. Kozłowski, D. Camuffo, „Target microclimate for preservation derived from past indoor conditions", the Museum Microclimates Conference, Copenhagen, Denmark, 2007.

44. Ł. Bratasz , „The CEN TC346 draft standard on heating historic churches: an attempt at practical implementation", Workshop of COST D42, Copenhagen, 2007.

45. Ł. Bratasz , C. Sabbioni, A. Bonazza, P. Massina, M. Cassar, P. Biddulph, P. Brimblecombe, C. M. Grossi, I. Harris, J. Tidblad, R. Kozłowski, M. Drdácký, C. Saiz-Jimenez, J. M. Gonzalez, T. Grøntoft, I. Wainwright, A. Bolea, „Climate Change Impact on European Cultural Heritage", Sustainable Neighbourhood – from Lisbon to Leipzig through Research, Leipzig, Germany 2007.

46. Ł. Bratasz, R. Kozłowski, S. Jakieła, „Climate-induced stress in wooden objects: numerical modelling and direct tracing by acoustic emission", Workshop of COST IE0601, Tervuren, Belgium 2007.

47. M. Łukomski, Ł. Bratasz, „Mapping damage of paint layers on wood by laser vibrometry and thermography", workshop COST IE0601, Tervuren, Belgium, 2007.

48. Ł. Bratasz, „Historic climate", Workshop of COST D42, Padua, Italy, 2007.

49. Ł. Bratasz, R. Kozłowski, "The CEN TC346 draft standard on heating historic churches: minimising disturbance to the indoor climate", Klimagestaltung im Spannungsfeld zwischen Kulturgutschutz und Nutzerwünschen, Potsdam, Germany, 2007.

50. R. Kozłowski, Ł.Bratasz, "Target microclimates for preservation of wooden objects - an attempt at standardisation", workshop COST IE0601, Florencja, 2007.

51. Ł. Bratasz, "The CEN TC346 draft standard on heating historic churches: an attempt at practical implementation", workshop of COST D42, Copenhagen, 2007.

52. R. Kozłowski, Ł. Bratasz, "Środowisko w muzeach i obiektach zabytkowych. Kierunki standaryzacji przyjęte przez europejski komitet normalizacyjny", konferencja „Rola konserwacji zapobiegawczej w muzeach", Polski Komitet Narodowy ICOM i Krajowy Ośrodek Badań i Dokumentacji Zabytków, Warsaw, 2006.

53. Ł. Bratasz, S. Jakieła, R. Kozłowski, „Szok mikroklimatyczny przy przenoszeniu obiektów drewnianych", conference „Rola konserwacji zapobiegawczej w muzeach", Polski Komitet Narodowy ICOM i Krajowy Ośrodek Badań i Dokumentacji Zabytków, Warsaw, 2006.

54. Ł. Bratasz, S. Jakieła, R. Kozłowski, "Allowable thresholds in dynamic changes of microclimate for wooden cultural objects: monitoring in situ and modelling", 14th Triennial Meeting of ICOM Committee of Conservation, Hague, the Netherlands, 2005.

55. G. Adamski, Ł. Bratasz, N. Mayr, D. Mucha, R. Kozłowski, M. Stilhammerova, J. Weber, "R. cement – key historic material to cover the exteriors of buildings", workshop of technical Committee 203-RHM RILEM, Delft, the Netherlands, 2005.

56. S. Jakieła, K. Cieślar, Z. Olejniczak, Ł. Bratasz, „Measurement of moisture transport in wood using low field 1D-MRI", XXXVIII Ogólnopolskie Seminarium na Temat Magnetycznego Rezonansu Jądrowego i Jego Zastosowań, Kraków, 2005.

57. Ł. Bratasz, "Response of historic materials – a key issue in making cultural heritage policy", 6. Conference of the European Commission *Sustaining Europe's cultural heritage: From Research to Policy*, London, UK, 2004.

58. Ł. Bratasz, "Laser monitoring of dimensional changes of wooden sculptures in the church of Rocca Pietore, Italy", International workshop COST G7 *Lasers & Optical Methods in Artwork Restoration*, Gdańsk, 2004.

59. Ł. Bratasz, S. Jakieła, "Acoustic emission monitoring to study environmental fatigue in wooden objects", 6. Conference *Indoor Air Quality*, Padua, Italy, 2004.

60. S. Jakieła, R. Kozłowski, Ł.Bratasz, "Allowable thresholds in dynamic changes of microclimate for wooden cultural objects", 6. Conference *Indoor Air Quality*, Padua, Italy, 2004.

61. S. Vasic, R. Kozlowski and Ł. Bratasz, "Modelling of internal stresses in wooden cultural objects", III International Conference of the European Society for Wood Mechanics, Vila Real, Portugal, 2004.

62. Ł. Bratasz, "Compatibility Assessment of a Nineteenth-Century Mortar", 3. International Conference *Science & Technology in Archaeology & Conservation*, Jordan, 2004.

63. R. Kozłowski, Ł. Bratasz, "Impact of heating system on the dimensional change of wood – a case study of the church in Rocca Pietore, Italy", Internal Air Quality Workshop, Norwich, UK, 2003.

7.4. SCIENTIFIC OPINIONS AND PRACTICAL CONSERVATION PROJECTS

1. Scientific opinion „Harmfulness of using flash for objects vulnerable to photodegradation" for the National Institute of Museology and Collections Protection.

2. Scientific opinion „Harmfulness of using flash for Wawel tapestries" for Wawel Castle.

3. Scientific opinion „Heating system in a church in Słuczewo" for Mazowsze Voivodeship Conservation Officer 2011.

4. Scientific opinion „Heating system in a church in Strzelce" Opole Voivodeship Conservation Officer.

5. Monitoring the microclimate of the twelfth-century crypt with a unique Romanesque gypsum flooring in Wiślica, Poland (2002-2003).

6. Monitoring the microclimate and metric changes of wooden objects in several churches in Poland, to assess the response of wood to intense IR radiation from heating (2003-2005).

7. Monitoring the microclimate in St. Paulus Cave in Ephesus, Turkey, the UNESCO World Heritage Site, to develop a preventive strategy against fungal attack on early Christian wall paintings (2005-2008).

8. Diagnosis of damage of a unique artefact of Japanese lacquer – "the Mazarin Chest", a collaborative project with the Victoria and Albert Museum in London (2005-2006).

9. Monitoring and implementing climate control in the Malbork Castle, Poland, the UNESCO World Heritage Site (2006-2008).

10. Implementation of conservation heating system in the Assumption of St Mary Church in Skępe (2006-2008).

Furthermore:

- I participated in making three films popularizing scientific achievements

- I coordinated the participation of the National Museum in Krakow in Science Festivals, which comprised presentation of the Laboratory in 2010 and presentation of the application of the research equipment in the Gallery of Polish Art of the 19th Century in the Cloth Hall in 2011
- I participated in the organization of the Science Festival and the Open-door Days in my mother Institute.

7.5. Education

Since 2007 cyclic lectures during Conservation Seminars in the National Museum in Krakow

Since 2007 lecturer at the Advanced Course „Conservation of Architectural and Urban Monuments", Faculty of Architecture, Krakow University of Technology

In 2008 lecturer at the Advanced Course „Modern analytical techniques for conservation of historic objects", Faculty of Chemistry, Jagiellonian University

In 2008 lecturer at the International Course „Wood Conservation Technology", Norway

In 2010 lecturer at the European Course "Management and protection of Cultural Heritage facing climate change", Italy.

In 2011 lecturer at the International Workshop "Preventive Conservation of Architectural Heritage", Taiwan.

Furthermore, I was directly engaged in co-supervising research in 5 PhD projects during my work at the Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences.

7.6. Awards

Grand Prize – European Union Prize for Cultural Heritage, Europa Nostra for the NOAH'S ARK project, of which I was a participant.

7.7. Dissemination of the research results

Lectures and presentations:

1. Invited lecture „Optimisation of panel painting protection", Metropolitan Museum, New York, USA, 2011.
2. Invited lecture „Panel Paintings: balancing needs and costs", The Smithsonian Institution, Washington, USA, 2011.

3. Invited lecture "Greening of museums a path to rational climate control strategies for the collection care", The Victoria and Alert Museum, London, UK, 2011.

4. Invited lecture “Model Framework for Advanced Education” The European Network for Conservation-Restoration Education, Vienna, Austria, 2010.

5. Lecture „Protection of wooden objects – physico-chemistry of damage process and its prevention” at the Polish Chemical Society, Kraków, 2006.

6. Lecture “Damage of historic Organs” at the Venice European Centre for the trades and professions of the conservation of architectural heritage - San Servolo, 2006.

7. Invited lecture “Response of historic materials - a key issue in preservation of cultural heritage”, the Building Physics Department, Technical University of Eindhoven, Netherlands, 2004.

8. Invited lecture “Physics in protection of cultural heritage” at the Institute of Physics, Jagiellonian University, 2002.

Dr. Łukasz Bratasz