BS EN 16782:2016

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# Conservation of cultural heritage — Cleaning of porous inorganic materials — Laser cleaning techniques for cultural heritage

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The UK participation in its preparation was entrusted to Technical Committee B/560, Conservation of tangible cultural heritage.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI StandardsLimited 2016

ISBN 978 0 580 87205 1

ICS 97.195

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This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 June 2016.

**Amendments/corrigenda issued since publication**

| Date | Text affected |
|---|---|

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

**EN 16782**

May 2016

ICS 97.195

English Version

# Conservation of cultural heritage - Cleaning of porous inorganic materials - Laser cleaning techniques for cultural heritage

Conservation du patrimoine culturel - Nettoyage des matériaux inorganiques poreux - Techniques de nettoyage au laser des biens culturels

Erhaltung des kulturellen Erbes - Reinigung von porösen anorganischen Materialien - Laserstrahlreinigungsverfahren für kulturelles Erbe

This European Standard was approved by CEN on 27 February 2016.

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Ref. No. EN 16782:2016 E

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# European foreword

This document (EN 16782:2016) has been prepared by Technical Committee CEN/TC 346 "Conservation of cultural heritage", the secretariat of which is held by UNI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2016, and conflicting national standards shall be withdrawn at the latest by November 2016.

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## Introduction

A cleaning method can be applied out if it follows the ethical code of conservation practice as stated in International Charters.

Laser cleaning consists in the removal of the unwanted surface materials from a substrate by using laser irradiation. The removal of unwanted substances on surfaces of artworks is done by photo-thermal processes and/or photomechanical processes, and/or photochemical processes.

Laser cleaning is generally characterized by a high precision and selectivity, which may allow the process to be stopped at a pre-determined level.

Laser cleaning requires very precise control to be selective and prevent surface damage. As with other cleaning systems, laser cleaning can only be performed by trained operators with sufficient knowledge of all relevant laser safety regulations and guidelines.

This standard specifies the requirements for the selection of laser cleaning methods and devices applicable to natural stone, ceramics and mortars (plasters, renders and stucco). When it is not possible to identify a safe working fluence (for example for certain stone lithologies or some painted artworks containing sensitive materials), laser cleaning is not suitable.

# 1 Scope

This European standard applies to porous inorganic materials constituting cultural heritage. It provides the fundamental requirements of the laser parameters and guidelines for the choice of the laser operational parameters, in order to optimize the cleaning procedure.

# 2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 15898:2011, *Conservation of cultural property — Main general terms and definitions*

EN 16572:2015, *Conservation of cultural heritage — Glossary of technical terms concerning mortars for masonry, renders and plasters used in cultural heritage*

# 3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 15898:2011, EN 16572:2015 and the following apply.

**3.1**
**cleaning**
removal of unwanted material from an object

Note 1 to entry: The criteria for something being "unwanted" can always be stated, e.g. potentially damaging, obscuring detail, unaesthetic, etc.

[SOURCE: EN 15898:2011, 3.5.3]

**3.2**
**mortar**
material traditionally composed of one or more (usually inorganic) binders, aggregates, water, possible additives and admixtures combined to form a paste used in masonry to provide for bedding, jointing and bonding, and for surface finishing (plastering and rendering) of masonry units, which subsequently sets to form a stiff material

[SOURCE: EN 16572:2015, 3.1.1]

**3.3**
**plaster**
coating composed of one or more mortar layers applied in one accomplishment sequence, used on internal masonry surface such as ceiling, walls, and partition

Note 1 to entry: Plaster is a traditional English term.

[SOURCE: EN 16572:2015, 3.2.5]

**3.4**
**render**
coating composed of one or more mortar layers applied in one accomplishment sequence, used on external masonry surfaces and which has protection function and surface finishing

Note 1 to entry: Render(ing) is a traditional English term.

[SOURCE: EN 16572:2015, 3.2.6]

**3.5**
**stucco**
mortars used for making decorative mouldings, architectural castings and other decorations on the facades and in the interiors of the buildings

[SOURCE: EN 16572:2015, 3.2.8]

**3.6**
**laser**
**Light Amplification by Stimulated Emission of Radiation**
radiation source that generates a coherent, monochromatic and very powerful beam of light in the range of ultraviolet, visible or infrared wavelengths

**3.7**
**laser ablation**
removal of material from an object induced by the laser radiation absorption, in the form of molecular radicals, vapours and particles of different sizes

**3.8**
**photo thermal ablation**
ablation process caused by heat generated by the laser radiation absorption

**3.9**
**photo mechanical ablation**
ablation process caused by mechanical stress and strains induced by the laser radiation absorption

**3.10**
**photo chemical ablation**
ablation process caused by chemical bond cleavages induced by the laser radiation absorption

**3.11**
**light**
radiation that is considered from the point of view of its ability to excite the visual system

Note 1 to entry: It corresponds to the so-called visible radiation in the range between 380 nm and 780 nm.

Note 2 to entry: In the field of conservation, this term sometimes extends the range outside the visible portion, including parts of the ultraviolet (UV) and near infrared (IR) regions.

[SOURCE: CIE S 017/E:2011]

**3.12**
**infrared radiation**
part of the electromagnetic spectrum with wavelength longer than those of the visible radiation, from about 780 nm to tens of micrometres

[SOURCE: CEN/TS 16163:2014, 3.18)]

**3.13**
**ultraviolet radiation**
part of the electromagnetic spectrum with wavelengths from 10 nm to 380 nm

[SOURCE: CEN/TS 16163:2014, 3.36]

**3.14**
**irradiated area**
**spot**
area of the object subject to the laser beam during one single shot, in $cm^2$

**3.15**
**laser fluence**
amount of energy divided by the irradiated area, in joules per square centimetre ($J/cm^2$)

Note 1 to entry: The energy density can be changed at the sample surface if lenses are placed in the path of the laser beam.

**3.16**
**power density**
power divided by the irradiated surface, in watt per square centimeter ($W/cm^2$)

**3.17**
**laser continuous wave emission**
**CW emission**
stationary emission of a radiation laser at a constant power, in which the interaction of the laser beam and a surface is largely thermal

**3.18**
**average power for laser continuous wave emission**
energy emitted by a laser in one second, in watts (W)

**3.19**
**laser pulsed emission**
mode of laser emission consisting of successive temporal pulses having a constant duration and characterized by an instantaneous power (see 3.16) much higher than the average power.

Note 1 to entry: In pulse mode, the interaction of the laser beam and a surface is commonly believed to be a combination of thermal and mechanical processes.

**3.20**
**peak power**
single pulse energy divided by the duration of the pulse, in watts (W)

**3.21**
**average power for laser pulsed emission**
result of multiplication of pulse energy by the repetition rate, in watts (W)

**3.22**
**pulse duration**
Full Width Half Maximum, or width at which the pulse energy/power is half that of the maximum energy/power

Note 1 to entry: The duration of a pulse from a laser is a key factor in determining how the light will interact with material. Pulse durations range from “ultra short” femto seconds ($10^{-15}$ s) to “long pulse” micro seconds ($10^{-6}$ s).

Note 2 to entry: This definition refers to how “pulse duration” is usually defined.

**3.23**
**laser repetition rate**
<pulsed laser> number of pulses per second, in hertz (Hz)

**3.24**
**reflectance**
ratio between the light intensity reflected by a surface and the incident light on the same surface, in percentage (%)

**3.25**
**depth of optical penetration (into the material)**
distance measured from the surface coincident with the reduction of the intensity of incident light radiation equivalent to 1/e and by means of absorption (e ~2,7)

**3.26**
**Q-switched laser**
laser generally having a pulse width in the range 5 to 30 ns, put to use by the technique of q-swithching that is used to produce a pulsed output laser beam, allowing the emission of pulses with extremely high peak power

**3.27**
**free running laser**
laser in which the emission lasts as long as the pumping process is sufficient to sustain lasting condition

Note 1 to entry: Typical pulse durations are in the range of µs-ms.

**3.28**
**laser ablation fluence threshold**
**$AF_{th}$**
lowest fluence that causes ablation of the material to be removed

**3.29**
**laser damage fluence threshold**
**$DF_{th}$**
lowest fluence that causes unwanted changes to the material to be preserved

# 4 Symbols and abbreviations

$F_L$ laser fluence

$F_{th}$ threshold fluence

$AF_{th}$ laser ablation fluence threshold

| | |
|---|---|
| $F_{th}$(A) | threshold fluence at point A (beginning of ablation of layer A) |
| $F_{th}$(B) | threshold fluence at point B is the damage threshold fluence $DF_{th}$ |
| $DF_{th}$ | laser damage fluence thresold |
| $F_{lim}$ | threshold fluence limit |
| *CW* | continuous wave |
| *QS* | Q-Switched |
| *FR* | free running |
| *SFR* | short free running |
| $m_{abl}$ | amount of material removed for each laser pulse |
| $F_{th(sat)}$ | threshold fluence corresponding to the saturation of the removal process |

# 5 Key features of the laser system with respect to the cleaning of porous inorganic materials

## 5.1 General

The choice of the most appropriate laser system shall be carried out after the characterization of materials, their condition and after having established what shall be removed and what shall be preserved. A laser, emitting at a given wavelength, will only remove layers containing components able to absorb the energy at this specific wavelength. Where the possibility exists of undesirable dis-/coloration effects established methodologies that have been proven to reduce or overcome the issue shall be considered and tested (such as combination of wavelengths, longer or shorter pulse durations etc.). As a consequence, the choice is dependent on the nature of the layers to be removed, and on the wavelength of the laser. Pulse duration will influence the interaction mode (see Annex A).

## 5.2 Wavelength

The following parameters are influenced by the wavelength:

1) the optical absorption of the material involved in the laser cleaning. This parameter can be estimated by measurements of reflectance at the wavelength of the laser radiation (see Annexes B and F);

2) the penetration depth of the laser radiation in the material which shall be chosen in relation to the depth of the material to be removed;

3) the ablation processes in general.

## 5.3 Laser pulse duration

This parameter influences the physical processes that are causing the ablation and consequently the possible harmful effects such as thermal damages for the long pulses (hundreds of microseconds), or photo-mechanical damages for the short pulses (nanoseconds) (see Annex C).

## 5.4 Regime of pulsed emission

The use of a pulsed laser system is indicated where it is necessary to minimize heat buildup and the resulting thermal damage to the substrate.

The pulse may be applied in intervals measured in femto-seconds to a few hundreds of microseconds, usually between 5 and 25 ns (QS) and 100-200 μs (FR).

### 5.5 Stability of laser emission

New equipment shall provide an emission stability of ± 10 % of average power during the operational working, in relation to the set value. As the emitted energy depends on the pumping source, flash pumped lasers loose energy over time due to slow deterioration of flash lamps.

### 5.6 Transmission system of the radiation

Two transmissions systems are currently available: these are optical fibres and mirror based systems (articulated arm). With an optical fibre system working may be undertaken at distance from the laser source, however the maximum pulse energy should be lower. Optical fibre systems produce a homogeneous distribution of energy within the beam. With an articulated arm the pulse energy may be higher, but working is in closer proximity to the laser source. An articulated arm generally does not allow an homogeneous distribution of energy within the beam.

### 5.7 Handpiece

The laser beam emerges through a handpiece, which is held by the operator. Lenses within the handpiece allow collimating or focusing of the laser beam and control of the energy density at the surface of the object.

### 5.8 Irradiated area

The surface of the irradiated area (“spot”) shall be measured or determinable on the target in order to calculate the laser fluence,

a) if the handpiece has a fixed focus the distance at which the beam is focused on the smallest surface shall be specified;

b) if the handpiece has a variable focusing system, the above mentioned distance for maximum and minimum focal values should be specified.

### 5.9 Targeting system

Laser cleaning systems operating out of the visible spectral band shall have a targeting system, indicating the irradiation area (for instance a diode laser emitting in the visible range). The targeting system shall not be absorbed by the required safety glasses The optical pathway and the focal spot of the targeting system shall coincide with the cleaning laser beam.

All laser systems should be equipped with a pointer system which is not absorbed by the respective required safety glasses.

The following parameters shall be quantifiable (by a display or other reading system) and adjustable:

1) output energy or average power;

2) repetition rate.

## 6 Preliminary cleaning tests for selecting laser operating parameters

### 6.1 General

Each surface to be cleaned should be characterized in terms of materials, condition and which layers shall be removed by the laser cleaning and which shall be retained. Following this, the operational parameters here listed shall be determined for each surface, in order to achieve the highest effectiveness and the minimum of harm:

a) output energy;

b) spot area;

c) fluence;

d) pulse repetition rate.

## 6.2 Working fluence

The aim of this test is to identify the working fluence, which is the range of energy density over which photo ablation occurs, but which is significantly below the damage threshold of the substrate. Tests described below are typically carried out *in situ*, therefore without the need to take samples.

If required, a systematic determination of the exact damage threshold can be carried out by performing the following steps:

1) the laser handpiece is fixed in position, for instance on a tripod, in order to maintain a set distance from the surface and a set spot size;

2) the surface of the laser spot is measured (e.g. using a photosensitive paper) in order to calculate the fluence;

3) the irradiation duration shall be set as a function of repetition rate and fluence (Annex E);

4) the material shall be irradiated with the laser using the established settings;

5) the laser handpiece is then moved to target an (or at an) adjacent test area while maintaining the previous distance;

6) the energy output is increased and the new test area is irradiated with the same repetition rate and exposure time;

7) visual observations (by naked eye and microscope), shall be reported in a document as in the example in Table 1;

8) photographic documentation (macro, micro, raking light) of the test areas before and after each trial shall be recorded;

9) the fluence can be calculated as the pulse energy is divided by the irradiated area ($J/cm^2$).

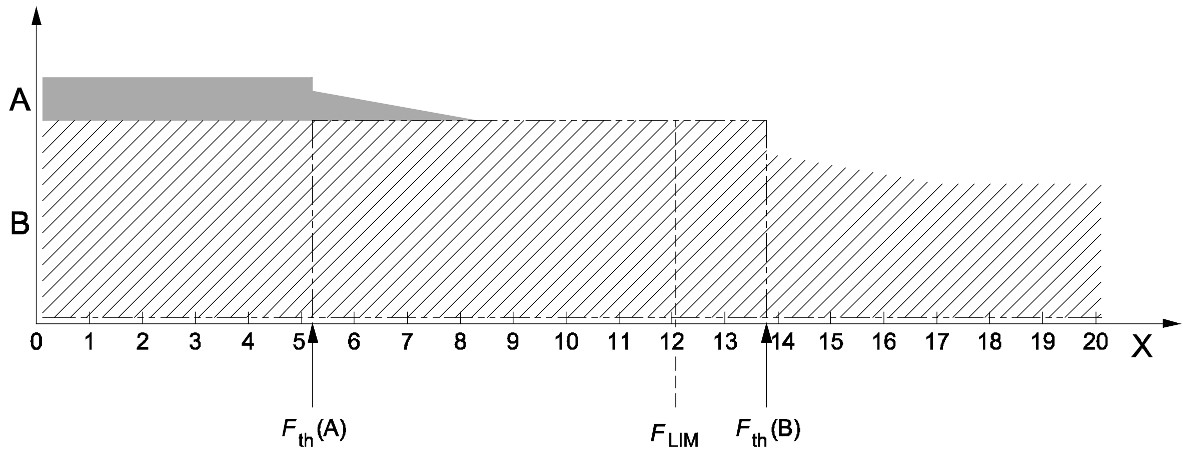
**Table 1 — Indicative documentation of a laser cleaning test on a lithotype with two layers**

**- Trial name:** Area 1 - Lithotype with layer A above layer B
**- Trial description:** Laser cleaning on a surface wetted with deionized water
**- Laser Type (type of source and pulse duration):** SFR – short free running
**- Operative wavelength (nm)**; Xxxxx
- **Brand name:** xx+xxxxxxxxx
Test parameters maintained for the irradiation test:
**- Distance of the surface with respect the handpiece output:** 5,5 cm
**- Spot diameter:** 2,7 mm
**- Area:** 0,0573 cm²
**- Irradiation time:** 10 s
**- Repetition rate:** 5 Hz
**- Wetting agent: (if yes, indicate the type**) Deionised water

| Trial | Laser energy (mJ) | Fluence (J/cm²) | Observation |
|---|---|---|---|
| 1 | 100 | 1,75 | No effect on layer A; no effect on layer B |
| 2 | 200 | 3,49 | Weak effect on layer A; no effect on layer B |
| 3 | 300 | 5,24 | Ablation of layer A; no effect on layer B |
| 4 | 400 | 6,99 | Ablation of layer A ; no effect on layer B |
| 5 | 500 | 8,73 | Ablation of layer A; no effect on layer B |
| 6 | 600 | 10,48 | Ablation of layer A; no effect on layer B |
| 7 | 700 | 12,23 | Ablation of layer A; no effect on layer B |
| 8 | 800 | 13,97 | Ablation of layer A, weak effect on layer B |
| 9 | 900 | 15,72 | Ablation of layer B |
| 10 | 1000 | 17,47 | Ablation of layer B |

Layer B is the material to be maintained and layer A the one to be removed. Table 1 demonstrates progressive increase of energy through the ablation threshold and the damage threshold. It is not necessary for testing to proceed to the point of damage of the layer to be preserved in all cases.

In the above example, the lower limit of the operational range (Annex A) corresponds to the ablation threshold $F_{th}$(A) of the layer A (5,24 J/cm²), while the upper limit of this operational range corresponds to the threshold of damaging $F_{th}$(B) of the layer B, (13,97 J/cm²). The data measured in the cleaning tests are used to draw the diagram of Figure 1 which synthesizes the results and of the observation reported in Table 1.




**Key**

X laser fluence, in J/cm²

$F_{th}$ threshold fluence

A layer A

B layer B

$F_{LIM}$ level of damage threshold to preserve layer B

**Figure 1 — Diagram of the optimal range of working fluence determined in the cleaning tests of Table 1. Within that fluence range, an effective removal of the layer A and no visual damage of the layer B are obtained**

The dashed line in Figure 1 shows the limit of the operational range of the fluence which allows the laser removal of layer A in safe condition, i.e. in a fluence range allowing the preservation of the of layer B. Above the ablation threshold value $F_{th}$ (A) an increase of removal depth is occurring approximately proportional to the laser fluence (see Annex A). To preserve the layer B it is advisable to operate approximately at the level of 30 % below the damage threshold value $F_{th}$ (B) which is indicated by $F_{LIM}$ in Figure 1.

Therefore, the operation parameters for an effective cleaning without visual damage are in this example within the range of fluence between 5,24 J/cm² and 12,23 J/cm² ($F_{LIM}$).

### 6.3 Working spot size

Working spot size shall be chosen taking into account the morphological characteristics of the surface to be cleaned and the maximum efficiency of the cleaning system.

On flat surfaces the maximum spot should be used; on carved surfaces it shall be reduced in order to effectively clean the details. Nevertheless, the fluence shall be in the experimentally determined safe operational range as described previously at 6.2.

### 6.4 Repetition rate

The repetition rate shall be maintained below the limit that causes thermal damage on materials to be treated.

## 7 Cleaning test report

In the cleaning test report the following items shall be recorded.

### 7.1 Laser instrument

The following shall be reported:

a) type;

b) manufacturer;

c) the conformity to requirements to Clause 6 (working fluence, working spot size, repetition rate);

d) wavelength (single or combination);

e) pulse duration;

f) type of energy delivery system (articulated arm, single optical fibre, multiple optical fibres);

g) handpiece focal length.

## 7.2 Preliminary tests for selecting laser operating parameters

**7.2.1** For each of the representative areas of the different substances to be removed from the object the data gathered during the preliminary test (see Clause 6) for selecting laser operating parameters shall be recorded:

a) The location, the macroscopic description and the photographic documentation of the test areas on the surface of the object before and after the cleaning test;

b) table of the threshold ablation fluence measurements as reported in the example of Table 1;

c) the diagram of the results of the measurements and of the observation reported in each table (as in the example of Figure 1);

d) the range of operational fluence;

e) the description macro and microscopic of the cleaning spot surfaces;

f) the photographic documentation of the cleaning spots carried out.

**7.2.2** If the macroscopic observation to determine the working fluence is not sufficient it is necessary to report:

a) the description of the sampling areas;

b) the description and photographic documentation of cleaned and not cleaned samples;

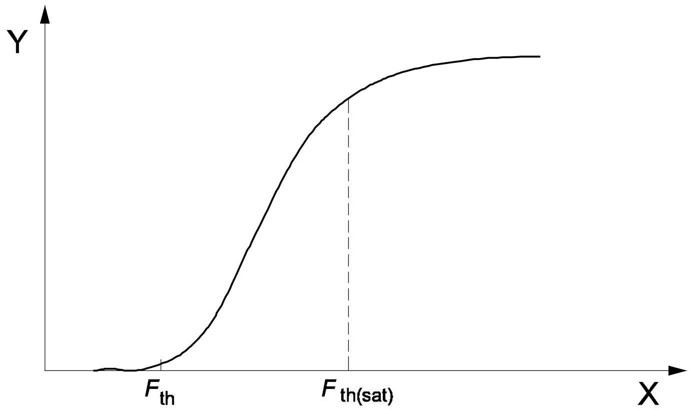
c) the description and the photographic documentation of the observations carried out.

# Annex A
(informative)

## Measurement of the ablation curve

The photo ablation (material removal by laser) is typically described by the fluence parameter, energy per surface unit. In particular "the ablation curves" relates the laser fluence $F_L$ with the amount of material removed $m_{abl}$ for each laser pulse (or alternatively the depth of removal), as shown in Figure A.1. Below the "threshold fluence" $F_{th}$ no removal effect but only thermal effect is occurring. Above the removal starts and increases proportionally to the fluence, till to reach a limit fluence value $F_{th(sat)}$ which corresponds to the saturation of the removal process. In fact, above this limit value the speed of removal decreases due to different factors (like for instance optical screen effects due to plasma formation or nonlinear absorption effects that reduces the depth of penetration of the radiation into the material). Then the operational range for a better efficiency of the removal process is the one that lied between $F_{th}$ and $F_{th(sat)}$. It shall be underlined that for the same material, the ablation threshold and the ablation curves varies according to the wavelength of the laser radiation.

The measurement of the ablation curve for each material and for each laser wavelength is generally carried out in laboratory, because it needs a high precision for the evaluation of removed material for each pulse laser.




**Key**

| | |
|---|---|
| X | laser fluence $F_L$, in J/cm$^2$ |
| Y | thickness/volume of removed material $m_{abl}$, in µm/pulse or µm$^3$/pulse |
| $F_{th}$ | threshold fluence |
| $F_{th(sat)}$ | threshold fluence at saturation |

**Figure A.1 — Ablation curve related to laser fluence**

# Annex B
(informative)

## Optical absorption



Knowledge of the optical absorption of the materials being cleaned and of the unwanted layers at a chosen wavelength allows an estimation of the amount of energy which will be effectively absorbed by the irradiated object.

Absorbance (A) is the physical quantity which describes the optical absorption. The direct measurement of the absorbance is difficult to accurately quantify, but can be estimated by the measurement of reflectance (R), which in strong absorption conditions is related to A by the formula A = 1-R.

Optical absorption at a chosen laser wavelength is related to selectivity of the laser cleaning process.

If the optical absorption of the unwanted materials to be removed is much higher than that of the substratum to be preserved, the ablation threshold of the first layer will be, in general, lower than that of the second one. In this case, operating with a laser fluence which lies between those values it is possible to remove the alteration and automatically stop cleaning at the interface of the unwanted layers and substratum.

This is a typical condition when using a laser emitting in the visible near infrared for the cleaning of a dark decayed layer (for instance a black crust) on a light stone material substratum.

It is stressed that the reflectance shall be measured in the operational conditions of the laser, like, for instance the cleaning of dark area which is preventively wetted to have a higher efficiency in the removal process.

# Annex C
(informative)

# Duration of laser pulse

Research on the interaction of laser and stone show that with short pulses (less of a microsecond duration) and high power the ablation process induces a plasma formation, with particular "photomechanical" characteristics.

For example, when high-power laser pulses are directed into a transparent medium (water) the medium becomes suddenly opaque to laser radiation as soon as a certain irradiance threshold is exceeded. This sudden rise in the absorption coefficient is due to the formation of a dense optically absorbing plasma. This plasma is caused by the high laser photon flux on the target, which induces escape of electrons from the material surface, causing a cloud of free electrons and gaseous ionized atoms.

This plasma formation leads to rapid heating of the material in the focal volume followed by its explosive expansion and the emission of a shock wave.

Where these conditions exist the dynamic of ablation process does not depend by the optical absorption of the material, but by the plasma absorption which is heating and expanding very rapidly, causing intense pressure waves (shock waves).

In contrast, for long laser pulses (more than a microsecond), the photomechanical effects decreases and the removal process are mainly a rapid vaporization. For even longer pulses (0,1-1,0 ms) the thermal effects becomes more important and the ablation process is more similar to a static vaporization.

# Annex D
(informative)

## Role of water



In laser application, the surface can be wetted by gentle brushing or spraying with deionized water thus producing the following positive effects:

— a significant increase of cleaning efficiency, because water typically increases the optical absorption of the unwanted materials and thus reduces the laser ablation threshold fluence value with respect to the dry application;

— an effective cooling of the surface thanks to the vaporization of the water film;

— significant increase of the cleaning efficiency caused by water vaporization.

The attention of the operator is drawn to adverse effects of water. Wetting should be kept to minimum levels because it may cause damage such as:

— damage to water soluble binders of polychromes;

— mobilization of soluble salts;

— impregnation of porous materials.

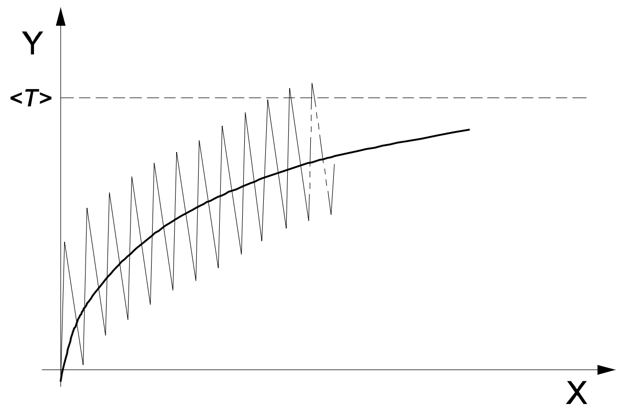
# Annex E
(informative)

# Repetition frequency

In the case of laser cleaning by a series of repeated pulses, an increase of the average temperature of the surface, which varies depending on the materials, is observed due to the cumulative effect of the series of pulses, which reaches the surface before the heating effect of the previous pulse, has completely disappeared.

In this condition, the behaviour of the surface temperature is according to the example illustrated in Figure E.1 that is the modulated increase heating that is due to the cumulative effect which tends to a stationary value < *T* > which is proportional to the laser repetition frequency.

An inappropriate duration can have harmful effects which are described in Annex G.




**Key**

X pulse numbers

Y surface temperature

< *T* > stationary value

**Figure E.1 — Behaviour of the cumulative thermal effect**

# Annex F
(informative)

## Reflectance measurement

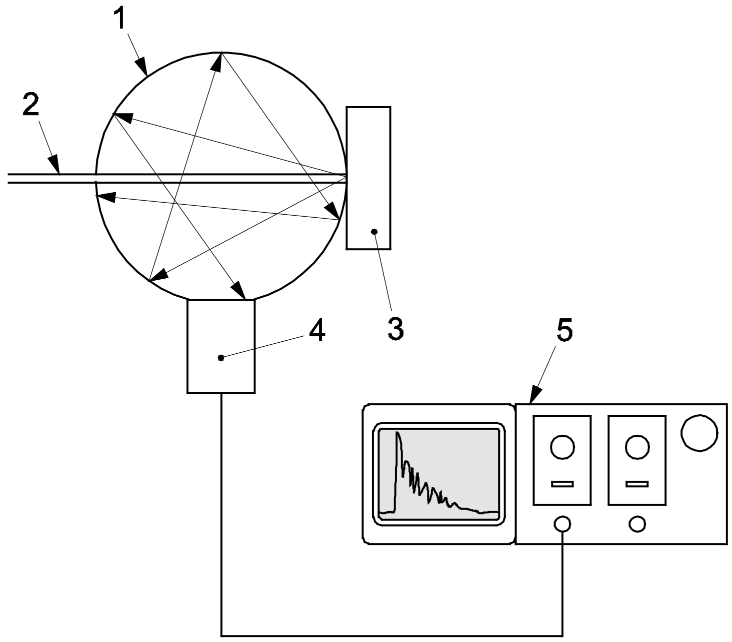


The measurement of the reflectance at the laser wavelength can be carried out with a portable spectrophotometer, if the spectral band of analysis includes that particular wavelength. Otherwise it shall be used an integrating sphere following described and showed in Figure F.1.

This value is useful to measure optical absorption (see Annex B).

The integrating sphere is a cave sphere, internally covered by a totally reflecting varnish at the light wavelength to be examined. The laser beam is incident on the specimen passing through two openings of the integrating sphere.

The fraction of energy diffused by the specimen in all directions is collected by the integrating sphere inside which a distribution of energy is assumed to be homogeneous. An energy measuring apparatus, placed on a third opening, is measuring the energy level obtained. By making the ratio between the diffused energy of the specimen under examination and the one of the specimen with known reflectance, the absolute value of reflectance to be determined.




**Key**

1 integrating sphere

2 laser beam

3 specimen

4 photodiode

5 oscilloscope

**Figure F.1 — Example of apparatus with integrating sphere for reflectance measurement**

# Annex G
(informative)

## Possible harmful effects of laser cleaning on objects

For the purpose of the practical cleaning application of the laser photo-ablation, it is extremely important to evaluate the possible side effects associated to certain duration of laser pulse. For instance, for short pulses it is important to limit the transient pressure on the surface associated to the wave shock formation, because it can cause a photo-mechanical damage (local micro-fragmentation with consequent increase in surface roughness).

The thermal damage is instead the main risk factor with long laser pulses, more than hundreds of microseconds, which are causing the typical effects induced by the continuous laser radiation, like melting or surface vitrification.

Further harmful effects are changes in the hue of a substrate due to laser cleaning, namely for substrates containing iron compounds as impurities. When cleaning polychromed surfaces discoloration due to mineral phase transition are also to be considered as a damage (typical examples of colour changes are well known for cinnabar, lead white and copper carbonates (malachite and azurite).

# Annex H
(informative)

# Health and safety



The health and safety conditions used during the cleaning operation shall be mentioned, as for instance the use of appropriate glasses and a mobile system for a continuous extraction of the vaporised dirt. Information about the emitted waste shall also be documented.

For the analysis of waste material from the cleaning process, emitted particles and gas can be extracted up by a mobile system during the cleaning *in situ* and be analysed in the laboratory afterwards by determination of the emitted total amount, particle size distribution and chemical composition. Taking into account the particle size distribution and the chemical composition, the maximum permissible workplace concentration can be calculated for the volume of a specific working place without any air exchange. Considering a homogeneous distribution of the waste material in the air of the workshop, the time of exposure of the operator can be calculated.

# Bibliography

[1] FOTAKIS C., ANGLOS D. *V, Zafiropulos, S. Georgiou, V. Tornari, Lasers in the Preservation of Cultural Heritage*. Taylor & Francis, 2007

[2] CIE S 017/E:2011, ILV: International Lighting Vocabulary

[3] Cleaning Safely with a Laser in Artwork Conservation — COST G7 Artwork Conservation by Laser. Liverpool: National Museums, 2006

[4] EN 207:2009, *Personal eye-protection equipment — Filters and eye-protectors against laser radiation (laser eye-protectors)*

[5] EN 208:2009, *Personal eye-protection — Eye-protectors for adjustment work on lasers and laser systems (laser adjustment eye-protectors)*

[6] EN 12254:2010, *Screens for laser working places — Safety requirements and testing*

[7] EN ISO 11553-1:2008, *Safety of machinery — Laser processing machines — Part 1: General safety requirements (ISO 11553-1)*

[8] EN 16085:2012, *Conservation of Cultural property — Methodology for sampling from materials of cultural property — General rules*

[9] International Charters

[10] ISO 11553-1, *Safety of machinery — Laser processing machines — Part 1: General safety requirements*

[11] ISO 11553-2, *Safety of machinery — Laser processing machines — Part 2: Safety requirements for hand-held laser processing devices*

[12] M. Cooper, Laser Cleaning in Conservation, An Introduction. Butterworths-Heinemann, 1998

[13] R. Henderson, K. Schulmeister, Laser Safety, CRC Press

[14] R. Pini, C. Baracchini, From the research lab to the restoration yard: practical procedures to evaluate in situ the use of laser cleaning on facades. Laser in the conservation of artworks LACONA 5, Springer, 2003

[15] UNI 11187:2006, *Cultural heritage — Natural and artificial stone — Laser cleaning techniques*

[16] CEN/TS 16163:2014, *Conservation of Cultural Heritage — Guidelines and procedures for choosing appropriate lighting for indoor exhibitions*

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