Mauro Marabelli, Cecilia Bartuli , B. Colombo

The Conservation of Marcus Aurelius' Monument

Technical Studies

Summary

The equestrian bronze monument of Marcus Aurelius in Rome has been further investigated, after restoration, mainly to foresee possible damages caused by outdoor exposure. At the same time a copy of it has been cast by following a new original method to obtain the intermediate model.

New non-destructive tests have been carried out to execute the above researches and in the end old and new methodologies can be considered as a complex experimental tool to study and control outdoor bronze monuments.

Introduction

In these years, Marcus Aurelius' equestrian monument has been an important research pole for the institutes in charge of its protection and restoration as well as for the university scientific departments working in the cultural assets field. It has prompted connotative studies and new experiments with regard to deterioration processes and consequent conservation problems. For this purpose a new system to make the model for the copy of the monument has been developed and put in use, and furthermore non-destructive processes (by devising ad hoc prototypes too) have been applied to determine the chemical-physical state of the monument and to check the results of the conservation process and of the conservation project.

The efforts of all people involved have contributed both to the restoration as carried out by the Istituto Centrale del Restauro (ICR) and to the final conclusions as established which have led the Rome City Council to store the monument inside a museum site and to exhibit a copy of it in Capitol Square.

From 1981 to 1988 the equestrian statue underwent a long series of tests and analyses prior to the necessary definite restoration by ICR, Rome. The results of those initial researches and of the subsequent restoration carried out have already been made known through several publications (the most important of which are mentioned in bibliography under Nos. 1-3 and 5-7). The said researches, some of which really innovative, are fully listed in Table 1.

As to the restoration, its actions aimed at gently wiping off the effect of corrosion and the deposits hiding the residual gold leaf, removing the soluble salts, reversibly fixing the surface patina and the gold leaf showing scarce cohesion and adhesion (mostly on the horse's flanks and belly). In order to reduce invasivity as much as possible, the reversible consolidating fixative (Paraloid B72) was applied in very diluted solution (3% in trichloroethane, see Lit. 1 and 7), thus avoiding to form a continuous protective film.

Once the restoration of the monument was completed, a commission was entrusted to look into the problems related to the conservation of the monument. In other words the question was: could the equestrian group be safely placed again outdoors or did it have to be stored as safely as possible indoors? Before answering the question it was decided:

1. to verify area by area the reactivity of the corroded surface with regard to both the chemical corrosion of the patina and the electrochemical corrosion of the alloy and to assess the degree of adhesion of the residual gold;
2. to establish the degree of environmental danger of Capitol Square in Rome;
3. to test surface-protective products at present available by applying a "double layer" system according to a practice already experienced by ICR in the past (4);
4. to make a scientifically correct copy of the original in order to record the original shape and to permit at the same time, if necessary, the storage of the original in a museum site after its restoration;
5. to devise and make a system of reversible links of the equestrian group (either the original one or its copy) to the base.

Since all the above actions implied studies and technological applications of very different sources, all the various institutes and companies which contributed to this complex undertaking will be mentioned at the end of this report.

Control of the Deterioration – The Surface

Two points have clearly resulted from the first investigations, i. e.:

a) the patina as examined on various areas happened to be more frequently constituted by two compounds usually traced on bronze works sited in outdoor environments polluted by sulphur dioxide: brochantite and anglesite.
b) Antlerite, chalcanthite and atacamite were present though limited, leading to think that acid water condensation on the surface and capture of chlorine and chlorides from the air had occasionally occurred, causing pitting corrosion in some areas (5).

Subsequently, Colombo (8) has calculated in the course of her experimental thesis the stability range only of the three above-named copper sulphates (brochantite, antlerite and chalcanthite), since anglesite is a stable and insoluble compound even in an acid environment.

Figure 1 shows the stability range of the three compounds as resulting from the concentration of copper ion (stability range lies above each straight line): the conditions are those of stagnant water, as caused by a film of humidity, and of [Sulphate Anion] = 0.1 ppm.

It can be easily maintained that under scarce/average concentration of Cu^{2+} ions and at pH values higher than 4 , brochantite is more stable than antlerite; such a difference disappears and then reverses when pH<4, whilst very acid pH (i. e. slightly higher than 1) or very strong concentrations of copper ions make chalcanthite more stable.

Technique	Study of
ultrasonics	thickness of the alloy; defects; joining technique
strain-gauges	weight, strains
emf model calculation	structural analysis
speckle interferometry	structural deformations
radiography	assembling and welding, defects, repairs
I.A.C.S. conductivity	types of alloys
X.R.F.A.	analysis of the alloys
I.C.P.S.	analysis of the alloys
metallography	microcrystalline structure
acoustic emission	mechanical behaviour
thermovision	thermal behaviour
climatic survey	climate-microclimate
capillary condensation	electrochemical corrosion rate
X.R.D.	patinas and encrustations

Table 1. First main researches on Marcus Aurelius monument

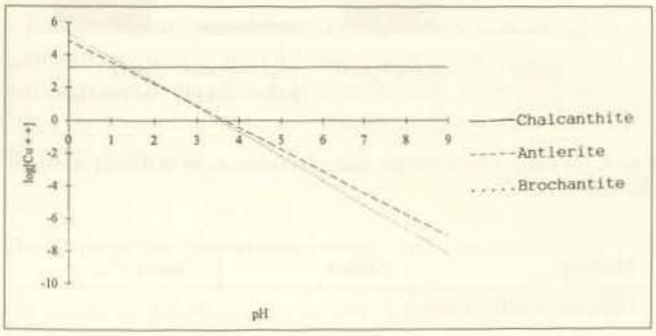


Fig. 1. Lines of balance of the compounds of the patinas in function of the pH and of the concentration of copper ions for a 0.1 ppm concentration of sulphate ions (the compound is stable above its line of balance)

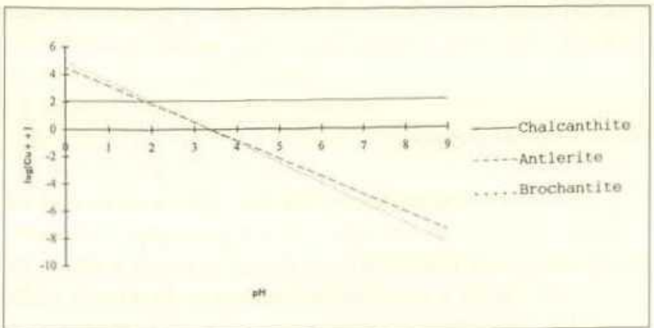


Fig. 2. Stability ranges of the compounds of the patinas in contact with rain water (the concentrations of sulphate ions is equal to 1.5 ppm; the compound is stable above its line of balance)

Figure 2 shows that under stagnant rain water with a concentration of sulphate ions almost ten times greater (1.5 ppm) and with an average acidity around 4, brochantite and antlerite result almost equally stable (actually the diagram does not differ much from the former one).

It is worth being noted though that under hard rain water washing with a concentration of copper ions equal to 10^{-6}M and low concentrations of sulphate ions, none of the three compounds turns out to be stable when pH is below neutrality (Fig. 3).

In the light of the foregoing results it can be asserted that under acid water condensation as well as under heavy rain water washing, slow though progressive leaching of the patina consisting of copper sulphates occurs.

Formerly the deterioration (electrochemical corrosion) of the alloy had been assessed by calculating its average corrosion rate as it resulted from the time of wetness and the damage function related to copper and bronze alloy (2, 5).

In the subsequent phase of this research the rate of corrosion has been experimentally calculated by taking into account the specification of the surfaces (presence or absence of gold leaf and of chlorides) as well as different composition, porosity, thickness and orientation of the various patinas of the monument.

For this purpose Colombo has applied a method already in use by the industry and employed for the first time for works of art during the restoration of the Bronzes of Riace (8, 10, 12): the measurement of the resistance of polarisation (R_p).

Actually everyone knows that by connecting the alloy, inclusive of the patina, of an artefact (working electrode, w. e.), a counter-electrode (c. e.) and a reference electrode (r. e.) and by releasing an electrical charge, such as to keep the w.e. potential within the maximum values of $V_{eq} \pm 15$ mV (where V_{eq} is the potential of the equilibrium), $E = E(\log I)$ is a linear function and Tafel's equation can be written in the simplified form:

$$I_{corr} = (b_a \cdot b_c) \cdot I / 2.3 \cdot (b_a + b_c) \cdot \Delta E$$

where b_a and b_c stand for the inclination of the anode and cathode curve of $E = E(\log I)$ as linear function.

In addition, for the sake of further simplification, by assuming b_a and b_c equal to 120 mV, independent of the corrosion process concerned,the result is:

$$I_{corr} = 26 \cdot I / \Delta E = 26 / Rp$$

where $R_p = \frac{\Delta E}{I}$ (ohm x cm^2).

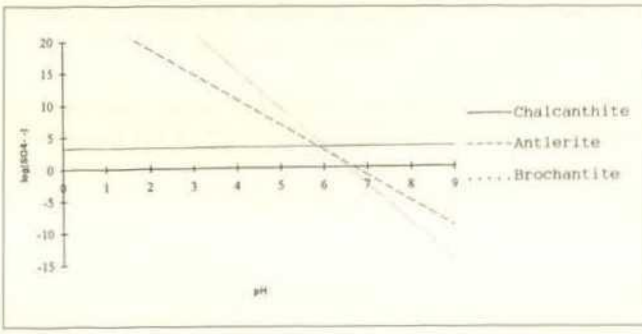


Fig. 3. Lines of balance of the compounds of the patinas in function of the pH and of the concentration of sulphate ions for a 63 ppb concentration of copper ions (the compound is stable above its line of balance)

In the circumstances I_{corr} and the corrosion rate v_{corr} (μm/y) are inversely proportional to R_p, and R_p is being calculated by measuring the I current circling in the w.e.-c.e. system when 10 mV difference of potential in respect of the potential of equilibrium is reached. R_p and I_{corr} values of course depend upon the interposed solution, upon the surface of the artefact which has been connected as well as on the presence or absence of insulating layers on the surface (8).

This means that the values under reference are subsequent to a thorough measurement of thickness and composition of the corrosion products, of the protective and insulating film if any and to the previous establishment of standard measurement conditions (e. g. by always cleaning and washing the surface first and by using, to effect the necessary measurements, the same electrolyte with known conductivity).

It goes without saying that the above set of measurements will have a relative value as they can be compared only with other figures related to the same artefact , carrying out the survey in different areas or in the same area at different times.

Bearing the above considerations in mind and applying the experimental scheme set forth in Figure 4, v_{corr} , as measured in various areas of the rider and of the horse, has been set out in µm/y (8, 9, 13).

Figures 5 and 6 show the average values of the rate of corrosion: for most of the areas which have been inspected the average value is about 1.5 µm/y, whilst in areas coated with scratched gold leaf the average rate of corrosion is about 8 µm/y.

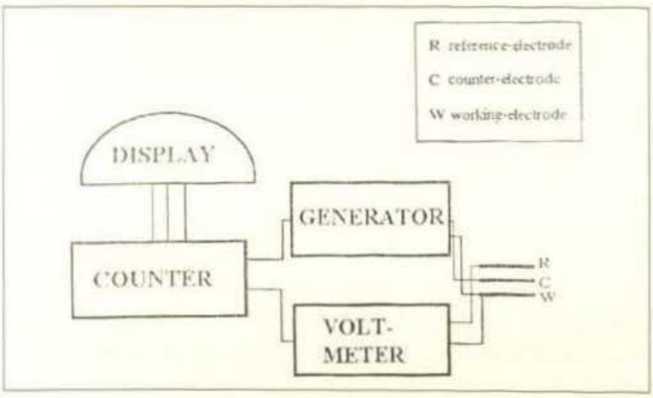
To permit a comparison, Table 2 shows the results obtained by applying the method of capillary microcondensation and those derived from R_p measurements, before and after taking into account the correction due to the time of wetness (t_w).

It can be noted that the differences in the values obtained by the two methods, once the correction has been applied, are very slight and therefore quite comparable as far as areas with no gold leaf are concerned, whilst in areas with gold the rate of corrosion is almost a point of magnitude higher. In these circumstances should the monument be placed outdoors again, the areas covered with gold leaf would require special, continuous protection and maintenance.

In addition to the R_p measurements, Colombo (8) has checked the adhesion of gold to the surface in areas which appeared to be in good state of conservation. For this purpose a device has been made consisting of a screw running inside its feed nut and fixed to a spring of known stiffness; the bottom of the screw (∅ 3 mm) is attached to the gold leaf by cyanacrylate. By twisting the screw the force necessary to pull the spring and to detach the gold leaf from the underlying surface is measured. Table 3 shows that the values obtained are satisfactory, almost all of them being higher than $6.6 \cdot 10^4$ Pa.

Furthermore, by measuring electrical resistance between the gold leaf and the bronze surface underneath, it has been found out that, contrary to expectations, in the areas with a good gold adhesion there is always at least one point of contact between gold and alloy.

Fig. 4. Scheme of the device for the R_p measurements



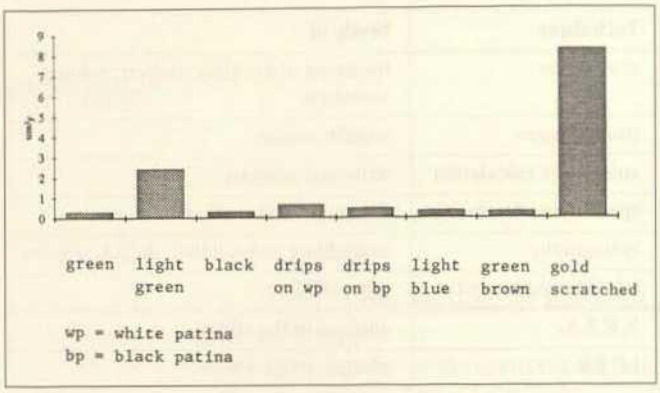


Fig. 5. Average values of the rate of corrosion in various areas of the horse different as to colour

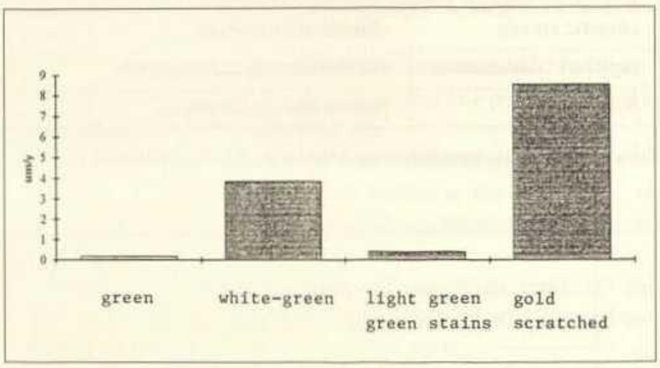


Fig. 6. Average values of the rate of corrosion in different areas of the rider

Method	Values	Values x t_w
Capillary condensation		0.2
R_p	1.5-8.0	0.3-1-8

Table 2. Electrochemical corrosion rate (µm/y)

In conclusion it can be asserted that adhesion of the gold plate, where the latter can yet be traced, is satisfactory apart from those fragments, of course, which appear to be partially detached.

Environmental Danger

In the course of a measurements campaign carried out by ETT of Milan and Purafil of Atlanta (U.S.A.), some copper and silver - sheets (henceforth coupons) were placed in Capitol Square in Rome according to a patented method set up by Purafil itself (11). After one month of outdoor exposure (Capitol Square, Rome) during the winter season, as regards some coupons and following three months of indoor exposure (exhibition rooms of the Capitol Wolf and of Marcus Aurelius) with regard to other coupons, the measuring of the products of corrosion was carried out. The coupons underwent exposure from November 95 to January 96: those placed outdoors were replaced every month, thus involving three series of samples.

The degree of environmental danger, according to Purafil, has been classified in Table 4.

As far as the samples placed outdoors are concerned environmental danger has turned out to be C5 and S4 with regard to copper and silver respectively. On the other hand, the coupons placed inside reacted as in a protected area (C3, S3).

Despite the limits of the method (short time of exposure, disputable classes of risk), it cannot be denied that the outdoor environment appears to be quite dangerous in comparison with the indoor one.

The Protection of the Surface

With the co-operation of ICR, CISTeC has devised and arranged, a campaign of tests to establish the effective protection secured by some commercial products used to shield bronze artefacts placed outdoors (5). This is done according to the method recommended by ICR to combine a reversible acrylic primer with a replaceable top layer subject to deterioration.

Table 5 indicates the protection products which have been used and the ways in which the tests have been carried out. The results of the tests show that the most effective combination is Paraloid B72, as primer, and, as top layer Soter 202 LS + Soter 201 LC. The system of protection which has been chosen can be applied, of course, not only to the monument under reference but to similar monuments as well: obviously such a protective coat calls for maintenance works on the surface every three to five years to cope with the deterioration due to weather agents.

This maintenance might require, depending on circumstances, cyclic integrations of the film bound to be removed in the areas more exposed to the erosion of direct rainfall, as well as, in some cases, the removal and the subsequent complete replacement of the entire outer film.

The Copy of the Monument

The results of the measurements and of the studies conducted by CISTeC (9) have led the authority in charge of surveillance of the monument to decide for the outdoor exposure of a scientifically correct copy of the monument, thus refraining from direct moulding because the latter would have polluted the surface of the monument. The model – a twin of the original monument – was made according to a new methodology devised by the ICR's laboratory of Physics. The main steps to bring this model to completion were the following:

1. Execution of the photogrammetric map, with 5 mm-distant contour lines of the volumes as output, by sampling 478154 points for the rider and 463489 points for the horse (as a whole, a 18 km-long track).The contour lines are as many as the section planes perpendicular to the axis of main symmetry, which is vertical for the rider and horizontal for the horse.
2. Development of a dedicated software to overcome some difficulties met in the course of cutting each section by means of a machine tool driven by the co-ordinates of the photogrammetric map; in this phase the scale has been enlarged by 2 percent to balance an equivalent shrinkage of the casting while cooling down.
3. Assembling in blocks of the PVC sections (820 for the horse and 686 for the rider) by means of hollow steel cylinders and terminal locking plates: the blocks were subsequently mounted on a steel skeleton.

At the end the model, made of plastic and steel, weighed as much as the original monument, about 2500 kg. The Istituto Poligrafico e Zecca dello Stato made the bronze copy, starting from the PVC model. The unevenness of the surface, due to the discreteness of the contour lines, was smoothed by adding plasticine and shaping the latter as to reproduce the superficial details of the original. Once the model had been completed, a silicone counter-mould and then the definite mould for the casting, according to the indirect method masterly described by Cellini in his work on sculpture, were carried out.

For the casting, consisting like the original of seventeen and fourteen parted sections for the horse and the rider respectively, an easily melting ternary alloy of copper, tin and zinc 88:7:5 was used. Subsequently, the various parts were soldered together with the same alloy, the surface was cleaned and refined and finally patinated and coated as necessary.

There was still to be decided how to fix the monument to Michelangelo's base. The study of the loads distribution of the original monument had shown a marked lack of balance in the body forces insisting on the three bearing legs (Table 6), which

Area	Adhesion (10^4Pa)
1) No direct washing	>6.6
2) No direct washing	4.5
3) Clear drippings	>6.6
4) Dark drippings	>6.6
5) Direct washing	>6.6
6) Clear drippings	36
7) Clear drippings	>90

Table 3. Force of adhesion of the gold leaf to bronze

Copper corrosion		
Class	**Quality of the air**	**Rate of corrosion**
C1	Very pure	< 90 Å per 30 days
C2	Pure	< 150 Å per 30 days
C3	Clean	< 250 Å per 30 days
C4	Slightly polluted	< 350 Å per 30 days
C5	Polluted	> = 350 Å per 30 days
Silver corrosion		
Class	**Quality of the air**	**Rate of Corrosion**
S1	Very pure	< 40 Å per 30 days
S2	Pure	< 100 Å per 30 days
S3	Clean	< 200 Å per 30 days
S4	Slightly polluted	< 300 Å per 30 days
S5	Polluted	> = 300 Å per 30 days

Table 4. Environment classes in respect of conservation of historic-artistic works

Tested surface coatings
Paraloid B72 + Reswax (microcrystalline and synthetic waxes)
Paraloid B72 + Soter 202 LS + Soter 201 LS (microcrystalline waxes+ BTA)
Paraloid B72 + Syremont FU610W (fluorpolymer)
Paraloid B72 + PSM 25 (microcrystalline wax)
Testing
ASTM B117- Salt spray – 240h
ASTM G53 – UV exposure + Condensation – 1008h

Table 5

resulted in a strong forward push of the rider-horse system: in the past there had been attempts to solve this problem, with no success though, by balancing the three legs with addition of 730 kg of metallone, a lead-tin alloy. The copy has no such defect, this having been avoided by charging the left hind leg with 350 kg of lead. The three hooves were fixed to the base by means of a locking system of stainless steel consisting, for each hoof, of a part inserted in the base (bar + plate + hollow cylindrical seat with four adjustable pivots to fasten the tenons) and of a movable part, joined to the hoof of the horse, which goes into the one fixed to the base (tenon, consisting of a plate tied up to the hoof + a cylindrical piece to be keyed to the relevant hollow seat on the base).

At this point the long scientific and technological journey came to an end.

Total weight	2660
Left fore leg	1510
Left hind leg	240
Right hind leg	910

Table 6. Weight distribution of the monument (kg)

Conclusions

This report shows the complexity of the problems which were faced and solved since 1981 both to obtain precious archaeometric information, to investigate the processes of deterioration, to carry out a non-invasive restoration and, in view of a possible future re-exhibition outdoors, to look into corrosion as well as protection and maintenance of the surface.

Besides the above, one step further was to make the scientifically correct copy of the monument which was placed on Michelangelo's base on April 21st 1997. All these researches, carried out between 1981 and 1997, can now be treated as a point of reference for future studies of other bronze monuments in that they contain a wide range of non-destructive diagnostic techniques, some of which surely innovative for works of art.

When in the end it was decided to place the copy outdoors instead of the original it was not for lack of adequate protection of the monument but merely because its surface is today unique and no doubt has to be saved in its total integrity.

Acknowledgements

It is impossible to recall here all the persons engaged in these researches or who stimulated and supported them. I will mention only the institutes, the companies and the specialists who were more involved in arranging and looking after the experimental work as well as the restoration, the safeguard and the appreciation of the monument:

1. ICR, and especially the two laboratories of physics and chemistry, directed by G. Accardo and myself respectively, as well as the restorer P. Fiorentino; the Ministry of Cultural and Environmental Property, who financed the model;
2. CISTeC (Interdepartmental centre of science and technology for the preservation of historic-architectonic property – University of Rome "La Sapienza"), and in particular the professors C. Giavarini, R. Cigna, A. Gallo Curcio, G. Santucci, G. Torraca and the engineers C. Bartuli and B. Colombo of the ICMMPM department of the University of Rome "La Sapienza";
3. Istituto Poligrafico e Zecca dello Stato, Rome, and particularly the doctors L. Cretara, G. Veroi and D. Pomari;
4. Rome City Council, and especially the superintendent E. La Rocca and Dr. A. M. Sommella;
5. RAS, Rome, official sponsor of both the restoration works and the casting;
6. Finmeccanica, Rome, for the first research regarding on-surface protective products and the firm I. Reindell for testing the second series of protective products.

Literature

1 A. A. V. V., *Marco Aurelio: Mostra di Cantiere – Catalogo a cura dell'ICR*, in: Arti Grafiche Pedanesi, Roma 1984

2 M. Marabelli/A. Marano/S. Massa/G. Vincenzi, *La condensazione capillare di vapore acqueo in patine di bronzi esposti all'aperto*, in: Preprints of the 2nd International Conference on Non-destructive Testing, Microanalytical Methods and Environmental Evaluation for Study and Conservation of Works of Art, Perugia, April, 17th-20th 1988, organised by ICR and AIPnD, Rome, 1988, pp. 2,25, 1-20

3 A. A. V. V., *Marco Aurelio: Storia di un Monumento e del suo Restauro*, RAS. Milano 1989

4 M. Marabelli/G. Napolitano, *Nuovi sistemi protettivi applicabili su opere e manufatti in bronzo esposti all'aperto. Materiali e strutture*, 1-2, 1990, pp. 51-58

5 M. Laurenzi Tabasso/M. Marabelli, *Il degrado dei monumenti in Roma in rapporto all'inquinamento atmosferico*, Ed. BetaGamma, Viterbo, 1992

6 M. Marabelli, *The monument of Marcus Aurelius: research and conservation*, in: Proceedings of the symposium "Ancient and Historic Metals", organised by the J. Paul Getty Museum and the Getty Conservation Institute, Marina del Rey, California, November 1991, The Getty Conservation Institute 1994, pp. 1-19

7 P. Fiorentino, *Restoration of the monument of Marcus Aurelius: facts and comments*, in: Proceedings of the symposium "Ancient and Historic Metals", ibidem, pp. 21-31

8 B. Colombo, *Studio della conservazione delle opere d'arte in lega di rame*, Thesis University of Rome "La Sapienza", 1994-1995

9 A. A. V. V., *Monumento equestre di Marco Aurelio, rapporto sugli studi e ricerche*", CISTeC, Roma 1996

10 M. Bartolini/R. Cigna/B. Colombo/G. D'Ercoli/M. Marabelli/A. Marano, *Capillary condensation measurements and electrochemical tests for conservation of artistic metals* in: Preprints of the "5th International Conference on Non-destructive Testing, Microanalytical Methods and Environmental Evaluation for Study and Conservation of Works of Art" organised by MKE, AIPnD and ICR, Budapest, September 24th-28th 1996, pp. 117-130

11 E. Sacchi, *La qualità dell'aria in edifici storico-museali. Una indagine su campo*, in: Preprints of the AICARR meeting "Microclima, qualità dell'aria e impianti negli ambienti museali", CNR, Florence, February 7th 1997, pp. 39-65

12 M. Bartolini/B. Colombo/M. Marabelli/A. Marano/C. Parisi, *Non-destructive tests for the control of ancient metallic artefacts*, in: Proceedings of the "International Conference on Metals Conservation", Semur en Auxois, September 25th-28th 1995, James & James, London, 1997, pp. 43-49

13 A. A. V. V., *Il Marco Aurelio e la sua copia*, by A. M. Sommella e C. P. Presicce (Rome City Council), Silvana Editoriale, Roma 1997

Note 1

After mechanical cleaning, the application by pads of the following products, as required, has been carried out on completion:

1 Bio-Rad Ag 50 W-X8 cationic resin in acid form;
2 12% solution of trisodium EDTA;
3 De-ionized water.