Final Report Summary - IMAT (INTELLIGENT MOBILE MULTIPURPOSE ACCURATE THERMOELECTRICAL (IMAT) DEVICE FOR ART CONSERVATION)

Executive Summary:
Insert Logo Here (Figure - 0)

Mild heating devices currently available to conservators are still limited in terms of precision, versatility, mobility, accessibility and cost. Moreover, they lack a whole range of operational features, such as low power requirements, efficient power use, temperature stability and uniform heat distribution. Carbon nanotubes-based technologies can provide a wide range of technical solutions to overcome these limitations thus allowing the development of more precise, flexible and portable heating devices. IMAT project, coordinated by University of Florence (Italy) and whose consortium is in Figure 1, concerns...
IMAT project, coordinated by University of Florence (Italy) and whose consortium is in Figure 1, concerns the design of an innovative carbon nanotubes-based intelligent mobile accurate thermo-electrical mild heating device, to be used in the art conservation field. The device consists of three different kinds of flexible heating mats with different designs (opaque and ultra-thin/woven, breathable and transparent) with different operational and physical properties.

**Figure 1 here**

IMAT standard (IMAT-S) is a highly accurate, low voltage mobile flexible heater, with an external skin of silicone, opaque and non-breathable, with a soft and non-tack surface. The IMAT-S is intended for the most frequent thermal treatments, where visibility and breathability are not required. The IMAT-S heater may be programmed to deliver steady, uniform and accurate heat from 25ºC to 75ºC, the most commonly used range of temperature in the conservation field.

IMAT breathable (IMAT-B) is an open mesh, low voltage heater with a non-tack silicone coated surface. A second type of IMAT-B consists of an electrically conductive, yet isolated open mesh heater that is faced with a perforated low-tack polyurethane skin. The breathable mats permit airflow and the migration of moisture, so often used in combination with mild heating in conservation treatments. The heater should not be used with organic solvents. The IMAT-B was designed to deliver heat in the temperature range from 25ºC to 50ºC, but is capable reaching temperatures up to 85 C.

The Transparent IMAT (IMAT-T) is made of an innovative lightweight polyethylene naphthalate (PEN 60-30) textile substrate, sputtered with silver nanoparticles, which are characterized by outstanding conductivity and reduced value of electrical resistance per surface unit, reaching as low as 1.1 to 2.3 Ohm/square. This mat allows a transparency over 80%, at the same time maintaining the necessary temperature with a voltage as low as 36V. The heater may be programmed to deliver steady, uniform and accurate heat from 25ºC to 75ºC, the most commonly used range of temperature in the conservation field.

Another transparent heatable textile developed for the IMAT project is Powerheat NT, which is an innovative fine polyester mesh with woven-in electrodes and electrically conductive yarns coated with carbon nanotubes. Both textiles are laminated with an external skin of transparent silicone.

The whole heating system is completed by a control unit that controls, monitors and registers the heating process and by a power supply unit. The IMAT control unit, appositely designed and prototyped for the project, consists of four distinct components: Power box, Control Unit and thermocouple (TC) Unit. Accordingly, IMAT Project now culminates in a series of innovative state-of-the-art precision mild heat transfer instruments for art conservation, in the form of ultra-thin profile, lightweight, flexible, transparent and breathable mats, powered by an intelligent easily portable console to control the temperature with readings acquired and adjusted more than 8 times/second. The IMAT console is regulated and programmed by an LCD touch screen, which allows unprecedented control over the heat transfer pattern, which can be monitored on touch-screen in real time with an accuracy of 1 second.

First tests both in Laboratory and in the field of Conservation, performed on a series of prototypes of the designed heaters show that the device is able to convey uniform heating on different working materials, thus proving to be effective for thermal consolidation.

**Project Context and Objectives:**

Thermal treatments and integration of accurate heating are commonly used in the conservation of paintings, works on paper and other cultural heritage objects. Heat transfer factors are amongst the most important phases for the majority of structural treatments, such as consolidation, treating planar...
important phases for the majority of structural treatments, such as consolidation, treating planar deformations, reinforcing degraded support and others. In particular, in paintings conservation, highly accurate and steady temperature, applicable either selectively in targeted areas or universally, is a crucial factor, and lack of control over the temperature may lead to incomplete or failed treatment (if not damage to the artwork). Even in relatively small areas, uniform and accurate heat application is problematic, and as the area of application increases, control of the temperature and uniformity of distribution of heat become progressively more difficult to achieve with the available instrumentation.

The prevalent heating instrumentation available and in use to date, capable of treating larger scale artworks, is the heating table fitted with suction. This equipment was developed to serve the increasingly pervasive practice of complete impregnation of paintings with natural wax-resin, followed by the widespread use of synthetic thermoplastic resins from the 1970’s on. While the heating table has had some improvements in design, and today comes in various models and sizes, it has not changed essentially since the mid 1980’s. Its ubiquitous presence as a laboratory device is long established, yet for most conservators, it constitutes a limited piece of machinery for its large footprint and fixed location, and inaccessibility to many conservators due to its high market price.

The heating table also has many inherent characteristics such as high power requirements (10-15 kW, 380 V for larger applications), and high heat sink mass that result in slow response, inefficient power use and high consumption costs. More importantly, even the best heating tables reveal significant temperature fluctuations and uneven heat distribution that render the all-in-one apparatus out of step with current conservation methodology and laboratory needs.

Present-day conservation practices are moving towards minimal, targeted and less invasive treatments, and accordingly the conservation profession’s challenges and best practices are becoming ever more global and mobile. It seems clear that the future of heating devices in art conservation will be with mobile, versatile, accurate and cost effective “smart” devices. In the search for mobile alternatives, flexible heaters offer the most attractive perspectives: they are lightweight and portable, can be designed in a variety of shapes and sizes, applied selectively and combined with other treatment devices in a most versatile way. For this reason, first steps toward the implementation of flexible mild heating systems were taken in 2003 where a prototype to be used in the treatment of mural paintings on canvas by H.S. Sewell (1899-1975) in Oregon City, Oregon, USA (see Figure 1a) was devised. The device was made of silicon rubber and wound wire heating elements connected to a custom designed control unit with an external thermal sensor adapted from industrial use. Later, a second prototype was created in 2005, with some improvements in its design (see Figure 1b). Both prototypes and other later designed heaters have been used since in the treatment of numerous artworks, which differ in size, period and materials and the results have solicited considerable interest from the conservation community.

The simple application, impressive precision, mobility and versatility showed by the silicone and wound-wire prototypes encouraged further development of the concept of a mobile mild heating system for art conservation, improved by novel technologies such as carbon nanotubes (CNTs). As widely known, CNTs are molecular scale sheets of graphite (called graphene) rolled up to make a tube and can be described as a new member of carbon allotropes, lying between fullerenes and graphite. Single Wall Nanotubes (SWCNTs) consist of single rolls, while Multi Wall Nanotubes (MWCNTs) consist of two or more coaxial tubes-within-a-tube. Properties of individual CNTs can be influenced significantly by their chirality (twist) and geometry. Held together by the Van der Waals force, CNTs tend to bundle in ropes, forming agglomerates, but depending on the production (“growth”) method can also form highly aligned structures. CNTs are interesting for various applications in cutting edge electronics, optics and material engineering since they are characterized by interesting physical and mechanical properties: thanks to sp2 bonds they
Since they are characterized by interesting physical and mechanical properties, thanks to sp2 bonds they are the strongest and the stiffest materials known, with an E-modulus 10 times greater than steel; they are lightweight and highly conductive, and have numerous other outstanding properties and applications, which are still in the process of being discovered. They are the best field emitters of any known material and, in theory, metallic nanotubes can carry an electric current density of $4 \times 10^9$ A/cm$^2$. Moreover, CNT thermal conductivity along the axis has been measured as high as 3500 W m$^{-1}$ K$^{-1}$, although in theory it could reach a value equal to 6600 W m$^{-1}$ K$^{-1}$.

Although metallic CNTs are excellent conductors, they do not have metal bonds and possess very unusual features: they are exempt of thermoelectric effect, and from a quantum mechanics point of view SWCNT do not follow Joules law ($P=IV$).

While CNTs are revealing ever more remarkable features that will enable the creation of a broad range of “smart” materials and products with revolutionary characteristics, most researchers agree that perhaps the greatest technological potential at the present time lies in the electrical properties of CNTs to generate heat in a way unattainable with other technologies. The material is not only extremely light and robust, but can also efficiently heat up surfaces of any size, and feature a very rapid thermal response, which is an important factor in maintaining ultra-steady temperatures, and in reducing heating and cooling times. For traditional materials, the change in temperature is usually slow and delayed due to their large thermal mass. In contrast, the thermal response of CNTs can be very fast even up to the incandescent state.

Conductive films made with carbon nanotubes and metal nanowires, in addition to their low sheet resistance, possess an optical transmittance in the visible spectrum and can form quite electrically conductive, yet almost completely transparent films, measuring only about 50-100 nanometers thick. Other promising developments in this sector were introduced in 2010 by Bayer Material Science (Leverkusen, Germany) that produced at industrial scale the first highly purified MWCNT, called Baytubes®. Baytubes in aqueous suspensions were applied to multifilament yarns resulting in a new textile heater made by weaving CNTEC® conductive yarns from Kuraray Living Co., Ltd. in Japan in 2010. This fabric heater is lightweight, thin and compact, thus demonstrating sustained durability to bending. Highly conductive CNT coatings, which could be applied like a varnish, were developed by Future Carbon (FC, Bayreuth, Germany) in 2009 and transparent conductive coatings have been researched with reported sheet resistance values as low as 1 ohm/square [$\Omega/\square$] for the opaque FC Carbo-E-Therm coating, and 0.3 $\Omega/\square$ in a transparent coating. All of these products were developed for very different uses than art conservation, and were applied exclusively to glass, polycarbonate, or PET substrate, rendering them impractical and difficult to use in art conservation, where the substrate must be soft, and resistant to the impact of solvents, heat, and to frequent rolling or bending.

According to the above mentioned issues, the main objectives of the Intelligent Mobile Multipurpose Accurate Thermo-Electrical Device (IMAT) Research Project (2011-2014) were to advance cutting edge technology of carbon nanotubes while designing a series of innovative, state-of-the-art precision instruments for mild heating, designed specifically for art conservation, in the form of lightweight, flexible, transparent and breathable film-like mats.

With this aim in mind, the main challenge of the IMAT project was to design and realize a completely new heat transfer technology consisting of (see Figure 2):

Figure 2 – here

1) IMAT heater: CNTs-based or AgNW-Particle-based heater to be applied on the artworks for the conservation intervention.
Three kinds of heaters have been designed and produced: IMAT-S, IMAT-B and IMAT-T. Such heaters have been produced in different sizes as described in the next paragraph. Moreover, both IMAT-B and IMAT-T have been produced using two different technologies. IMAT-S is composed by a fiberglass substrate with PUR 200 MWCNTs coating. Two different technologies have been devised to produce IMAT breathable. The first one, called IMAT-B-1 is based on a textile substrate where the filaments are coated with PUR 200 MWCNT. This kind of heater has been realized both using fine polyester meshes and multifilament polyester meshes. The second kind of IMAT-B, named IMAT-B-2 is based on the II generation SEFAR Petex with woven electrodes coated with PUR200 MWCNT. This prototypes outperform IMAT-B-1 ones since it is has excellent thermal stability. Also transparent heaters have been produced using two different technologies. The first kind of heater, named IMAT-T-1, is based on SEFAR PEN 30-60 with silver nanoparticles and a techtosil transparent silicone skin (see Figure 15). This kind of heater is designed to reach up to 85°C. The second kind of transparent heater has been designed and produced is based on SEFAR powerheat NT substrate with MWCNT.

2) Control and Power Unit Console (“IMAT console”) for IMAT heaters. The IMAT console serves as power source for the IMAT heater and for controlling over the temperature, for the accuracy and steadiness of the heating cycle and for the heating and cooling times. Two kinds of consoles have been produced:
- IMAT-LV (low voltage) working at 36V and providing a maximum power equal to 600W.
- IMAT-HV (high voltage) working at 96V and providing a maximum power equal to 1500W.

IMAT console consists of the following components:

a) TC unit: a wireless unit dedicated to the local measurement of the IMAT heater temperature. This unit dialogues with the Control unit (see below) via Bluetooth.

b) Power Unit: a unit providing the necessary power (36V or 96V respectively for IMAT-LV and IMAT-HV) to the heater on the basis of the desired temperature to be used for the conservation treatment. This unit is connected to the IMAT heater by means of a flat cable.

c) Control unit: a unit provided with a touch screen and a Graphical User Interface (GUI) to be set by conservators. This unit dialogues with the TC unit via Bluetooth and is attached to the Power unit by means of a USB cable.

Accordingly, the newly devised nano-mats are driven by a programmable mobile touch screen console with that will give the operator the ultimate control over the temperature and heating pattern that is unprecedented in art conservation. The devised system, as demonstrated by Laboratory and Field testing, will be advantageous in diverse structural treatments on cultural heritage assets, in dealing with local, global or specific conservation problems, allowing conservators to easily, and with unsurpassed accuracy, apply mild heating locally and over very large areas. The portability and low energy consumption make the IMAT an ideal multi-use instrument for work in the field or in the laboratory, indispensable in the treatment large scale works, in areas of limited access or in emergency response conditions. Finally, the IMAT project resolves at its core the pressing need for accurate mild heating in conservation methodology by inventing a long awaited mobile and accessible nanotechnology, that aspires to become an integral part of the conservators’ tool box and to expand the technical capacities of conservators worldwide, opening new, yet-to-be discovered possibilities in treatment methodology and enabling local communities to safeguard their heritage and sustain their culture for the future generations.

Project Results:
1. Introduction
The creation of new advanced conservation materials and sophisticated instrumentation is of fundamental importance in the process of advancing best practices in the profession and preserving artworks and other cultural heritage assets. Sophisticated and accurate instrumentation allows conservators to design new treatments and to treat artworks within the margins of minimal intervention and risk, while achieving the maximum result. The IMAT project, structured in the following Work Packages, focuses and responds to a critical omission in current conservation treatment instrumentation for mild heating. Highly accurate and versatile application of mild heat is essential for success in most structural treatments of various cultural heritage objects (paintings, works on paper, textiles, objects, and others), yet devices presently available to conservators in all areas of the profession are unable to guarantee the desired accuracy, control or uniformity.

Work Packages:
WP1: Management of the consortium (coordination of the project).
WP2: Technical opportunity study: establishing technical parameters for targeted design.
WP3: Research and development of new and improved nonmaterial coating for the IMAT heater.
WP4: Research and development of heatable nonmaterial films and textiles for the IMAT heater.
WP5: Research and development of a reliable and efficient temperature control unit for the IMAT heater.
WP6: Research and development: field testing of IMAT prototypes.
WP7: Research and development: analysis of test results and finalising IMAT prototypes.
WP8: Research and development: from final design to production line.
WP9: Dissemination and exploitation of results.

The IMAT project developed a highly conductive CNT coating material in order to achieve low voltage heating even in large heaters. For the low voltage heating an extremely high conductivity in the coating material is required in combination with a stable low resistance at the interface between coating material and electrodes.

In detail, as mentioned in the Section “Summary description of the project context and the main objectives” IMAT consists of 1) a series of heaters produced in the form of opaque (IMAT-S), Breathable (IMAT-B) and Transparent (IMAT-T) mats and 2) a console encompassing power source, thermocouple unit and control console. The main S&T foregrounds of the IMAT project are related to the design and manufacturing of such an innovative system. As a consequence, the present Section will firstly describe materials concepts and mathematical principles constituting the basis for the early design of the system. Secondly, a description of the material combination (e.g. substrates, coatings, use of other nanomaterials than CNTs, etc.) developed for the three kinds of heaters are briefly recalled. Thirdly, the final design of the IMAT heaters is provided. Then, the console devised for controlling the heaters and for providing power source are briefly described. Finally the overall system is described together with some results obtained during field testing.

The present, final, report has been structured as a comprehensive “book” to help the reader in having a bird’s-eye view of almost all the S&T results obtained during the three-year program. For this reason the description of outcomes is not structured in WPs and tasks as per the I and the II Periodic Report. In fact, by merging together such Periodic Reports as well as referenced deliverables, it is possible to have a deep view of all the work “behind the scene”. The intent here is rather to propose a publishable document.
Deep view of all the work "behind the scene". The intent, here, is rather to propose a publishable document summing up the most relevant aspects of the project without requiring the reader to be aware of deliverables, tasks, milestones and other formal documents defining the overall project. The only exception is for sub-section 11 where formal results are presented.

2. The basic component of IMAT system: Carbon Nanotubes
The preliminary study and bibliography analysis performed in WP2 demonstrated that several materials could be used for the IMAT heater (see Figure 3). Among them, Carbon Nanotubes (CNTs) proved to be the most effective for IMAT purposes. CNTs are extremely long and thin hollow nanofibers in which the carbon atoms are bonded together in graphitic structures that are the origin of the high electrical conductivity of the nanotubes along their axis. Depending on their production process they can have a length up to several mm and their diameter usually is in the range of 5-20 nanometers, so that they usually have a length to diameter ratio in the range of several thousands. When they are produced they are highly entangled and agglomerated. High mechanical forces are necessary in order to break them apart and disperse them evenly in a liquid or coating material.

Figure 4 here
On the other hand, during drying process re-agglomeration occurs and new entanglements are formed which will keep the CNTs together even under high mechanical strain. Therefore, such CNT coatings display an astonishing high elasticity and flexibility even at a very thin coating thickness, especially when these structures are fixed within a chemically cross-linked coating system. Such highly entangled CNTs in a chemically cross-linked binder matrix are the basis for the coating system developed for the IMAT project. Due to the nanoscale dimensions of the CNTs these coating layers give very even heating over large surfaces. The chemical reactivity of the components needed to be further adjusted in order to get sufficient adhesion onto the substrate and yet sufficient flexibility of the coating layer.

Figure 5 here
FutureCarbon has invented such high-efficiency, electrically conducting coatings based on aqueous CNT dispersions in polyurethane binders. They can be used in non-hazardous low-voltage range and is suitable for temperatures up to approx. 500°C. Its excellent applicability to very different geometries and surfaces plus its high heating power open up a wide field of possible uses. Basically, Carbo e-Therm consists of a binder matrix and a specially matched carbon formulation. The excellent conductivity of the coating makes it possible to implement high heating power on non-hazardous low voltage (e.g. 12/24 V). Compared to conventional resistance heating, Carbo e-Therm distributes heat absolutely evenly without hot spots. Carbo e-Therm heating layers are highly rugged mechanically. For use in IMAT heaters this coating material has been optimized for high elasticity as well as high adherence to the polyester substrate. Depending on the thickness of the coating, electrical conductivity can be adjusted: the thicker the coating, the higher the conductivity is. However, thicker coatings are more brittle and stiff as well as much more expensive, and thinner coatings are more difficult in obtaining a very even coating thickness for even heating temperatures. Thus, a coating thickness of 40 µm has been chosen for the standard heater with an electrical resistance of about 16 Ohm/sq. which will be sufficient for the standard Din A4 size heaters.

In addition FutureCarbon has invented an electrically conductive impregnation for heating absorptive surfaces up to 100°C. In fact, it is a very simple application, operation on non-hazardous low voltages plus high-performance heating, thus allowing a whole variety of possibilities of use. Surfaces impregnated in
high-performance heating, thus allowing a whole variety of possibilities of use. Surfaces impregnated in this way can be electrically heated by applying a non-hazardous low voltage (e.g. 12 or 24 V). Unlike coatings, CarboImpreg soaks into the surface of a material and fuse with it internally. In this way full processing of the material without any restrictions is still assured. Basically, CarboImpreg consists of a binder matrix and a special, highly conductive carbon preparation. Excellent conductivity allows high heating performance solutions on non-hazardous low voltages (e.g. 12 or 24 V). Furthermore, treated surfaces exhibit high ampacity, enabling very fast heat build-up rates. CarboImpreg heating solutions are highly robust. The impregnation does not degrade the processing characteristics of the carrier material, and exhibits excellent resistance to water and alkalis. Due to its low viscosity, CarboImpreg can be easily applied by a dripping process. Compared to Cabo e-Therm, CorboImpreg has a slightly lower content of carbon nanotubes and a lower content of binder so that it has slightly reduced adhesion and usually is slightly less conductive than Carbo e-Therm. Its big advantage, however, is its low viscosity which makes it an ideal candidate for infiltration beneath any surface. In our trials CarboImpreg was used for coating a glass fibre mesh made up of multifilament yarns as well as PET meshes of SEFAR. The material was sprayed onto the substrate. With CarboImpreg the CNTs get between the filaments into the yarns. Due to the low viscosity, plugging of pores in the mesh used as a substrate for the IMAT prototypes has been mostly avoided. Alternatively, air pressure was used to unclog the meshes. Based on Carbo e-Therm and CarboImpreg a series of new highly conductive CNT coating has been developed. The resistivity has been distinctly decreased from 1200 µΩ to 612 µΩ (actual Carbo e-Therm PUR-120 1W). Both coatings are water based 1K PUR systems in which the dispersion of carbon particles in the polymer has been distinctly improved. The coating showed best results with regard to conductivity as well as mechanical properties. In addition, it had excellent flexibility and adhesion to various substrates like PET and others. Addition of higher amounts of carbon particles would make the coating brittle, badly applicable and difficult to dry so that further development of the standard IMAT heater will be performed with this optimum coating composition.

3. Conceptual Design and basic equations
The conceptual design and architecture of the proposed mild heating device (see Figure 6) comprises a conductive film heater, made with CNTs and an associated control unit (console) that also serves as a power outlet for the heater. The console includes an electrical “power box” that drives the heater, a digital touch screen console to control and programme the heating process, and a thermocouple (TC) that is connected to the console via a Bluetooth (wireless) connection. The architecture was designed to provide maximum versatility and mobility for the device in the most diverse treatment situations by separating the sensor, control pad and power source elements of the console. For example, the heavier “power box” can be conveniently placed under the working table and the touch screen console can be kept nearby the treatment area. The wireless TC may be positioned easily in any location and the flat flexible connecting cable makes placement of the heater uncomplicated. In all aspects, the mild heater’s design aims for miniaturization and simplification in design solutions. The prototypes operate with a universal 110-230 V input and have two separate power boxes; 36 V (for smaller heaters) and 96 V (for larger heaters). Figure 6 here
The flexible mat is composed of a substrate (see Figure 6), covered first with a conductive nanomaterial coating and then finished with an exterior protective coating, which also provides the non-tack surface and electrical insulation. Highly entangled CNTs in a flexible and chemically cross-linked binder matrix are the basis for the coating system to be developed for the IMAT heaters. When permeability to gases is
The basic equations for designing IMAT heaters start from the relationship between power (P), voltage (E) and current (I) according to the following equation:

\[ P = E \cdot I \] (1)

Furthermore, it is possible to state how the applied voltage E, the length L (separation between the electrodes) and the sheet resistance \( R_s \) are connected in the conductive film heater, according to the following equation:

\[ P_D = \frac{E^2}{(R_s \cdot L^2)} \] (2)

where:

- \( E \) = Applied voltage [V];
- \( L \) = Length (i.e. separation between the electrodes) of conductive coating [m];
- \( R_s \) = Coating resistance \([\Omega/□]\);
- \( P_D \) = Power density \([W/m^2]\).

Moreover, coating resistance is related to the so called “resistance on the approximate line” \( R_L \) \([\Omega]\), i.e. the overall resistance of the heater, assuming negligible the resistance from electrodes, wire and connectors, or wire to wire:

\[ R_s = \frac{R_L \cdot W}{L} \] (3)

Finally, from equations (2) and (3) it can be demonstrated that:

\[ W \cdot L = \frac{P_T}{P_D} \] (4)

where:

- \( W \) = length of conductive coating [m];
- \( P_T \) = total power of the system [W].

The power density is determined on the basis of the heat requirements (desired temperature) according to the curve presented in Figure 7, stating an almost linear relationship between reachable temperature and power needs. If, for instance, a heater with a surface of 0.25m x 0.16m = 0.04m² is designed to reach a temperature equal to 80°C, the necessary power density results will be equal to 1500W/m². From Eq. (4), it is possible to derive a needed power \( P_T \) equal to 60 W. By considering Eq. (1), this means that if, for instance, a voltage of 24 V is used, the actual needed current is I=2.5 A and the resistance \( R_L \) results are equal to 9.6 Ω.
Once $RL$ is known, it is possible to evaluate the thickness of the heater. With this aim, it is first necessary to determine the coating resistance $R_s$ using Eq. (3); depending on where the electrodes are placed (along the short or long sides of the coated area), a different coating resistance will be achieved. Referring to Figure 8, since electrodes are placed along the long sides of the coated area, $R_s$ results were equal to $15 \, \Omega/\square$. On the other hand, when the electrodes are placed along the short sides of the coated area, the coating resistance results are equal to $6.2 \, \Omega/\square$.

Finally, from coating resistance, it is possible to evaluate the thickness of the coating layer according to the experimentally evaluated chart depicted in Figure 9, where the relationship between the layer thickness $d$ and $R_s$ is drafted. Referring to the example, when electrodes are placed along the long sides of the coated area, the thickness results equal $92 \, \mu$m; when the electrodes are placed on the short sides, the coating results equal $195 \, \mu$m.

On the basis of the above considerations, it has to be noted that for larger sizes (e.g. $1000 \, \text{mm} \times 1600 \, \text{mm}$ in Figure 8c), high voltage and low sheet resistance are needed to reach the desired temperature (in this example, $48 \, \text{V}$ and $1.5 \, \Omega/\square$ are required). In order to overcome this problem, segmentation is the best option. As illustrated in Figure 8d, by segmenting the substrate it is possible to reduce the power needs for each element (from $2400 \, \text{W}$ to $800 \, \text{W}$ per element), thereby increasing the sheet resistance up to $14 \, \Omega/\square$. Since the reduction of resistance using CNT-based materials is not a complicated task, segmentation may be considered a straightforward method for overcoming this relevant problem, i.e. for obtaining the same thermal behaviour with higher resistances.

4. Desired properties of the heated mats
The design of the heated mat evolved as the project developed. The desire was to have a flat, non-stick, flexible mat which could be thin enough to insert into narrow gaps. The mat temperature should be regulated by a thermo-couple device linked to a control unit. It became clear at the start of the project that more than one mat needed to be designed, each with specific qualities. Transparency and breathability could not be included in one mat. Thus three separate mats were envisioned. Specifications for each of the mat types would differ depending upon the desired end-use for each mat.
Specifications for each mat type were discussed at the various meetings and established by conservators at the field testing centres involved as partners in the project.
Areas of concern included the width of the electrodes as these could produce cold strips along the edges of the mats; the distance between the electrodes which would determine the power necessities of the mat; the thickness of the connecting wires and electrodes in order not to bulk out the mat; and the type and colour of the coating. The flexibility of the mat and its ability to heat uniformly from a low temperature were paramount.
5. Material combinations and studies for creating IMAT heaters

A brief description of research and development of flexible, chemically resistant, breathable and transparent films and textiles (with electrical connections and temperature sensors) for use in the IMAT heater is proposed in this sub-section thus reassuming the outcomes of WP3 and WP4 with particular reference to Deliverables D3.1, D3.2, D3.3, D4.1, and D4.2.

The results obtained in such WPs, demonstrated by the above mentioned deliverable, allowed the definition of the final heater prototypes described in the next sub-section. Accordingly, outcomes are described with reference to the three kinds of heaters (IMAT-S, IMAT-B and IMAT-T).

5.1. IMAT-S

Numerous attempts have been undertaken for designing and producing the standard IMAT heater. Polyester and PVC plastics films as substrates have been looked at as well as polyamide and polyester textiles and meshes. Since textiles made from multifilament yarns feel less stiff and are expected to give better conductivity and adhesion due to infiltration of the liquid in between the filaments, also multifilament polyester and fine glass fibre meshes have been included in the trials.

Transparent polyester films as well as polyamide textiles can be easily coated by Carbo-e-Therm. The coating sticks quite well to the substrate and does not show any delamination. A constant coating thickness in the lab samples has been realized by spray coating. In continuous production, a screen printing process for such films is planned for sizes up to 1.50 m width and more, leading to highly constant coating thickness (see Figure 11). However, even a very thin PET film substrate of less than 0.5 µm thickness has still certain stiffness and is not as flexible as a textile. In addition, although the CNT layers as well as the protective silicone layer show an excellent adherence to the PET substrate, there might still be a low chance of delamination after long time of service at elevated temperatures and in combination with water vapours or aggressive solvents.

PVC film generally is softer than PET so that it was expected that a standard IMAT-heater based on a PVC film would be less stiff than a comparable heater based on a PET film. Therefore, several coating trials were done using soft PVC film. However, results clearly showed an extremely poor adhesion of the improved Carbo-e-Therm coating to the soft PVC film material. Using corona treatment of the PVC film, adhesion of the Carbo-e-Therm coating has been distinctly improved. Testing the adhesion with a cross cut test (DIN ISO 2409) showed similar results like PET substrates. However, soft PVC like used in the trial usually has very poor temperature stability. The film starts to soften at 45°C due to the softener evaporating already at these low temperatures. Therefore, soft PVC should not be used at higher temperatures and was omitted as optional candidate for the IMAT heater which shall be designed for use at temperatures up to 85°C.

If a textile made of multifilament yarns or a mesh is used instead of a film, the coating layers become much better physically locked onto the substrate, especially when the silicone is applied from both sides and sticks together through the pores of the mesh or textile (see Figure 12).
Hence, further development for the standard IMAT heater has been focused on multifilament textile meshes and grids as the substrate together with a protective silicone top coating on both sides and completely around the edges. The main advantage of using multifilament meshes was the possibility of integrating electrodes into the substrate by using conductive metallic fibres directly sewed onto the meshes. A very coarse mesh showed good results with regard to electrical conductivity that could be reached. However, temperature distribution proved to be extremely uneven, since heating mainly occurred very close to the fibre strands and temperature stayed low in the regions of the huge pores. As a consequence, finer meshes (polyamide as well as polyester textiles) have been tested. Due to the chemical basis of the polyamide and the physical structure of the woven textile surface, an excellent adhesion by physical and chemical forces has been achieved. Compared to the PET mesh the PA textile is distinctly thicker but has similar stiffness. Accordingly it was an option for the standard IMAT heater with regard to its low modulus. However, due to the thickness of the textile the heater is somewhat thicker than the other materials. In addition, highly elastic Trevira polyester textiles were used for preparing the standard IMAT heater. The elastic polyurethane coating showed good adhesion to the Trevira textile and decreased the elasticity only slightly. On the basis of the above mentioned considerations, it was decided to use Trevira textile with fibre glass meshes, as a substrate for the IMAT-S prototypes. In detail, as depicted in Figure 13, a Trevira is coated with glass fibres to slightly increase the stiffness and, at the same time, improve the thermal response.

Figure 13 here

Once the feasible substrate is selected, several methods for coating such a substrate with CNTs have been explored: dipping process, spray coating, printing, doctor blade, continuous coating. Temperature distribution is highly dependent on coating thickness. The process of choice needs to give a highly even thickness of the CNT coating, so that the heater will have an even temperature distribution over the whole heating area. A reasonable option for applying the CNT coating is a spraying process. Spraying leads to an even thickness and hence, an even heat distribution provided that an expert in spray coating does the application. It has been the process of choice in the lab for manufacturing the demonstrators. By the spray coating process several thin layers can be applied consecutively until the final thickness is reached. It is possible to coat only certain areas by using a cover sheet what has been done in preparing the demonstrators. Another option is the printing process. Printing usually is used in production processes. It is the most sophisticated method for receiving a highly even thickness of the coating and the coating of only certain areas of the films can be easily achieved. Since the electrodes of the IMAT heaters needed to be designed in a certain way in which electrical cables can easily be connected to it, printing was among the best choice for the production of small and large IMAT heaters (see Figure 14).

Figure 14 here

For manufacturing of large heaters electrodes have to be fixed on the substrate so that electrical cables can be easily connected on one side. The CNT coating needs to be applied between the parallel sections of the electrodes. In the lab it can be done by spraying. However, printing technique is preferred since it gives very even coating thickness and hence a very even heat distribution.

Coating can also be done by use of a doctor blade. The big advantage of coating by doctor blade is the extremely even thickness of the coating provided that the substrate itself is very even and flat. If the substrate already has some buckling or does not lie totally flat on the apparatus, the coating thickness becomes uneven and so will be the temperature distribution in the finished product. Additional problems arise from the electrodes which usually are fixed on top of the plastics film and will get a thinner coating layer on top. However, coating by doctor blade is the process of choice for applying a protective silicone top coating onto small IMAT heaters (see Figure 15). Regardless of electrodes, cables, and connections.
top coating onto small IMAT heaters (see Figure 15). Regardless of electrodes, cables, and connections used for the electrical current, the surface of the finished part will be even and flat with everything included underneath. In the lab this process can be carried out easily, but for larger heaters it will be a problem, since large devices for coating by doctor blade hardly exist. In addition, this process becomes even more complicated and expensive in production.  

Figure 15 here  

For producing high number of prototypes, finally, the best option is the dip coating.

5.2. IMAT-B  

In principle, there were various options for the design of the breathable IMAT heater. First of all the substrate itself had to be breathable and of course, had to be still breathable after that all coatings (conductive coating as well as protective coating) have been applied. Textile fabrics are more or less breathable depending on the tightness of the weaving. However, the conductive coating material forms a closed film on top of the textile, so that no air or vapours can get through any more. This film could be perforated mechanically, but such film formation with a pluggage of pores could easily occur again when the protective coating is added.

Therefore, the only way to produce a breathable IMAT-B heater was to start with a mesh or grid, dip it into a relatively low viscous coating material, blow off the excess liquid in order to reopen any plugged pore, and then use a low viscous protective top coating. A textile mesh as fine as possible and made from multifilament yarn had to be used for the final design, in order to get good adhesion to the substrate and a very even heat distribution over the whole surface. As per IMAT-S, coarse meshes easily lead to small temperature deviations with higher temperatures close to the coated yarns and lower temperatures in between. However, if the mesh is too fine, pluggage may occur during any of the two coating processes. As a consequence the first choice to realize IMAT-S substrates was to use fine or multifilament meshes. First tests were performed using polyester meshes; compared to glass fibre, they have a much lower modulus and are less stiff. Adhesion to polyester has been proven to be excellent, so that polyester meshes have been tried. By using diluted CNT coating mixtures and the air blasting technique, pluggage of the pores has widely been avoided. There were also done trials on a polyamide textile. Due to the chemical basis of the polyamide and the physical structure of the woven textile surface, an excellent adhesion by physical and chemical forces has been achieved. Compared to the PET mesh the PA textile is distinctly thicker but has similar stiffness. On the basis of extensive analysis, fine polyester meshes and multifilament polyester meshes with a thin polyurethane coating have been used for IMAT-B samples. These meshes have been coated with Carbo e-Therm PUR 200 CNTs with a maximum operative temperature of 200°C. Addition of a light grey polyurethane protective coating by spraying technique has been successfully proven in numerous trials. Breathability was excellent. However, polyurethane coatings are chemically not as resistant as silicone protective coatings are. For better protection against vapours and solvents various possibilities for applying an additional silicone coating has been explored. The problem was to find a low viscous silicone material that does not plug the pores and can easily be applied by spraying. The final transparent silicone top coating on this kind of IMAT has been applied by laminating a pre-cured silicone film onto both sides, thus covering also the electrodes and the electrical connections. Another option explored for IMAT-B was to use SEFAR Petex woven fabrics usually consisting of PET and electrically conductive filaments in a dense pitch. A 1st generation, created by SEFAR was firstly tested. It had a thickness in the range 100-300μm and consists of heating fibres which can be made by several materials such as copper alloys, stainless steel, twisted filaments, Tinsel or conductively plated filaments. The heating curve, depending on time, is reported in Figure 31.
The heating curve, depending on time, is reported in Figure 31.

Since the thermal behaviour of this substrate was not optimal for IMAT purposes, SEFAR developed, for the IMAT project a 2nd generation of textiles, light-weight (<90 g/m², filament diameters 40-80 micron) and with high air permeability (> 90 g/m²/s). In particular a new textile-based prototype, named V1, essentially based on SEFAR PETEX 07-465/49 has been designed. This new prototype share with the PETEX sample the same warp chain and the same electrode space. As depicted in Figure 17 however, no comb wires are present in this new sample. The fabric is basically composed by PET (Polyethylene terephthalate) fibres i.e. by thermoplastic polymer resin of the polyester family with an intrinsic viscosity range equal to 0.40 – 0.70. In particular, two different sizes of fabric have been developed: wide (V1a) and DIN A4 (V1b) sized. For the wide fabric, warp is composed by 16 filaments/cm with a diameter equal to 200 µm. Weft has 10-20 filaments/cm with a diameter equal to 100-140 µm. This demonstrates that density of the fabric can be adjusted along weft direction. Electrodes are made of stranded copper wires Ag coated with a cross section equal to 0.7 mm² and 20 mm width.

Regarding the DIN A4 size, the electrodes (again made of stranded copper wires Ag coated) has a total cross section equal to 0.19 mm² and 5 mm width. As depicted in Figure 18 warp has a density of 16 filaments/cm with a diameter of 200 µm and weft is adjustable in the range 10-20 filaments with a variable diameter equal to 100-140 µm.

Another generation of heating fabric to be used as a substrate for the IMAT-B prototypes has been devised by SEFAR. Again based on SEFAR PETEX 07-465/49 and named V2, it consist of a comb structure with same warp chain and same electrode space as V1 but with comb wires. Comb wires are, basically, copper wires each with diameter equal to 100 µm. The wire spacing y depends on the area resistance of the CNT ink and the required voltage and power density while keeping in mind not to exceed the comb current. On the basis of the comb wire structure, the final result consists of a 2nd generation of Power Heat, called PowerHeat NT that has nearly the same structure as PowerHeat but with an additional yarn with a very high electrical resistivity (or an CNT coating) in warp direction. That means, that the voltage drop is not over the fibres in weft direction, it is over the yarns in warp direction between the wires in weft direction (see Figure 19).

Depending on the coating to be applied on the fabric substrate, two different kinds of Power Heat are designed:
1. Power Heat NT + CNT coating
2. Power Heat NT + Carbotex

In both cases electrodes and electric connections are positioned on the same side and can be cut on a specific area. Once the structure is chosen, this novel structure had to be electrically designed. With this aim a computer-based procedure has been devised by SEFAR in order to decide size and dimension of each component. By a way of example, with a desired power of 1200 W/m² and a 36 V voltage, and choosing a 16 mm distance between lead wires (i.e. segment height) it results:
- a number of 6250 squares per meter width.
Starting from these calculi the lead wires are modelled as follows:
- current per square in segment equal to 0.009 A/sq
- current to segment per meter width equal to 0.53 A/m
- current density equal to 33.3 A/m²
- length of lead wires equal to 0.6 m
- total current per meter length equal to 20 A/m
- max current in lead wire equal to 0.64 A

Other electrical parameters are evaluable by setting an appropriate value for lead wire (Cu) diameter. If this is set to be equal to 0.2 mm, it results:
- resistance of lead wire per meter equal to 0.55 ohm/m
- maximum power in lead wire per meter equal to 0.227 W/m (the target is to stay below 0.5 W/m).

5.3. IMAT-T

Transparent coating materials are scarcely available on the market today. Therefore numerous attempts have been made to develop kind of translucent IMAT heaters. In the very beginning when the development of breathable IMAT heaters based on fine meshes as substrate was started the idea was born to create kind of translucent IMAT heaters based on such widely open meshes. After the CNT coating had been added, these meshes with numerous open pores still allowed light to pass through (see Figure 20).

Starting from coarse and fine textile meshes and using a transparent silicone protective coating, such heaters have been prepared for low voltage heating (see Figure 21).

Such semi-transparent heaters were explored deeply as an option for the IMAT-T. They can be equipped with a thicker and completely chemically inert protective coating made from transparent silicone. They can be heated up to about 50 °C by low voltage of 36V. Due to the physical interlinking of the silicone material in the textile mesh, they cannot delaminate and are expected to withstand any mechanical forces in day to day usage. In order to obtain absolute transparency, a completely transparent plastic film had to be used in combination with a transparent conductive coating as well as a transparent protective silicone coating. For the conductive coating material, a transparent SWCNT based coating material as well as transparent AgNws-based coatings have been evaluated. A first prototype has been prepared made from transparent polyester film and transparent SWCNT coating. The fine meshes resulted in a very even temperature distribution with almost no temperature differences between yarns and pores, as demonstrated by temperature trends shown in Figure 22. Unfortunately, transparency of such heaters (54.51% using the IP-T method) resulted lower than the desired value of 65%.

Consequently, in a second attempt, an extremely fine translucent ‘power-heat’ polyester fabric produced by SEFAR with heating wires woven into the fabric was used. It was equipped with a copper electrode on either side of the fabric and had good heating performance as well as sufficient translucency, and, most important of all, could be easily handled and cut into any size. For better resistance against solvents and...
Important of all, could be easily handled and cut into any size. For better resistance against solvents and vapours frequently used in art conservation the fabric was embedded in a highly flexible transparent silicone. Flexibility as well as elasticity of this heater was excellent (see Figure 13) due to the high flexibility of the liquid silicone that was used, and heating performance was sufficient. Nevertheless, transparency of this heater still was not optimal. These considerations pushed the IMAT Consortium to explore the possibility of developing IMAT heaters based on AgNWs. AgNW films are characterized, in ideal conditions, by an optical transmittance (T) of ≈99% and surface resistivity (Rs) of 15Ω/sq. Unfortunately these values decrease using more AgNWs (needed to have the correct heat transmission). At a wavelength of 550 nm, the optical transmittance values of the AgNWs-based electrodes with AgNWs contents of 40mg/m2, 80mg/m2, 200mg/m2, and 400mg/m2 are, respectively, 96.1 91.7 44.3 and 34.8%.

For early prototypes, a film with 7 Ω/sq sheet resistance and total transmittance greater than 80% was possible to reach a maximum temperature near to 80°C, using a 36V voltage for mats sized 400mm x 300mm. Unfortunately, after a first very short run at 12VDC with little current of 0.47A (about 25ohm -> 33ohm/square) and a little heating (up to about 35°C), any electric current flowed in the film and a number of imperfections was reported (see Figure 23).

For these reasons the use of a film covered by AgNWs was discarded as a solution. Due to the interesting properties of AgNWs, however, another idea for developing transparent IMAT was to use a metalized polymer fabric. The fabric (see Figure 24) is based on the polymer PEN (Polyethylene Naphthalate). PEN has some excellent properties such as the melting point, around 270°C, and the glass transition temperature at 85°C (PET: Tm = 250°C; Tg = 60°C). This results in less shrinkage during each thermal treatment process. Moreover, due to the two condensed aromatic rings of PEN, strength and modulus, chemical and hydrolytic resistance, gaseous barrier, thermal and thermo-oxidative resistance and ultraviolet (UV) light barrier resistance are better than the same for PET. For a good transmission, a very thin yarn with a diameter of 30 μm was used.

Another option for creating transparent heaters was to explore the potentiality of single wall carbon nanotubes (SWCNTs). SWCNT are known to be able to form transparent conductive films although SWCNT as well as their dispersions come in a deep black colour like the multi wall carbon nanotubes - MWCNT. However, if such deep black SWCNT dispersions are spread extremely thin and evenly on a flat surface they become transparent with hardly any impression of a grey colour left (see Figure 25).

However, conductivity of SWCNT dispersions had to be increased considerably by special additives and/or treatments in order that their films supply sufficient conductivity at an acceptable transparency as well as light colour. In addition, the plastics films have to be prepared in a certain way so that the SWCNT dispersion spreads evenly and thin onto the surface. Otherwise, the black colour of the SWCNTs becomes visible.

The actual conductivity of such heating films is dependent on the coating thickness, if a wet thickness of 10-20 μm is applied, conductivity in the range of 200-600 Ohm/sq. can be expected. This conductivity will be sufficient for a voltage of 96 V at an electrode distance of up to 15 cm (see Figure 29).
Using the highly conductive CNT dispersion and special PET films several transparent heating films have been prepared. These films were then equipped with special conductive copper electrodes which are furnished with a layer of conductive glue on one side for achieving good electrical contact to the SWCNT layer as well as a thin layer on the other side for easy soldering to the FFC cable.

Using the transparent PET heating film also an alternative design of the heater was tried. Due to a certain thickness of the soldering connection at the edge of the heater that cannot completely be avoided and which may be problematically by using the heater in art conservation, the electrical soldering connection has been put about 20 cm outside of the actual heater into a tiny plastic box. Thus, the heater can be used in between paintings without causing any marks.

5.4. LAB TESTING ON FIRST PROTOTYPES
A huge number of intermediate prototypes for IMAT-S, IMAT-B and IMAT-T have been prepared during design phases described above. The most promising prototypes have been tested in Lab. These tests were performed in WP5. In detail two Bachelor Thesis have been carried out by UNIFI, aimed at performing a characterization of the IMAT prototypes. Results of the experimental test are mostly described in Deliverable D5.2. Basically, test performed were:

The tests were the following ones:
- Evaluation of load profiles and heating times;
- Punctual analyses on key pad points;
- Mean analyses on limited pad surfaces;
- Long-term tests (duration);
- Evaluation of unload profiles and cooling times;
- Evaluation of transmittance/transparency;
- Evaluation of breathability;

Tests were performed on different substrates such as wood, metal and fabric using a provisional console manufactured by SEFAR (due to the fact that the actual final console was under development).

Laboratory testing provides interesting results that shows the following main critical issues:
1) Final IMAT devices were required to guarantee more adherences to the treated surface. This is due to the fact that air pockets have strong influence on the thermal behaviour of the provisional prototypes for IMAT (see Figure 26).

2) Final IMAT-S prototypes were required to be more flexible according to a qualitative bending test.
3) A more precise and accurate control of temperature was required; in particular the console under development was required to have a proper PID setting and to provide temperature ramps.
4) As expected, results were not directly transferable to the Cultural Heritage field.

6. Final Design and manufacturing of IMAT heaters

The final design and manufacturing of IMAT heaters was the main objective of WP4 and WP7 and all the S&T results obtained are described in Deliverables D4.1. D4.2. D4.3 D7.1. and D7.2. In the present section the main outcomes obtained for the project are described in order to help the reader in understanding the main properties of the novel device. The final design of IMAT prototypes derives from
understanding the main properties of the novel device. The final design of IMAT prototypes derives from the considerations made in the above sub-section and from the results of laboratory testing.

6.1. IMAT-S

Final IMAT-S consists of a conductive low voltage heater with a soft and non-tack surface, which is opaque and non-breathable. The IMAT-S is intended for thermal treatments where visibility and breathability are not required. In terms of its use, it is similar to the pre-IMAT prototypes, but new added features have improved distribution of heat over the surface, instant thermal response, increased accuracy and notably, low voltage application, as well as its easy handling, which allows rolling it up and using it at any location “in the field”.

The IMAT-S prototype substrate consists of a fiberglass substrate with PUR 200 MWCNTs, as described in Figure 28 and in Figure 29. Heating mats with thin PUR top coating proved to be extremely thin and lightweight, and show an extremely fast thermal response. Protective 0.5 mm Arlon silicone is used to protect the CNTs-based substrate.

Figure 28 here

IMAT-S is able to reach a temperature of 90°C, depending on size and power.

Figure 29 here

Laboratory tests performed on several differently sized IMAT-S prototypes (see for instance in Figure 30 the temperature trends in a selected point of the IMAT-S coupled with respectively, a wooden desk, a metal table and a textile substrate) demonstrated the effectiveness of such systems in reaching and maintaining the desired temperature within 1°C. This thermal uniformity can nonetheless be considered sufficient for typical applications in the art restoration field.

Figure 30 here

Moreover, the IMAT-S performance is maintained also during long-term use as demonstrated in Figure 31 where the temperature measurements obtained by running the heating device for eight consecutive hours with a target temperature of 35°C, 47.5°C and 57.5°C are depicted. The temperature trends for a given point on the mat at the three differently set temperatures (see Figure 20) showed that no significant temperature variation occurred. Moreover, visual analyses of the thermal mats, performed by technicians of the authors’ laboratory, showed no visible changes in the overall structure of the IMAT.

Figure 31 here

6.2. IMAT-B

Two different technologies have been devised to produce final IMAT breathable. As a consequence two kind of IMAT-B have been produced and named, respectively, IMAT-B-1 and IMAT-B-2.

IMAT-B-1 is based on a textile substrate (fine polyester meshes or multifilament polyester meshes) where the filaments are coated with PUR 200 MWCNT (see Figure 32).

Figure 32 here

IMAT-B-2 is based on the II generation SEFAR Petex (with 60% reduced yarn diameter with respect to the I generation described in the I Periodic Report) with woven electrodes coated with PUR200 MWCNT. This prototype (see Figure 33), as demonstrated experimentally (see II Periodic Report) outperforms IMAT-B-1.
The design of this new kind of heater comprises two options, respectively named “Type A” and “Type B”, one for low voltage (36V) and one for high voltage (96V).
Type A: 36V; 1500 W/m²; 20 ohm/sq (see Figure 34).
Type B: 96V; 1500 W/m²; 20 ohm/sq (see Figure 35). This heater was originally designed for 110V (see D7.1.) but proved to perform also for lower voltage.

6.3 IMAT-T
Also final transparent heaters have been produced using two different technologies. The first kind of heater, named IMAT-T-1 (see Figure 38), is based on SEFAR PEN 30-60 with silver nanoparticles and a techtosil transparent silicone skin. This kind of heater is designed to reach up to 85°C.
Thermal response obtained for IMAT-T-1 samples, using a proper PID algorithm for regulating the power source from the control console, is depicted in Figure 39 where the initial temperature of the mat is not set to the environmental temperature (around 20°C) but rather is set to 29°C, around 35°C and around 45°C respectively for the mat working at 30°, 40° and 50°C.

The second kind of transparent heater, named IMAT-T-2, has been designed and produced is based on SEFAR powerheat NT substrate with MWCNT. In Figure 40 some examples of this kind of heater are shown.

Since transparency is one of the most relevant parameters to be assessed for IMAT-T, this has been measured as explained in Deliverable D3.3. and in the II Periodic Report. Results of transparency for IMAT-T-1 and IMAT-T-2 prototypes are in Table 2.

6.4. INCLUDING ELECTRODES IN THE DESIGN

The inclusion of electrodes (performed in WP5) and sensors as well as their electrical connections has become a major task of the project, since all parts have to be extremely thin, in order to fit underneath the protective silicone top coating. And the whole heater has to be completed before the final protective top coating can be applied in a way that it also protects the edges. Any continuous production of heaters by the meter is not feasible, since edges need to be covered separately at the final end. Standard electrodes in thin heating mats are thin copper tapes (see Figure 41). They can be ordered down to thicknesses below 100 µm so that they would not give any visible mark in the coated surface. However, at low voltages and large heated surfaces the power requirements have to be taken into account so that the electrodes do not heat up too much at the high currents needed.

Although the copper tapes are extremely thin so that they can be hidden underneath the thin CNT layer, they often lead to distortions due to their stiffness and due to their different heat expansion compared to the substrate material. When the protective silicone top coating is applied and cured at temperatures up to 120°C, the heating mats expand. After cooling down to room temperature the course of the copper lines can clearly been seen in the final heater, since the copper tapes shrink differently to the substrate material. Only in combination with glass fibre meshes the distortions of the heater can be neglected, so that copper tape electrodes can only be used on glass fibre meshes.

As an alternative option for the electrodes some sewed on wires have been tested (see FFF). Since they do not run in straight lines but have been applied in curves, they are much less vulnerable to the heat.
do not run in straight lines but have been applied in curves, they are much less vulnerable to the heat expansion and shrinking process than the copper tape is. In order to reach the current rating required a large number of the tiny wires are necessary which usually are braided, so that the braided wire is highly visible underneath the coating due to its overall thickness.

Figure 42 here
Therefore, within the project, the copper tape electrodes together with glass fibre meshes have been chosen as best and feasible material combination. For further manufacturing of IMAT heaters the use of special textile with woven in electrodes is highly recommended.

One of the main tasks in designing the electrodes is the fact that the current can easily become quite high when high heating power shall be supplied by a low voltage: First trials have shown that a power of about 1500 W/m² is needed in order to reach a temperature up to about 100°C. If this power is supplied by a voltage of e.g. 15V to a heater of size 1m² then the current reaches 100A which would require very thick and compact electrodes. Hence, the electrical supply for the large heaters was chosen to be about 100V so that currents below 10 Amps for thin copper wires can be realized also in large heaters. The next task after the conductive coating with the two electrodes on both sides has been applied is the installation of electrical connections that are closely and entirely tied to the heater substrate and which are thin enough to fit underneath the silicone top coating without blistering. Therefore a thin FFC cable with a feasible Amps rating has been selected. If a continuous coating is applied on the plastics film or textile, FFC cables with electrical insulation can be glued onto the front side or the back side of the substrate and joined to the electrodes by crimping or soldering. If screen printing can be used in order to realize small uncoated areas in between it might be possible to extend the electrodes by gluing additional copper electrodes onto the film, however, care has to be taken in order to get a sufficient mechanical connection of the electrical cable to the substrate.

Two major problems arose whenever temperature sensors needed to be included within the coating process. First of all, there was no way of including temperature sensing equipment at certain places into a continuously running coating process. Installation of sensors at certain distances would always stop the process and lead to extensively increasing costs. In addition, there are now thin and cost efficient sensors on the market that can guarantee the high accuracy needed for control of the heaters (see Figure 43).

Figure 43 here
Even the tiny thin thermocouples which can give sufficient accuracy for temperature measurement cannot easily be included in the coating process. Applying them separately before the protective silicone top coating is applied is not as easy as it looks, and the thin sensing cable easily results in a small blister in the otherwise totally flat surface, so that it has been decided to use separate sensing equipment. In order to be as flat as possible thermocouple sensors have been laminated in between two films with high pressure, so that surface is totally flat and blistering can be avoided.

7. Final Design and manufacturing of IMAT Console
As described in the Deliverable D7.2. one of the main objectives of IMAT project was to design and implement a new control and power unit designed both for small and big size heaters. The main difference between small and big IMAT Consoles is the AC/DC Switching Power Supply: for the small size IMAT the output voltage is 36V capable up to 16A (around 600W electric power) big size IMAT the output voltage is 96V capable up to 30A (around 3kW electric power).

Two versions of IMAT console have been produced:

Upto DIN A4 IMAT Prototypes: IMAT LV working at 36V - 600W. In particular 7 prototypes have been
- Up to DIN A4 IMAT Prototypes: IMAT-LV working at 36V – 600W. In particular, 7 prototypes have been realized.
- Larger IMAT Prototypes: IMAT-HV working at 96V – 1500 W. In particular, 2 prototypes have been realized.
Both are based on the same electronic concept of Figure 44 and thus based on a TC unit, a Power unit and a Control unit.

7.1. TC UNIT

The final prototype of the TC unit (see Figure 45) consists of an electronic board measuring temperature with a thermocouple and able to transmit data via bluetooth toward the IMAT Main Board. The board is powered by a portable Rechargeable Lithium-Polimery Battery 3.7V – 980mAh with a 20 day full-time working.

IMAT TC Board electric schematic is shown in Figure 46. This board use power from a 3.7V rechargeable 980mAh Lithium-Polimery battery that is regulated to about 3.3V by low power, low drop-out linear voltage regulator (IC8) and connected to the bluetooth control chip (IC1). The BLE112A Bluetooth chip is a SOC (System On Chip) device produced by Bluegiga Technologies Inc. that embeds a CC2540 integrated circuit provided by Texas Instruments based on 8051 microcontroller architecture. CC2540 has 128 or 256kb of flash memory, 8kb of SRAM (Static Random Access Memory) and a lots of peripherals like 12-bit ADC (Analog to Digital Converter), Timers, integrated operational amplifier and comparator, full-speed USB interface, serial interface, internal battery monitor and temperature sensor.

7.2. POWER UNIT

Power unit consists of two main components: a power supply and a mainboard appositely devised by UNIFI. Depending on the IMAT console power needed to heat the mats, two different power supplyes have been chosen (see Figure 47):
- For IMAT-LV (36V – 600W) a MeanWell HRP-600 series switching voltage power supplier is used. The electric specifications for the HRP-600-36 power supply are listed in Table 3.
- For IMAT-HV (96V – 1500W) two 48V power supplies are used. These devices assure galvanic insulation of the output voltage, increasing users safety. The electric specifications for the Meanwell RSP-1500 series are listed in Table 4.

The mainboard (Figure 48) is composed by:
1. TC signal receiver BLE112A Bluegiga Module
2. 8-bit Atmel ATxmega64A4BU uc – microcontroller
3. Integrated buck DC/DC controller
4. PWM Power Control: up to 4 Power MOS transistors
5. Acoustic alarm

Figure 48 here
The Main Board Core is the ATxmega16A4U Atmel Microcontroller with 16kB of flash memory, 2kB of SRAM and a 12MHz CPU master clock. The used power switches are 2 IPP110N20N3 MOS Transistors with 200V max drain-source voltage, 88A max drain current and 10.7 mohm on-resistance. Transistors are connected in parallel up to a maximum of 4 (TC1, TC2, TC3, TC4) to obtain a very low on-resistance and are driven by a FAN3214 high speed low side gate driver (IC7) to have small switch-on and switch-off time (see Figure 49).

Figure 49 here

7.3. CONTROL UNIT
The control unit is based on a Xflar core integrated with a resistive touch screen, USB and ethernet peripherals. The control unit is connected to the main board with USB cable, and retrieves information on the IMAT TC board (see Figure 50).

Figure 50 here
Accordingly, the MOS circuits design has been carefully designed to minimize the power loss dissipated on transistors with heatsinks. A high capacity (8 mC) capacitors bank is added to stabilize the DC voltage on the IMAT, to supply to the instantaneous electric current during PWM power regulation and to lower spikes voltage on the IMAT Heater.

In order to connect together each IMAT units, 1 software and 3 firmwares have been developed. Firmware was developed using Bluegiga SDK 1.1.1 (Bluetooth) or Atmel AVR Studio 5 (ATxmega uC). Software was developed using C++ language and QT 4.8.1 Library Framework.

A Graphical User Interface (GUI) has been also implemented (see Figure 51) to allow conservators to:
- Set a constant temperature to be reached for the desired conservation treatment;
- Set an heating ramp for the conservation treatment (desired temperature – desired time);
- Register the treatment to the internal memory (to be read using a PC).

Figure 51 here
The electric-schematic of the other components of the final console are shown in Figure 52, Figure 53 and Figure 54.

Figure 52 here

Figure 53 here

Figure 54 here
A 3D CAD-based procedure for designing the boxes for the console has been also devised. As shown in Figure 55, Figure 56 and Figure 57, all boxes have been designed and blueprints have been used to...
Figure 55, Figure 56 and Figure 57, all boxes have been designed and blueprints have been used to actually produce the console boxes.

Figure 55 here

Figure 56 here

Figure 57 here

8. IMAT System
In Figure 2 the rendering of the designed IMAT system is depicted. In Figure 3 the actual prototype is shown. The comparison between the two images shows that the “dreamed” system is actually the one achieved.

Of course also the final prototypes undergo to laboratory testing prior to use them in actual conservation procedures.

Tests conducted on the final prototypes are described in the II Periodic Report and here only briefly recalled. For what concerns the thermal analysis, the experimental layout proposed is the one in Figure 58.

To assess the properties of the heaters a thermal camera has been used. The camera has been calibrated according to the procedure stated in the D5.2. The console PID has been set as follows: P=90, I=1, D=200.

All kind of IMAT heaters were tested and in particular: IMAT-S, IMAT-B-2 and IMAT-T-1 (a complete description of tests carried out is provided in Deliverable “D7.2. Final IMAT prototypes”).

In detail:
- IMAT-S DIN A4 powered by 36V console, able to reach maximum temperature of 70°C.
- IMAT-B-2 22x32 powered by 36V console, able to reach maximum temperature of 55°C.
- IMAT-T-1 DIN A4 powered by 36V console, able to reach maximum temperature of 55°C.

The test has been conducted according to the procedure stated in Deliverable “D5.2. Lab testing results revealing functional and operational qualities of the IMAT prototypes” referring to a wooden surface; to recall such a procedure, the test envisages:
- heating obtained by setting three different temperature steps on the console, in particular 30°C, 40°C and 50°C to be reached in 200 s and to be maintained for other 200 s.
- heating obtained by setting a constant temperature on the console, e.g. 60°C. The mats were required to reach the desired temperature in 240 s and to maintain it for other 1800 s.

Figure 58 here

- long-term run: the device is heated for 24 hours at two constant temperatures targeted at, respectively, 47.5°C and 55°C. The structural properties of the mats are then assessed to understand if there are significant structural variations or damages. This test was performed according to the suggestions made by expert Prof. Robbiola in the Review Report.

In addition to the above mentioned test procedure, two further tests have been carried out: breathability test (for IMAT-B-2) and transparency test (for IMAT-T-1).

9. Manufacturing
Once the final design of IMAT prototypes has been defined and prototypes are manufactured and properly tested in lab, the IMAT consortium focused on the manufacturing processes aimed at achieving the industrial process for scaled production. In particular, a feasibility study of the production cycle for the
Industrial process for scaled production. In particular, a feasibility study of the production cycle for the heater, for the control unit and for the final assembly has been carried out. Results of this analysis are provided in Deliverable D8.1. and here shortly recalled.

Referring to the three kinds of heaters, the planned manufacturing process is the one proposed in Figure 61. Depending on the kind of heater, different processes are detected and the possibility of industrializing part of the production processes is explored. Mainly, all the production process has to be carried out by specialized companies such as SEFAR and FC.

9.1. Manufacturing of IMAT-S
The substrate for final IMAT-S consists of a multifilament fiberglass textile that can be industrially produced by SEFAR even for small quantities. Actually, the substrate selected for IMAT-S is easily produced by SEFAR simply changing the parameters for obtaining precision woven open mesh fabrics (see Figure 59). In particular, SEFAR will prepare, with its common processes, a highly specialized monofilament fabric, characterized by precisely defined and controlled, consistent and repeatable material properties such as pore size, thickness, tensile strength, dimensional stability and cleanliness.

Once the substrate is produced, it has to be coated with CNTs. The best option to coat the substrate is the CNTs spray coating. Such a process gives an almost even thickness of the heating layer and hence, an almost even heat distribution depending on the expert or the equipment that carries out the application. Once the substrates are coated the following step is to attach the electrodes. These can be sewed on wires, copper tape soldered on the heater borders or even woven in wires. In case high number of IMAT should be produced, electrodes can be attached in continuous using “endless” CNT or “intermittent” CNT (see Figure 60).

Once the electrode are attached, the following step is to attach the FFC cables. They can be connected directly to the electrodes close to the heating layer thus the soldering joints are covered by the silicone protective coating.

9.2. Manufacturing of IMAT-B
Both the fine polyester mesh and the medium coarse fibre mesh used as a substrate for the two kinds of breathable heater can be produced at an industrial scale by SEFAR or other textile companies. In case SEFAR is called to produce the fine polyester mesh, PET1500 can be used as final solution for IMAT-B pre-series.
Referring to the CNTs coating process, IMAT-B can be cured using dip-coating, performed by Future Carbon. Multiple coating cycles using highly diluted CarbolImpreg dispersions with air blasting in between yields are the best option for final manufacturing.

Also for breathable heaters electrodes are attached to the mesh using one of the three technologies described for IMAT-S: copper electrodes, sewed-on electrodes and woven in electrodes. All these solutions have been tested during the project. Also for this kind of heater the best option in terms of cost-benefits is the one with copper electrodes attached to the heater. The protective coating can be made both on silicone and polyurethane. silicone shall not plug the pores during application of the coating. Since only a specialized company in the US was able to do the coating by a spray coating process and using a special low viscous silicone protective coating, this solution is not advised for the post-project IMAT series (while for prototypes this solution was actually tested as demonstrated in D7.2. Final IMAT prototypes”).

9.3. Manufacturing of IMAT-T

With regard to transparent and translucent heaters many possibilities have been evaluated during the project and the most comprehensive designs and options have been forwarded to production.

A first possibility is to realize IMAT-T using as a substrate a fine monofilament polyester mesh with sewed on electrodes and a silicone protective coating. In this case the manufacture of the heater is similar to the one described for IMAT-S with the following differences:
- The coating is applicable with a lab process with doctor knife (as a consequence the maximum size of the heater is the DIN A4)
- The CNTs to be applied (by Future Carbon) are based on a SWCNTs dispersion on a highly transparent PET film (and so is not a textile like in the case of IMAT-S)
- The protective silicone top coating is made of a thermoplastic silicone film

Another possibility is to manufacture IMAT-T heaters based on the extremely fine PEN textile with silver deposition. These textiles, created in a prototypal form, present extremely high conductivity (close to the conductivity of pure metals). They could only be used for heating purpose when low voltages and narrow distances of the electrodes were used. Equipped with a thin protective coating made up of a thermoplastic Tectosil silicone film from Wacker they heat up very fast and can be used on small surfaces in conservation. According to the studies performed by the IMAT partners, the best option for manufacturing IMAT-T is to use the powerful translucent IMAT heater based on the power heat fabrics of SEFAR. The textile consists of fine monofilament polyester yarns with woven in main electrodes as well as woven in heating electrodes. Based on a unique weaving process of SEFAR appositely devised for the IMAT project the two main electrodes are located on only one side of the fabric isolated from each other and connected to the comb like electrodes in alternating manner, so that the whole textile heats up. Equipped with a protective silicone top coating made up of a thin thermoplastic film they can be manufactured in any required size. Electrodes used for transparent heater are quite different with respect to the one used for IMAT-S and IMAT-B. The best solution in prototyping was to use TiN coated electrodes. Since they are commercial equipment, their use is advised also for industrial production

9.4. Manufacturing of Control console

For what concerns the Control Console, its final production is a combination of industrial processes (including the creation of specific electronic boards), software/firmware implementation and laboratory-based assemblies to be performed by specialized companies working in the field of electronics. Boxes enclosing the electronic boards are realized in PVC using LASER cut machines and milling. In the future...
choosing the electronic boards are realized in PVC using LASER-cut machines and milling. In the future such boxes will be produced using industrial processes such as, for instance, injection moulding. Components like FFC cables, thermocouples, USB cables, Bluetooth modules, round cables, connection leads etc. are available in the market with a low cost. Scale economy is expected for such components in case high number of devices is to be produced.

10. Field testing
IMAT prototypes have been extensively applied to a series of case studies by the Conservators partners of the IMAT consortium. Described in the Deliverable “D6.1. Field Testing Results” and in the II Periodic Report, the results obtained by conservators are here briefly recalled.

10.1. Testing procedure
In order to test IMAT prototypes on the field, it was asked to conservators to use it on the basis of their know-how and experience in the Cultural Heritage field, without providing them a particular procedure. This allowed Conservators to maintain their own modus operandi and thus, the use of IMAT was an added value to their instrumentation. In this way, the objective of the field testing was twofold: on one side, IMAT partners were able to test the IMAT prototypes on real cases by determining their performance; on the other side the field testing was not an additional work for conservators on their everyday life since they tested IMAT on their real conservation works, where heating is a common procedure. Obviously, conservators were provided with operational instructions for the safe use of the device.

10.2. Tensioning, flatness recovery and colour fixing of paintings
The aim of the approach described was to demonstrate how the IMAT can be used to resolve a variety of problems that can be encountered during the restoration of paintings. In the following examples this is done by applying heat over an extended period of time at a constant, low temperature. The IMAT not only allows us to reduce unnecessary thermal stress due to the precision with which we can control temperature and time, but it is also cost efficient and highly versatile in that it is portable, i.e. it can be taken to the painting. In other words, the possibility of using highly accurate temperature control allows for the precise treatment of various deformations using the minimum temperature required—ensuring that the painting suffers minimal thermal stress. In these terms IMAT can be used to address deformations on the canvas or to consolidate paint and ground layers (see Figure 63).

Figure 63 - here
As a first example the 19th century painting, oil on canvas, depicted in Figure 64 is considered. The painting is characterized by planar distortion caused by irregular drying of paint and deformation of canvas due to mishandling. The paint has been applied with varying thickness, meaning that it dried at different speeds and therefore causing the canvas to contract. This problem was resolved by placing the IMAT-S (Standard) on top of a foam board, which provided a stable surface and the canvas directly on top of the IMAT with the paint facing upwards.

Figure 64 - here

IMAT was also successfully applied in Italy to the cases of 1) a painting representing Saint Jerome (oil on canvas, 88X67cm, unknown author, Italy, XVIII century, private collection, Florence, Italy) and 2) a copy of...
Moreover, within the so called “Spanish Panel project” the structural treatment of a 15th-century Spanish panel painting from Suermondt-Ludwig-Museum Aachen, depicting St John the Evangelist Drinking from the Poisoned Chalice, was performed by SRAL (see Figure 66).

Nina Olsson, Conservator working in Portland (Oregon) carried out the conservation of a juvenile painting of the famous photorealist painter Chuck Close (USA n. 1940, see Figure 67).

Conservator Rūta Kasiulytė from LDM restored painting “Women with naked shoulder”. The painting was hanging loose on the stretcher because of the losses on canvas edges. On the back side of painting holes were repaired with patches which made canvas distorted. The paint layer was fin, damaged, repaired holes were overpainted. In FFF the use of IMAT in combination with goretex® membrane is shown.

10.3. Application of IMAT on sculptures
IMAT was successfully applied on a sculpture by an unknown Lithuanian master from 18th century. The sculpture was carved from a single piece of wood, only hands were carved from another piece. It was polychromed and gilded. The priming and paint layers were loose from the support. The priming layer was thick and hard, so it was impossible to inject new glue. Conservator Rolandas Vičys decided to apply heating in order to improve penetration and to use IMAT (see Figure 69).

10.4. Application of IMAT in combination with enzymes
The first example of application of the IMAT system with enzymes was performed by LDM related to the conservation of the portrait of Cornelius Janssenius (see Figure 70), an engraving printed on laid paper. There were some small edge tears, small holes. Paper was slightly discoloured, dusty, with light brown adhesive stains on the right edge of sheet. The use of enzymes with constant temperature allowed a correct conservation of the artwork.

Another example is the restoration of the lithography “Portrait of Bielinsky”; the paper was discoloured, dusty, spotted with various spots. All left edge was covered with brown colour old adhesive. According to research results, it was protein glue mixture with starch. Also in this case IMAT combined with enzymes
research results, it was a protein glue mixture with starch. Also in this case IMAT combined with enzymes allowed a correct conservation (see Figure 71).

Figure 71 - here

10.5. Application of IMAT for heat shock treatments
The control of lichen growth, particularly important in the field of stone conservation of outdoor monuments, largely depends on the use of biocides, which may be dangerous for the users and the environment. Lichens are thermo-tolerant (up to 65–70 °C) when dry, but thermo-sensitive when wet. Accordingly, the use of IMAT for treating lichens has been explored.

10.6. Application of IMAT for resolving deformations in wax-resin lined paintings
Wax-resin lined paintings have often problems due to different deformations that can be removed by applying precise and even heat. In detail low temperatures (45-50°C) for long time are required for the treatment. Higher temperatures will melt the beeswax, lower temperatures are ineffective for the treatment. As a consequence, the use of IMAT for this kind of consolidation problems is highly advised. Three kinds of deformation have been treated: dent, distortion/fold and moating (i.e. deformation due to bad lining with impasto) as shown in Figure 72.

Figure 72 - here

In Figure 73 some examples of application of IMAT on this particular conservation problem are depicted.

Figure 73 - here

11. Synthetic list of results
The main results of the project are summarized as follows, referring to the deliverables of the project planned for producing S&T results:

WP2
D2.1. Functional Parameters and SWOT Analysis results.

WP3
D3.1. Highly elastic and highly conductive nanomaterial coating.
D3.2. Highly conductive nanomaterial impregnation for textiles.
D3.3. Highly conductive transparent nanomaterial coating for the transparent IMAT heater.
Two Milestones have been verified:
M 3 Impregnation Material Prototypes performance. Impregnation nanomaterial that gives a temperature up to 80°C on a breathable IMAT heater with power supply below 48 V.
M 4 Transparent coating material performance. Can be used in a small scale transparent IMAT heater for temperatures up to 80°C.

WP4
D4.1. Prototypes for the continuous coating/impregnation process for field tests. [Delivery date: month 24, actual submission date: month 28]
D4.2. Prototypes of electrodes and thermo-sensors included into the IMAT. [Delivery date: month 25 actual submission date: month 26]
D4.3. Prototypes of non-rectangular IMAT [Delivery date: month 30; actual submission date: month 30]
Moreover, three milestones were satisfied for this WP:
M 5 Production of a heatable film with electrodes included for field tests.
M 6 Production of a breathable porous membrane for the IMAT heater.
M 7 Production of a transparent heatable IMAT membrane.

WP5
D5.1. Prototypes for the IMAT heater.
D5.2. Lab testing results revealing functional and operational qualities of the IMAT prototypes.
A Milestone, M 8. Prototypes: Realization and testing, has been reached in this WP.

WP6
D6.1. Field testing results (treatment reports, images, notes, etc.) documenting the performance of IMAT in actual conservation treatments.

WP7
D7.1. Final IMAT design and possible variations.
D7.2 Final IMAT prototypes.
D7.3 Patenting and legal protection of inventions.

WP8
D8.1. Feasibility study of the production cycle for the heater, for the control unit and for the final assembly.
D8.2 Set-up of the distribution network to the final user.

Potential Impact:
Current conservation practices are moving towards ever more minimal and less invasive treatments and from the “big picture” perspective, the future of heating instrumentation in art conservation is clearly with highly mobile, versatile, accurate and cost effective “smart” devices. While a need for such “smart” device is apparent, little to no research has been done in this direction. The IMAT project bring together the expertise of art conservators, thermoelectric engineers and researchers working with nanotechnologies to develop a new innovative universal mobile thermoelectrically device - IMAT, which fills this core gap in treatment instrumentation and will be targeting very large audience in the field. The new device has particularly broad application in conservation of artworks and of heritage object in general, providing conservators with essential treatment instrument for their everyday work.

After prototyping, IMAT can be produced in variety of configurations and sizes and fully integrated with all conservation treatments, where accurate thermal application is required and could replace completely the metal heating tables, as well as numerous adopted and often for conservation standards highly inaccurate thermal devices, such as handheld irons, home-made heating tables, heating plates, etc. Perhaps it will be most useful with paintings, both traditional and modern, and other 2D object, such as works on paper, textiles and other. While IMAT could be used in variety of applications in combination with low pressure or vacuum devices, perhaps it could be particularly useful when working on large scale artworks, in situ, or where the power source is limited.
In this project the IMAT system has been designed with the aim of advancing most recent thermoelectrical superconductive nanomaterials (MWCNTs, SWCNTs, AgNWs, etc.) so as to provide improved...
electrical superconductive nanomaterials, (MWCNTs, SWCNTs, AgNWs, etc.) so as to provide improved temperature control in terms of even heat distribution with minimal temperature fluctuations. The device is easily transportable, storable and quite economically accessible. This versatility will make it a useful for the museum laboratory and for conservators in private practice and will target a very broad audience in the field, essentially all conservators using thermal treatments in one or another form. IMAT has been designed and developed through extraordinary and close collaboration between art conservators, nano-scientists and thermos-electrical engineers. It undergo prototyping and rigorous lab and field testing, which allowed carrying out improvements and collecting the analytical and empirical data. The project involved close cooperation with SME among conservation suppliers, envisioning and implementing the future manufacturing and the distribution of the device. The far-reaching objectives and implications of the IMAT project epitomized a European approach, and exemplify many of the broad goals of the European Commission and the 7th framework program, by bringing together cutting edge expertise available in different EU countries to produce new knowledge and technology that will advance higher standards for art conservation and benefit the preservation of cultural objects in the EU and globally.

In summary:

1. The proposal addressed the development of novel advanced compatible technique and novel instrumentation for the application for the protection, conservation and restoration of cultural heritage assets.
2. The IMAT system, comprising heaters and control console open new opportunities in treatment methodology, can be easily integrated into broad range of existing traditional and experimental methods and techniques, used in conservation, enhancing considerable their effectiveness and reducing the associated risks.
4. By introducing an advanced essential tool, which is accessible and cost effective, the project will have huge socioeconomic benefits for conservation professionals, and to the conservation of cultural heritage generally neglected due to the costs of conservation.
5. By offering enhanced versatility, efficiency and accuracy, the device reduces the risks / and or inappropriate interventions and secures the conservation of the original objects and/or improve the physical state of damaged objects.
6. Considerably reduced power needs of the new device will have positive environmental effect, and will also contribute to the accessibility of conservators in protected historic buildings or remote locations to cutting edge technology.
7. The project included training activities, such as workshops and a website disseminating the information.
8. The proposed instrumentations does not have analogous devices and will be of a great demand in the art conservation market as in the EU as worldwide. Particularly the mobility and versatility of the IMAT would make it of a great benefit implementing conservation practices in the developing and partnering countries, as well as or in various field/in situ or emergency response projects, where heating tables are not accessible or cannot be used.

1. Main Field testing activities using IMAT system, demonstrating the potential of the newly conceived device.

The new device has a particularly broad application in the conservation of artworks and of heritage objects in general, providing conservators with essential treatment instrument for their everyday work. The device could replace entirely the metal heating tables often found in laboratories, as well as the numerous other thermal devices such as handheld irons, home-made heating tables, heating plates, etc., that are often
thermal devices such as handheld irons, home-made heating tables, heating plates, etc., that are often adopted, but highly inaccurate for conservation standards.

The IMAT can be used also in any of a variety of applications in combination with low pressure or vacuum devices.

In paintings conservation the new mild heating device (IMAT) may be used in treating diverse deformations and planar distortions, to reduce cupping and distortions to paint film, tear mending, consolidation of paint layers, reinforcement of degraded supports in diverse lining and backing treatments. Air permeability combined with highly accurate and stable mild heating at low temperatures will offer new opportunities for minimal intervention in treating planar distortions, improvement of the condition of earlier treatments, and more. The material of choice needs to exhibit low adherence (a non-tack surface) and high resistance to physical and chemical factors associated with various conservation treatments. The IMAT heater’s thin profile, flexible nature and availability in a wide size range are well suited for use in treating works on the stretcher. It may be used with all currently used conservation adhesives and may be incorporated into either traditional or recent methodologies where controlled mild heating is required. Optical properties, such as transparency, are highly desirable for visual control during treatment, especially when the heat source is applied to the recto. IMAT can find its application also in aesthetic treatments, such cleaning of painted surfaces with enzymes, which require very precise and specific temperatures of application, and which must stay constant during the treatment. The IMAT is particularly useful for in situ work, and in emergency response actions.

In paper conservation the IMAT is to be used in treating planar distortions and in consolidation treatments, where mild heating is required. The combination of highly accurate temperature control and permeability to gases, such as airflow and water vapours, as well as transparency would be a strong asset in many humidification treatments. As in paintings conservation, the new heating device will find its application in enzymatic cleaning treatments, which are frequent in paper conservation. Yet another application could be thermal disinfection treatments.

In textile conservation the IMAT could be applied in methods similar to those implemented in painting or paper treatments, used for consolidation, smoothing planar distortions, using enzymatic methods of cleaning and more. An added advantage of the device would be the option of placing the heat source simultaneously on both sides or on either side, as well as performing the work in sections on large pieces. Yet another application could be thermal disinfection treatments.

In 3-D objects and other applications IMAT heaters of diverse configuration and shape could be applied in consolidation treatments. These could be quite useful for polychrome sculptures, frames, furniture, mixed media objects and more. In other applications the availability of this new mild heating technology and the programmed field testing will allow conservators to find additional applications and ways of incorporating its use into both current treatments, and new methodologies that have yet to be developed. For example, developing and advancing other conservation tools where mild heating is required, such as heated syringes, heated spatulas, soft heated tips and more. One of such devices could be soft heated “glove” or “fingertip”, which like a glove could be placed on the finger at mild temperatures (below 45º C) used to re-attach or consolidate delaminated paint, for example.

According to the statements above, IMAT prototypes have been successfully used by a number of Conservators for performing actual treatments. In particular:

1) Tensioning and flatness recovery of a painting representing Saint Jerome, oil on canvas, 88X67cm, unknown author, Italy, XVIII century, private collection, Florence.
2) Colour fixing and partial flatness recovery of a copy of Maria Luisa infante di Spagna portrait by Lorenzo
2) Colour fixing and partial flatness recovery of a copy of Maria Luisa Infante di Spagna portrait by Lorenzo Tiepolo, XVIII century, oil on canvas, 70x60 cm, Galleria Palatina di Palazzo Pitti, Florence

3) Spanish panel Project. This activity has been focused on the structural treatment of a 15th-century Spanish panel painting from Suermondt-Ludwig-Museum Aachen, depicting St John the Evangelist Drinking from the Poisoned Chalice.

4) Application of IMAT on Untitled, Chuck Close, mixed media on cotton, private collection (Portland, Oregon, USA).

5) Application of IMAT on a Lithuanian Sculpture (unknown, 18th Century)

6) Application of IMAT on a painting depicting a woman with naked shoulder (unknown, 18th Century)

7) Application of IMAT for the conservation of ancient paper, using enzymes.

8) Application of IMAT for shock treatments

9) Development of a new approach to structural treatment

10) Resolving deformations in wax-resin lined paintings using IMAT

2. Main Dissemination Activities

In accordance with suggestions found in the EU “Guide to Successful Communications”, the dissemination of the Project Results have been accomplished in a number of directions: publications, lecturing, workshops, website, media communications, RTD Magazine, audio-visual ‘publications’. The findings of IMAT project, including historical background, earlier works, analytical and technical data, lab and field testing results, operational recommendation and instructions, and selected case studies are published in one volume, edited by Nardini. While the publication is essential for the dissemination of the new methodology, direct contact and instruction from inventors and researchers of IMAT project has been no less important. The workshops made in collaboration with CTS, SRAL and Palazzo Spinelli, are a combination of theoretical and practical studies and were addressed to both the technical and functional characteristics of the new device; instruction on how the device operates, its advantages and potentials, and how it could be integrated in various conservation treatments.

In the near future, since a further exploitation of IMAT system is planned, workshops could be offered regularly, in collaboration with participating educational institutions, as well as by SME offering higher education in conservation of cultural heritage, and may also be given at traveling venues and available upon request by conservation or education institutions, both in EU and internationally. The new method has been presented in expert meetings and in conferences, presenting the interim results, as well as at the end of the project. In other words, it is an end goal to make the methodology of Conservation using IMAT widely accessible.

According to the “clauses relevant to communication”, it will be specified that the Project has received Community research funding and all the documents will display the European emblem.

The main dissemination activities for the IMAT project are listed below.

Dissemination Action 1) Dissemination and Exploitation Plan

Agreed by all partners, this document, planned the dissemination of the above listed products in the most effective way, according to the events planned in the renewable and environmental sectors during the second and third years of the IMAT project (i.e. dates could be revised in view of maximizing the benefits of the dissemination action).

Dissemination Action 2) Project website into the .eu domain.

A publicly assessable project website has been established with related protocol for updating information on activities, techniques, and results of the project. It includes calendar of events, press release system, and contact point. A secure web service (password protected) has been established for internal project.
and contact-point. A secure web service (password protected) has been established for internal project
communication. The registered domain is www.imatproject.eu.
Dissemination Action 3) Book of extended abstracts
A Book of extended abstract has been released after the II Progress Meeting in order to present some of
the results of the project.
Dissemination Action 4) Final Book
A final Workshop or Conference has been realized thanks to the contribute of the partner Nardini.
Dissemination Action 5) Dissemination report
In this report the IMAT Consortium presented the actions taken to disseminate the work performed during
the Project. The Report summarizes the activities carried out in order to promote the technical and
scientific Project results and ensure the widest possible use of knowledge derived from the Project.
Dissemination Action 6) Video
A Video explaining the results of the project and presenting the new IMAT device has been produced.
Dissemination Action 7) Operational recommendation and instructions
An instruction manual explaining the modality of using the IMAT has been realized.
Dissemination Action 8) Publications in International Journals
A number of papers were published in International Journals and mainly contained in the Scopus®
database (Elsevier B.V.). The list of papers is provided in Section A of Paragraph 4.2. of the present Final
Report.
Dissemination Action 9) Workshops
In order to distribute the IMAT prototypes to final users, a series of meetings have been planned by CTS
and SRAL as listed below:
Date Place
16/10/2014 Vicenza (Italy)
20/10/2014 Maastricht (The Netherlands)
22/10/2014 Milano (Italy)
30/10/2014 Roma (Italy)
31/10/2014 Napoli (Italy)
These meetings are specifically addressed to provide a small number of conservators, agents and
operators some final IMAT prototypes and to illustrate the potential impact on the market of such an
innovative product. In particular, beside the spread of technical innovation related to IMAT project, the
meeting is focused on the market potential and on the possible future development in design.
Dissemination Action 10) Press Releases
- Press Release for the Salone dell’Arte e del Restauro – Firenze 2012
From 8 to 10 November 2012 Florence hosted its third International Art and Restoration Fair at the
Fortezza da Basso Exhibition Centre. A press release was created for this event.
- Press Release for Creactivity 2012
IMAT project was invited at the Crea©tivity 2012. This event, organized at the Museo Piaggio (Pontedera,
Pias, Italy), was aimed to disseminate Tuscany Region projects activities. For this fair the press release
depicted in Figure 2 was created.
- Press Release at the “Notiziario dell’Università di Firenze”
The IMAT project is managed by University of Florence (Italy). With the aim of highlighting this aspect, the
University published a contribute on its own Bulletin (Notiziario dell’Università di Firenze).
- Press Release at the ECOWEB website
ECOWEB provides information on European eco-innovations, including technologies, applications,
ECOWEB provides information on European eco-innovations, including technologies, applications, products, processes and other solutions. It aims to link enterprises, in particular SMEs, and eco-innovations to increase the uptake of EU-funded research.

- Press Release at “The Parliament Magazine”

According to their mission, reflecting on the dynamic and changing world of European research, The Parliament Magazine’s Research Review brings the bigger picture on Europe’s research and innovation developments.

- Press Release for the Salone dell’Arte e del Restauro – Firenze 2014

From 13 to 15 November 2014 Florence hosted its third International Art and Restoration Fair at the Fortezza da Basso Exhibition Centre. A press release was created for this event.

Dissemination Action 11) Environmental policy-related report (policy brief)

IMAT is a CNTs-based device thus implying a certain degree of risk related to the use of such a class of material. In production, risks are strongly reduced since the realization of CNTs substrates is performed by operators usually working with potentially hazardous materials, according to a specific set of regulations such as REACH. Regarding the prototypes, IMAT is a safe device to be used by Conservators according to a set of operational instructions. Even in case the device is not used properly, the related risks are quite negligible since CNTs are not easily spread in the environment. Some risks are related to high voltage, even if a galvanic isolation was used to design the control console, but the risk is comparable to the one related to the use of a common electrical appliance. Further analysis will be performed in post-project phase prior to put the IMAT device in the Market.

Dissemination Action 12) Technical Courses

Since 2001, the IMAT partner Palazzo Spinelli organises several Master Courses of High Professionalization in the field of Conservation and Promotion of Cultural Heritage, and Organization of Events and Design. These Masters are structured to enable participants to acquire practical, operational and design skills, and use these skills to become the cutting edge of their profession. The lessons are taught by industry professionals who, through their work experience, give the opportunity to students to have a more practical approach to the problems and paths of development in the various sectors are. All Masters develop over a period of 10 months and 60 CFU release, structured over 1500 hours, split between lectures, design workshops, internships in business as well as seminars, conferences and events. Among such Master Courses, the “Master in Art Conservation and Restoration” will include a workshop where the use of IMAT prototypes is encouraged with the aim of creating a novel set of innovative procedures where heating is the main core of conservation.

3) Main Exploitation Activities

A list of exploitable foreground is depicted in Section B of the Paragraph 4.2. Use and dissemination of foreground. The main outcome of IMAT project consists of a system dedicated to conservation of artworks using heat; such a product is a “close to the market” outcome. Since the final IMAT prototypes are innovative with respect to the current state-of-the-art devices, Consortium is planning future distribution on the market, once the design and product process is finalized. IMAT is created using knowledge and equipment provided by a number of technical partners including a University, that devised electronic components and two important SMEs located in Germany and Switzerland that were responsible for designing the CNT-based mats. Accordingly, IMAT is a multidisciplinary project involving different entities. This may be a problem for exploiting IMAT in the market, as also explained in the Business Plan and in the
This may be a problem for exploiting IMAT in the market, as also explained in the Business Plan and in the Consortium Agreement, since the nature of the final product encompasses different technologies. For this reason exploitation of the IMAT project will be further carried out in the near future by accessing National or European fundings. The main idea is to establish a separate legal entity, which will inherit the IMAT project and will become responsible for future realization of IMAT design guaranteeing further distribution and technical support. This legal entity, probably located in Lithuania, will also manage IPR issues related to product and processes. Another idea is to establish a University Spin-off involving in its staff some researchers that have worked for IMAT project. This particular kind of society, that could be established in Firenze (Italy) could be devoted on designing a market ready IMAT product by establishing a commercial contact with FC and SEFAR for CNT-based products. In this idea, CTS could work as a commercial entity devoted to put the IMAT product on the market. Of course this solution will entail a commercial agreement between technical and commercial entities coordinated by the Spin-off. In fact, a legal entity or a Spin-off are required to manage the IMAT product also for technical reasons related to support. It is evident that once the IMAT system is introduced in the market, a strong technical assistance will be required especially in the first period. Moreover, it is expected that firstly the new product will be given to conservators using particular formulas such as, for instance, rent-to-buy; in these cases, a society responsible for following the further testing provided by renters is advisable.

To the present section are attached the presentations, in pdf format, of all IMAT partners during the final Event in Firenze, Italy.

List of Websites:
Website: www.imatproject.eu
Contact Details:
Prof. Monica Carfagni, Via di Santa Marta 3, 50139 Firenze (Italy) - Coordinator. mail: monica.carfagni@unifi.it
Prof. Rocco Furferi, Via di Santa Marta 3, 50139 Firenze (Italy) - Project Manager. mail: rocco.furferi@unifi.it
Dr. Tomas markevicius, co-leader of IMAT Project, tmarkevicius@imatproject.eu
Dr. Nina Olsson, co-leader of IMAT Project, ninaolsson@imatproject.eu

Related documents

Last update: 29 September 2015
Record number: 172063