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Laser Removal of Graffiti

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Final Report

Laser Removal of Graffiti

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New Technology Program

by

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Abstract:
Q-switched Nd:YAG lasers can be used to remove graffiti from concrete and brick walls, as well as unpainted wood and metal surfaces, in a cost-effective manner. More research is needed to develop a process that works on highway signs.

Executive Summary:

We have demonstrated cost-effective removal of graffiti from concrete and brick walls, unpainted wood surfaces and unpainted metal surfaces. We have performed a cost-benefit analysis and predict that laser removal can be competitive in cost with sand and water blasting without environmental hazards and mess. The rather large initial capital equipment outlay needed for laser removal techniques is made up for in terms of reduced labor costs and long-term reliability of lasers. The only thing left before lasers can be used for graffiti removal in the field is the development of a beam delivery system. The result of this year's research effort is the discovery that short pulse Q-switched lasers are much more efficient than CW lasers in removing paint from all surfaces. This is a new and unexpected result. Furthermore, we have developed an engineering model for removal rate which is valid for most laser pulse widths, powers and duty cycles. Although developed for concrete, it is believed that this model can be extended to other material surfaces using Q-switched lasers.

Experiments on highway signs have shown promising results, but more research is needed to determine optimized conditions. Combining laser ablation with chemical removal seems to offer an effective technique. Finally, indications are that oblique incidence may be better than normal incidence operation, but we have not had an opportunity to try such experiments.

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DISCLOSURE/DISCLAIMER

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology Program (AHMCT), within the Department of Mechanical Engineering, Aeronautical and Materials at the University of California, Davis and the Division of New Technology and Materials Research at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not neccessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION and the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The authors wish to thank Monika Kress of Caltrans for her continuous guidance in our project. We wish also to thank Caltrans in Los Angeles, for making it possible for us to obtain high intensity highway signs and to see how painting is done to remove graffiti. Finally, the authors wish to thank Robert Russell for his engineering assistance in latter parts of the project.

INTRODUCTION

The motivation for this research is that the clean-up of graffiti is very costly, time consuming and labor intensive. Because the conventional ways of cleaning graffiti (by chemical, sand blasting, etc.) are not satisfactorily effective and are environmentally unfriendly, we have carried out research to attack this problem by applying the technique of laser ablation.

Laser removal of paint has been used in the past to clean art objects and to strip paint off aircraft and ships. The energy of the laser beam is absorbed by the paint material, raising its temperature to a very high point in a very short time; the surface layer of the material is either evaporated or ablated by means of a laser-induced shock wave. This process of laser ablation has proven the most useful for our application.

Multiple layer ablations can also be useful. The short pulse laser beam emits energy in a very short period of time, faster than the velocity of heat transfer in the material. Thus paint can be removed layer by layer and the underlying surface is not attacked. Varying the energy and the number of pulses can vary the ablation depth, i.e. control the paint removal depth.

The laser pulse width and wavelength can be selected based on the absorption and thermal properties of the graffiti and the substrate to achieve the best possible ablation result, i.e. removing graffiti without damaging the underlying surface.

Our results show that laser removal of graffiti is simpler on unpainted walls because the materials there (concrete, bricks, etc.) are normally insensitive to local heating and small surface disturbances. Surfaces like Plexiglas and highway signs are much more complex. We carried out experiments on graffiti removal from different substrates. Laser systems for most efficiently removing graffiti in terms of average power, pulse width, pulse energy pulse duration, and wavelength have been determined. In the case of removing graffiti from freeway signs, the combination of laser and chemical treatment shows promising advantages over chemical treatment alone in terms of graffiti removal capability, efficiency and labor intensifies.

This final report is a condensation of the three quarterly reports previously written, keeping only the data relevant to our final conclusions. This report also includes the work we did in the last quarter.

CHAPTER 1

BACKGROUND

A. Analysis of Literature

A computer search was used to look for publications in the area of laser stripping of materials and laser removing of paint. We have found several major applications related to this topic, which are summarized as follows:

Removing paint off aircraft

Stripping off the paint and repainting the surface of aircraft is a maintenance procedure required for all air craft normally on an average of every four years. Experiments stripping paint off military aircraft using Nd:YAG and CO_2 lasers were highly successful [1]. Automated systems have been designed for this procedure. However, this technique seems to be limited to the military applications. No commercial systems are available yet. Laser stripping has been found to be environmentally safer than chemical paint removal and to reduce the volume of the waste products (by actually destroying some paint). It can be used on all aircraft substrates.

Cleaning art objects

In the past, many art objects were left damaged or destroyed when cleaned manually with chemicals or water. Physicist John Asmus found in 1972 that lasers could remove the grime and dirt from statues. Lasers can clean paintings, murals, even documents without affecting or harming the artwork in the least.[2] The scientific explanation is that a) the laser pulse destroys the offending material faster than the underlying piece of art can conduct heat; b) in the case of marble sculptures the original surface of the art object highly reflects (does not absorb) the laser beam so that it is not attacked.

Stripping coating off metal wire and other material stripping in semiconductor industry

The computer and microelectronics industries often require stripping that is precise and clean. Lasers are often the tool of preference. An example of the technique is to remove insulating materials off very thin wires to permit electrical conduction of a circuit.[3] Polyurethane, a common coating material, absorbs UV wavelengths very well and has been studied for laser stripping. The wire stripped by a UV laser was completely cleaned, with well defined edges and no surface damage to the wire.

Removing paint from buses, trains, walls, bridges, etc.

No publication has been found that shows a direct study of paint removal from painted surfaces, concrete, highway signs and bricks with lasers. From a research point of view, our work has been original and we have apparently been the first to get first hand information about laser removal of graffiti.

B. Surface Quality Assessment

The criteria we use for surface quality assessment is to compare the laser treated surfaces with the original surfaces not being attacked by graffiti and also with the surfaces treated by conventional methods. We found that graffiti can be cleaned off surfaces of concrete and bricks by the laser technique to almost exactly the same as the original surface, which is much better than being treated by the currently most popular method of painting over. On surfaces such as steel and aluminum, laser removal of paint can completely recover the original metal surface, especially when the original surface is smooth and shiny. We did not compare our results with samples of steel and aluminum treated by conventional methods, but it seems that the laser treated surfaces are highly satisfactory and almost perfect. As for freeway signs, the criteria is to compare the laser treated signs with the signs treated by the chemical SO SAFE Graffiti Remover currently being used in Los Angeles County. For graffiti signs made by solvent based paint and when the paint is fresh, SO SAFE works relatively well and shows a satisfactory result. But these surfaces are a small number and require absolutely immediate attention. For other kinds of paint, and especially when the paint has been out there for longer than several days, SO SAFE is not able to take the paint off and the combination of laser and SO SAFE appears to be an advantage.

CHAPTER 2

PRELIMINARY EXPERIMENTS

We started our experiments using the two most powerful lasers we have, a cw (continuous wave) CO_2 laser and a pulsed Nd:YAG laser. We showed that an intense laser beam efficiently removes paint off concrete. The efficiency (cm^2/min.) of paint removal is determined by the average power and pulse width of the laser under the condition that the laser beam intensity is above the threshold for the paint vaporization. The data we obtained is shown here.

A. Spray Paint Removal by CO_2 Laser Beam

The CO_2 laser used in our experiment gives a cw output beam with maximum power of 400 W, near Gaussian spatial profile, ~ 10 mrad beam divergence, and beam size of 1 cm in diameter. An experiment of paint removal was performed by exposing the sample (painted block) to the laser beam and recording the time duration after which paint is completely removed. The paint used in these measurements is glossy black spray paint made by KRYLON and the thickness of the paint layer is about 20 μm on most of the samples. The block material is concrete. Measurements were taken with a beam size of about 1 cm at different beam intensities. The recorded time interval is normalized to what is needed for removing paint in an area of 1 cm^2 for measurements with different beam sizes. Our results are shown in Fig. 1a. The squares are the experimental data, connected by a thick solid line, and the thin solid line is the fit by a power function described in the graph. According to the fit, the increase of stripping efficiency slows down as the beam intensity reaches 1 kW/cm^2.

An excellent model to explain the paint removal time from concrete using a CW laser is that it varies inversely with the input CW intensity. This is shown in Fig. 1b. This behavior means that, within the regime of our experiments, successful paint removal requires a certain total energy density.

B. Spray Paint Removal by Nd:YAG Laser Beam

The pulsed Nd:YAG laser can be operated in either free-running mode or Q-switched mode. In the Q-switched mode, the laser is capable of giving 1 J/pulse at 1-10 Hz with a pulse width of 15 ns. In the free-running mode, the pulse width is about 100 μs with the same repetition rate and similar pulse energy to the Q-switched mode. However, the 100 μs pulse consists of a series of ~ 1μs pulses under its envelope due to relaxation oscillation in a pulsed laser. Laser removal was measured using the same samples as were used for CO_2 laser measurements, i.e. the same paint and the same substrate. In the Q-switched mode, measurements were taken in terms of the number of laser shots needed to remove paint using a beam size of 0.8 cm in diameter at various beam intensities. Then the actual exposure time (actual pulse-on time) of the beam on the paint is obtained by the product of the pulse width and the number of shots. The result is shown in Fig. 2a, plotted as a function of beam intensity. Again, the experimental data is normalized for removing paint off an area of 1 cm^2. We can see that the actual exposure time (actual pulse-on time) required is very short, due to the very high intensity of the pulse. The low duty cycle must be included to determine the operation time which would be required in practice.

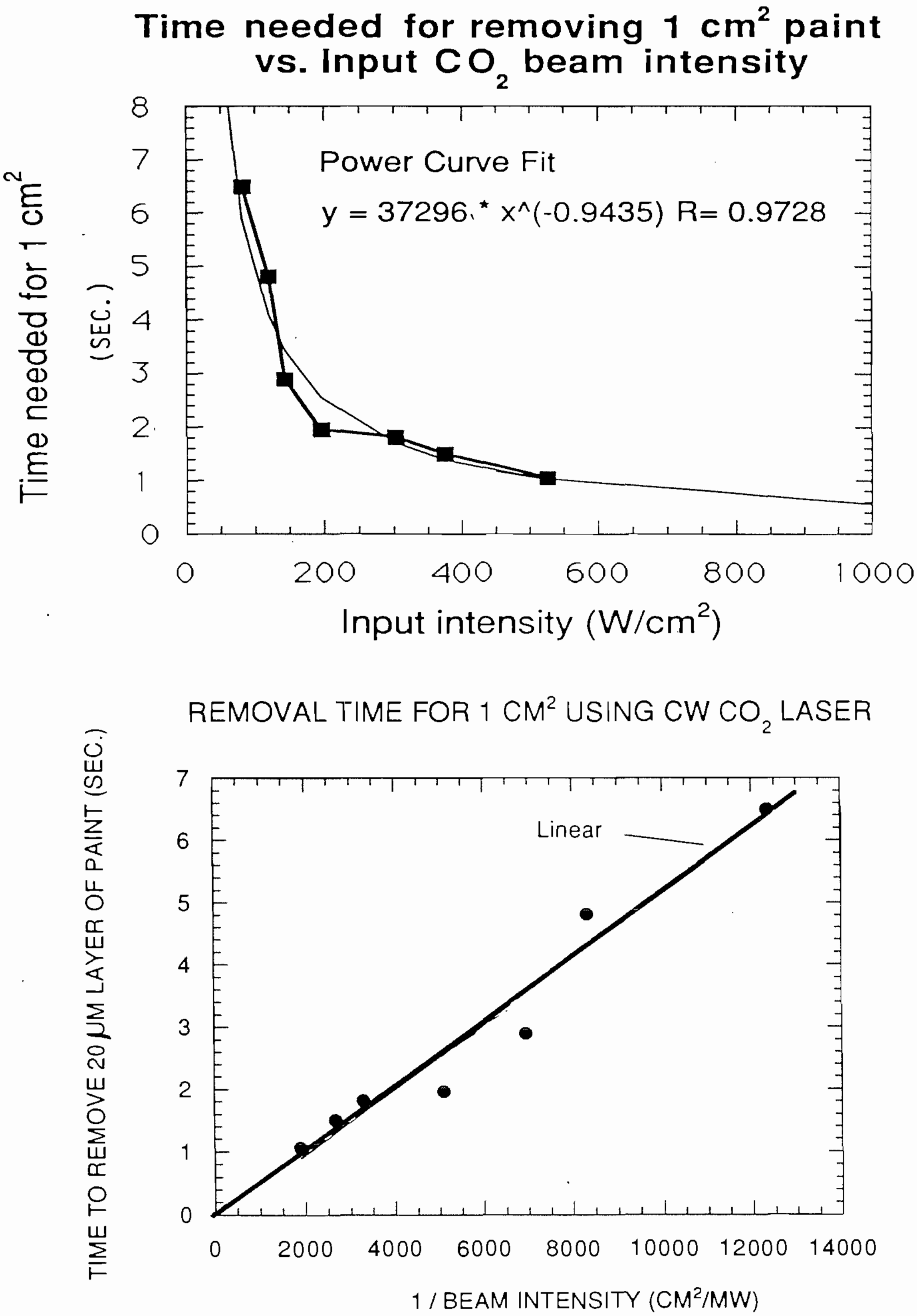
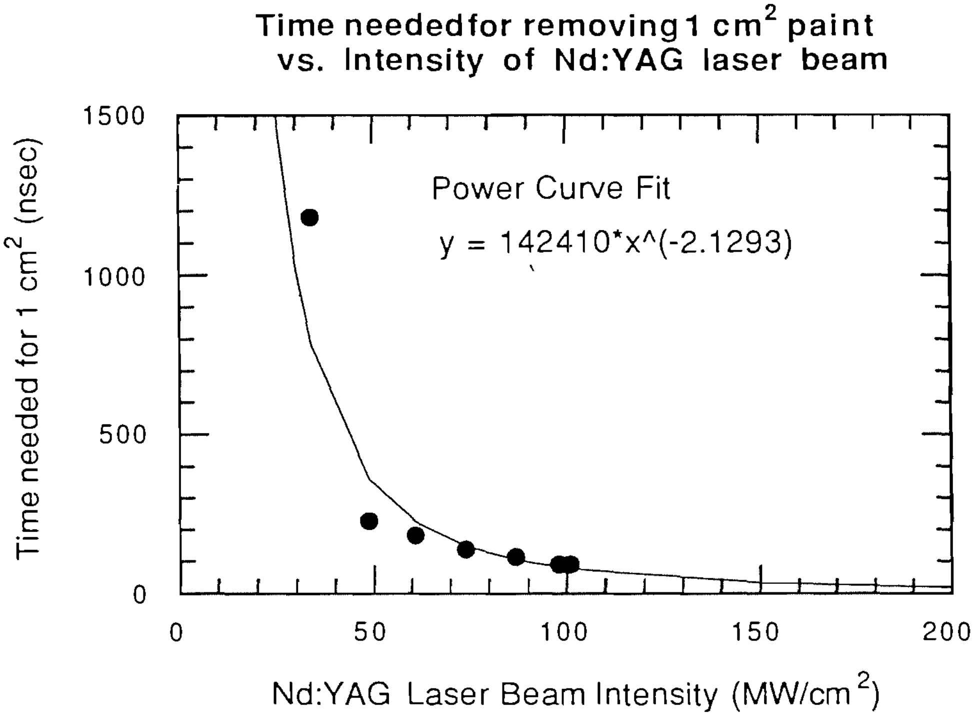


Figure 1. Time needed for CO_2 laser to remove 1 cm^2 paint from concrete block; a) as a function of beam intensity; b) as a function of inverse intensity. The squares and circles are experimental data points. The thin curves are theoretical fits. In (a) the fit is to the power law shown, and in (b) the fit is linear.



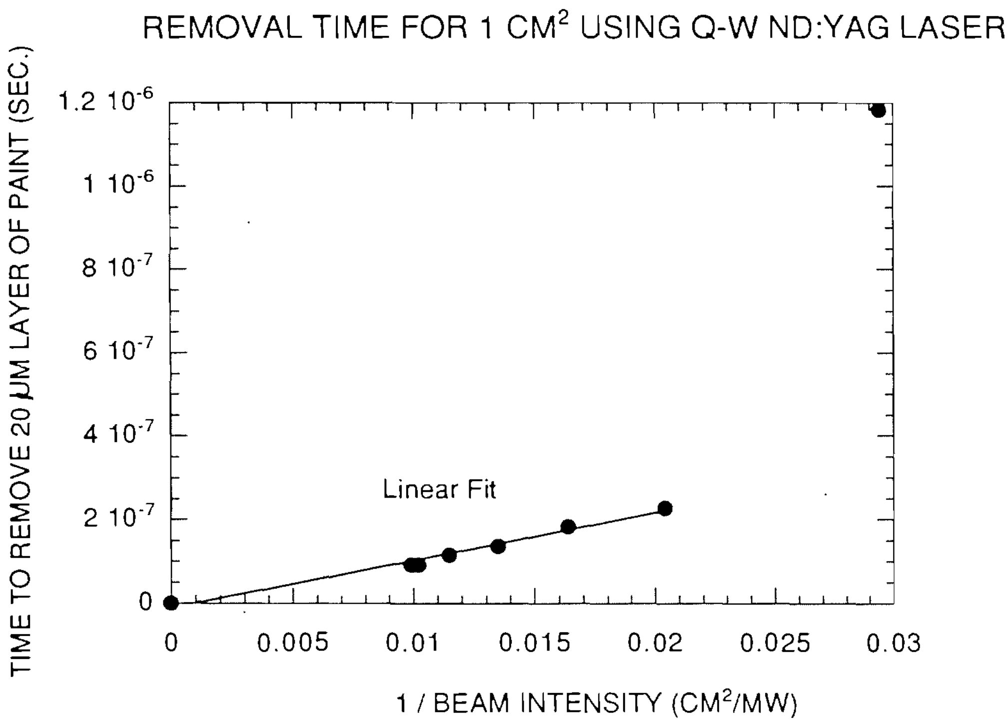


Figure 2. Exposure time (actual pulse-on time) needed for YAG laser to remove 1 cm^2 paint from concrete block; a) as a function of intensity; b) as a function of inverse intensity. The circles are the experimental results; the lines are theoretical fits. In (a) the fit is to a power law, as shown, and in (b) the fit is linear, in the regime of intensity higher than threshold (inverse beam intensity below the threshhold).

Figure 2b shows the paint removal time using the Q-switched YAG laser as a function of the inverse beam intensity. It can be seen that with the Q-switched laser there is an apparent threshold for paint removal. This is apparently because the removal is ablative and not thermal. At intensities higher than the threshold intensity of 50 MW/cm^2 (inverse intensity lower than the threshold) is achieved, the time for paint removal is apparently inversely proportional to laser intensity, as it was in the case of the CO_2 laser. That is, above the threshold, there is a certain required energy density to remove paint.

In the free-running mode, the beam intensity is low (due to the broad pulsewidth) and the laser beam could not remove the paint but only make some visible marks. In order to compare free-running and Q-switched lasers, we therefore must compare the conditions when either just makes a mark. This shown in Fig. 3. It can be seen that the pulse-on time is much longer for free-running lasers. However, since the intensity is also much lower, this result seems to still fit a power law, with an exponent of -1.6, rather of -1.

Fig. 2 and Fig. 3 confirm that sufficient intensity must be achieved to efficiently mark (or remove) paint. For the same energy per pulse, the shorter the pulse width, the more efficient the paint removal (until the pulse gets very short). We anticipate that the efficiency will stop increasing when the pulse duration is shorter than some characteristic time, if the energy per pulse remains constant.

We performed a simple experiment with another Nd:YAG laser operating in the cw pumped mode and in the cw mode-locked mode. The mode-locked mode gives a series of very short pulses (pulse duration of 0.1 ns) at a repetition rate of 76 MHz (13 ns between pulses), with an average power the same as in the cw mode. There was no difference in removing paint shown between these two modes of operation. We conclude that shortening the pulse width for the particular paint (KRYLON gloss black) and substrate (concrete block) we used in this experiment, down to 0.1 ns from 13 ns, does not improve the result. The characteristic shortest effective pulse width may differ for each individual paint, but we do not expect more than a factor of 10 difference for all spray paint.

C. Comparison of Using the CO_2 and the Nd:YAG Laser

Gathering the data from CO_2 laser measurements and Nd:YAG laser measurements together, we plotted graphs shown in Fig. 4 and Fig. 5. Fig. 4 shows the result in absolute exposure time (actual pulse-on time), and Fig. 5 shows the result in total elapsed time (at 10 pps for the pulsed Nd:YAG laser). We obtain the following conclusions from these graphs:

a) a pulsed laser beam is more efficient in terms of the total time the paint needs to be exposed to the beam due to the higher intensity of the pulsed beam

b) a pulsed laser is not necessarily more efficient than a cw laser when counting the total elapsed time (at 10 pps for the pulsed Nd:YAG laser) of the process, due to the very low repetition rate of the very high power pulsed lasers.

From Fig. 4 and Fig. 5 we derived Fig. 6, in which the power curve fit function of the experimental data is plotted on a logarithm scale and for various numbers of the pulse repetition rate times pulse width. This quantity is the fraction on-time of the laser beam. From this graph, we can predict paint removal efficiency for different average power, achieved by varying pulse width and repetition rate. Other the other hand, we can choose a more efficient laser, depending upon its average power, pulse width and repetition rate. Although this graph is based on data with two different laser wavelengths, we do not expect that the result will be differ much, since

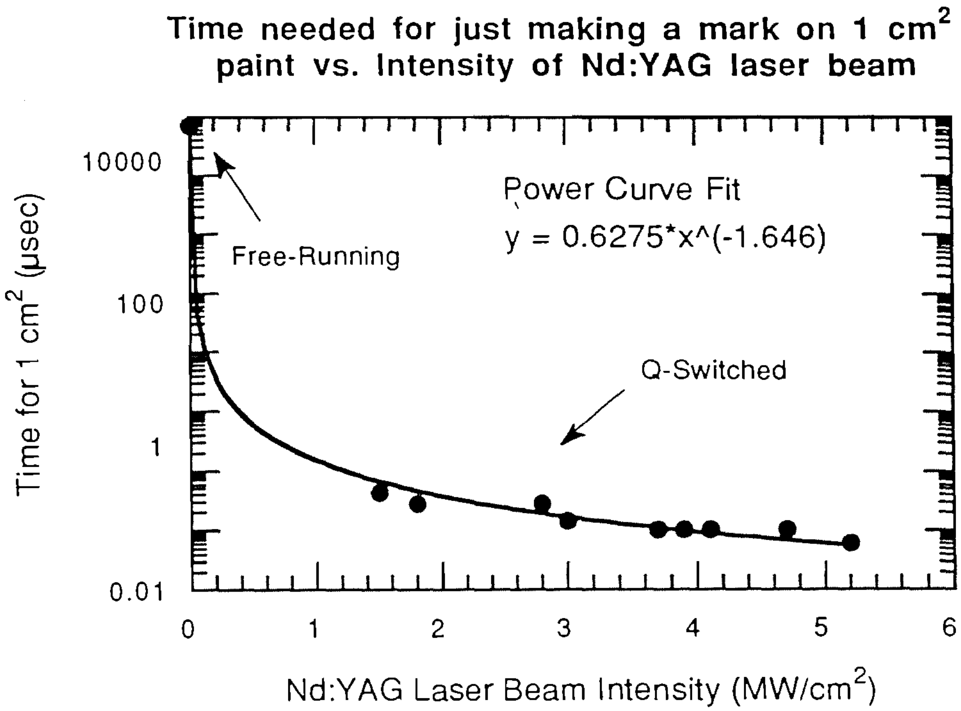


Fig. 3 Actual exposure time (actual pulse-on time) required for just making a mark on paint as a function of beam intensity using a pulsed Nd:YAG laser in free-running mode and in Q-switched mode.

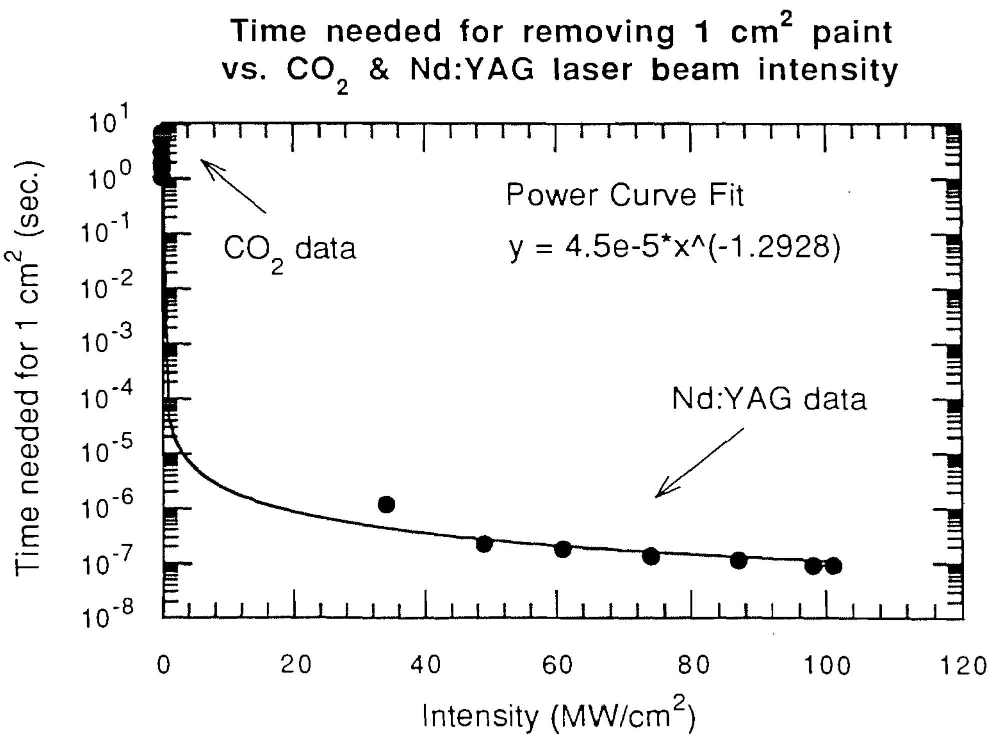


Fig. 4 Comparison of paint removal efficiency between the cw CO_2 laser and the Q-switched Nd:YAG laser in terms of actual exposure time (actual pulse-on time).

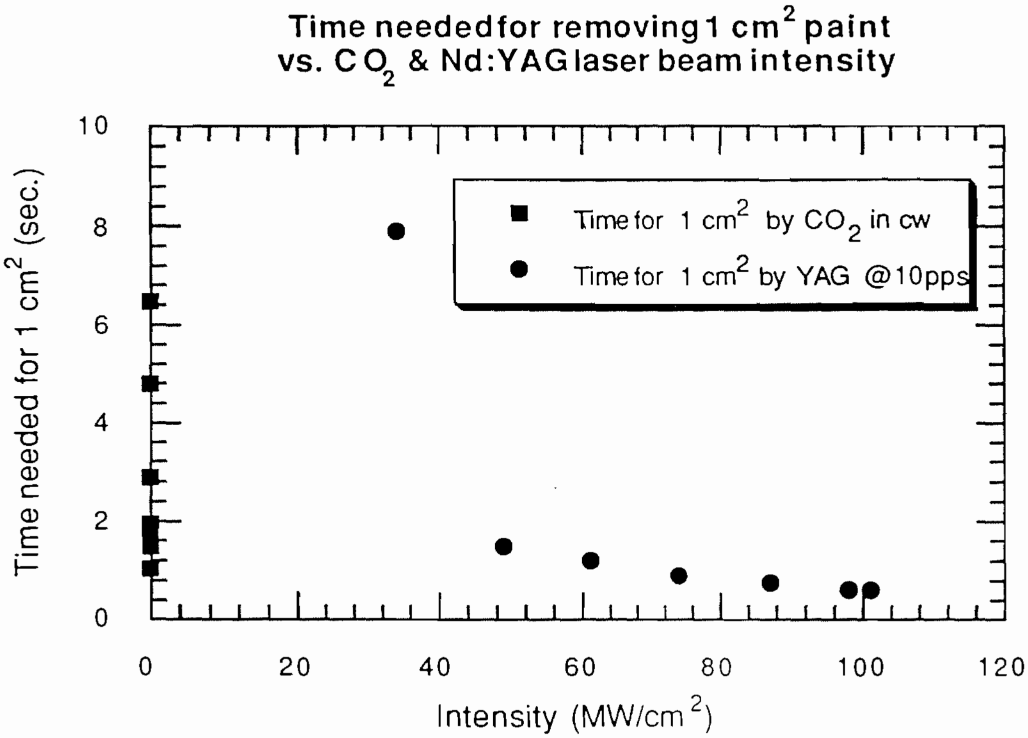


Fig. 5 Comparison of paint removal efficiency between the cw CO_2 laser and the Q-switched Nd:YAG laser in terms of total elapsed time (at 10 pps for the pulsed Nd:YAG laser).

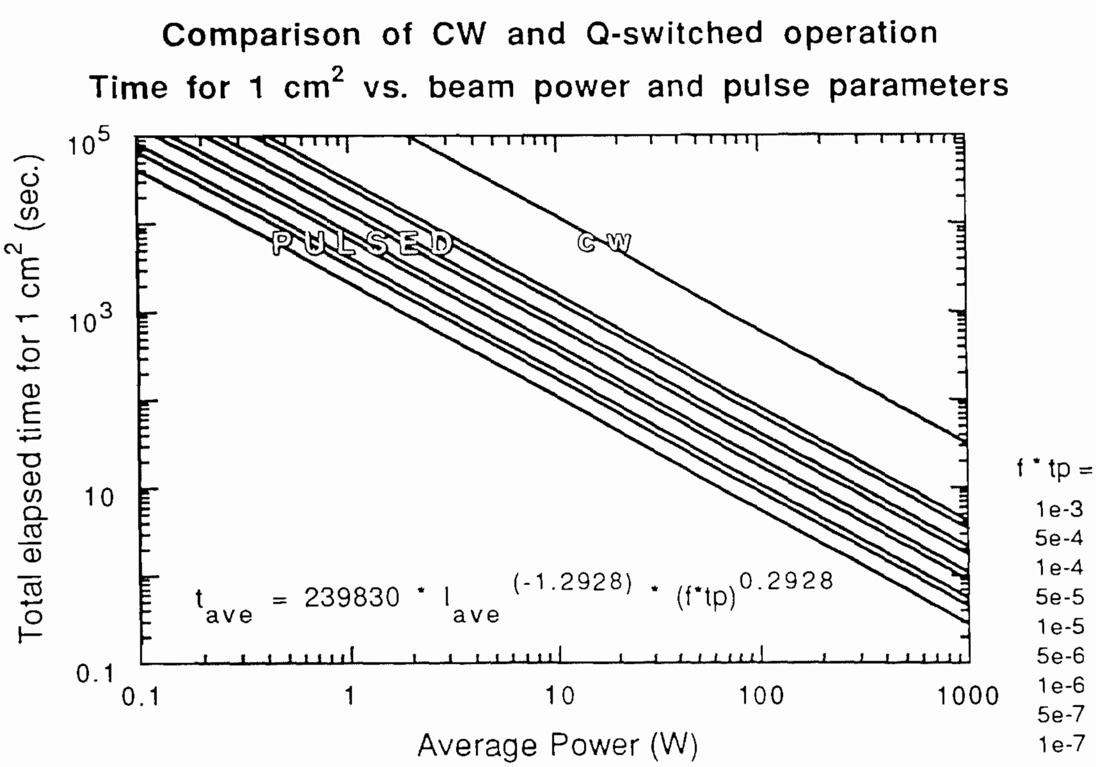


Fig. 6 Total elapsed time required for removing paint of 1 cm^2 as a function of average power at various number of f*tp, where f is the frequency (repetition rate) of the laser pulses, and tp is the pulse width.

we did not observe a strong wavelength dependence of paint absorption in our paint spectrum measurements.

D. Absorption Spectra of Spray Paints

We found that the absorption did not vary appreciably for many different spray paints. This section describes that experiment.

Transmission spectra of different colors of spray paint, which are commonly used in making graffiti, were measured by a Cary (spectro-photometer) from VARIAN. The following paint samples were measured in wavelength range from 300 nm to 3 μm : True Blue, Gardena Green, Yubba Yellow, Bright Yellow, Popsicle Orange, Banner Red, Pasenda Pink, Bright Silver, Gloss Black, Flat Black, and Ultra Flat Black from KRYLON, Flat Black from ILLINOIS BRONZE, and Glossy Black from GREAT DRY. Except for a large loss around the wavelength of the color of the paint due to its high reflection, transmission spectra showed no other peaks or significant structures but indicated a slow increase in transmission as wavelength increases. Spectra of black paint did not show any structure. The high loss in transmission around the wavelength of the paint color is due to the high reflection of light at that color. Other than this reflection, we think that the reflection of the paint in general is very weakly wavelength dependent. In addition, scattering of the paint is also small compared to transmission. Therefore, we assume that the total energy of the light incident on the paint sample is the sum of the absorbed energy and transmitted energy in general. Under this assumption, the transmission spectra can be directly related to the absorption spectra. Therefore, the absorption spectra also have no significant features similar to the transmission spectra but the absorption coefficient should slowly decrease as the wavelength increases. In the case of colored paint, we think that it would be unwise or inefficient to use a laser with the wavelength of that color.

E. Comments

During the course of our preliminary investigation, we realized that a successful laser graffiti system required understanding materials, laser systems, beam delivery means, and image processing (to achieve automated systems). Some brief comments as to topics we considered in our research follow. Later sections of this report will describe our conclusions regarding these comments :

Materials studies: The study of laser ablation of spray paint is essentially the study of the paint and substrate materials response to intense laser beam irradiation. For our application, paint needs to be removed and the substrate should not be affected or damaged. The laser beam burns off and evaporates or ablates a thin layer of various materials as long as the material has some absorption of the laser beam and the laser energy is sufficient high. The question is, what is the preferable laser wavelength, energy density, pulse width, and pulse repetition rate for removing graffiti? How does it depend on thickness of paint, or on the substrate such as bricks, metals, etc.? These parameters must be determined for the most efficient paint removal, as described in the next chapter.

Laser systems: A decision as to whether to use commercial lasers or to design a suitable laser system must be made in order to reach the final goal. Chapter 6 describes our analysis of commercial lasers.

Beam delivery means: A laser which works the best in the laboratory is not necessarily the best for working in the field. One important aspect is to deliver the beam from the laser to the target in an enclosed environment, due to the danger of exposing personnel to a laser beam. Optical fibers have been commonly used for beam guiding and beam delivery purposes. The Nd:YAG laser beam can be easily coupled into an optical fiber or optical fiber bundle as long as the beam intensity is under the damage threshold of the fiber material. However, this is in contradiction to the advantage of using a high intensity beam for higher efficiency of paint removal. On the other hand, there is not an easy way to guide and deliver a CO_2 laser beam in a flexible path. Normal glass or plastic optical fibers have very high absorption at the CO_2 laser wavelength. Therefore, good beam delivery systems for different lasers need to be sought. We have taken into consideration the need for good beam delivery systems in recommending that the Nd:YAG laser is the most practical laser for consideration.

Image processing: In order to automate the entire process of removing paint, an imaging technique can be used to determine the stripping results of the surface. The laser beam, therefore, can be automated to scan over a large target area according to the results at each spot. Further research in this area is beyond the level of the present program. However, it is important to keep this possibility in mind when envisioning working systems.

CHAPTER 3

EFFICIENCY OF LASER REMOVAL OF PAINT

The quantitative results presented in this section are based on measurements using KRYLON Quick Dry Gloss Black paint of ~ 14 μm thick on concrete block (cinder block). While the exact numbers will be different for different paint and substrate, the characteristic paint removal properties derived in this section are general.

A. Paint Removal Efficiency Using CO_2, Nd:YAG, Excimer, and Er:YAG Lasers

Based on the preliminary experimental results in III, using a cw CO_2 laser and a pulsed Nd:YAG laser, we concluded that the efficiency for removing paint strongly depends on the intensity (i.e. fluence per unit time - Joules/second/cm^2) of the laser beam which ablates the paint. In other words, the time period required for the laser beam exposure to remove the paint target strongly depends on the intensity of the beam. We interpret this time interval required for removing paint of a given thickness as the paint removal efficiency. As shown experimentally, the paint removal efficiency increases as the beam intensity increases. Our objective is to obtain a mathematical description for the behavior of the paint removal efficiency as a function of the beam intensity.

In order to obtain data over a wide range of beam intensity, multiple lasers with different pulse width and energy per pulse were used. With different lasers, we were able to achieve different intensity while the beam could still be maintained to a reasonable size, (in order for us to examine the surface quality of the laser ablation) and still ensure that the fluence (i.e. energy density - energy per unit area - Joules/cm^2) was still above the threshold for removing paint. In paint removal, there is a fluence threshold below which the laser beam is not able to remove the paint even if the intensity can be very high.

The lasers used in the experiment for measuring the efficiency are Nd:YAG lasers at 1.06 μm with pulse widths 2.5 ns, 8 ns, and 15 ns; excimer XeCl laser at 308 nm with pulse width 130 ns; Er:YAG laser at 2.94 μm with pulse width 1.2 μs; and CO_2 laser at 10.6 μm run cw. The sample is prepared with KRYLON Quick Dry Gloss Black paint on the substrate of concrete block. The thickness of the paint is 14 μm (with an error of 2 μm), enough to be opaque and about the typical thickness of graffiti tags. Each laser was set at a constant energy/pulse. In the case of the cw CO_2 laser, the energy per unit time was set at a constant. Then the beam size was either reduced or enlarged to obtain different fluence. The intensity is given by the fluence divided by the pulse width. For pulsed operation, number of shots required for removing the paint was recorded. The product of the number of the shots and the pulse width was taken as the absolute exposure time required for removing paint of ~ 14 μm thick.

The measured results plotted as the total absolute exposure time vs. the beam intensity are shown in Fig. 7. Although the measurements were not highly accurate (due to the error in examining the completeness of paint ablation with human eyes), the results show a very consistent characteristic as to how the removal efficiency depends on the beam intensity. For this reason, we will use the curve fit function of this data to derive some general results which we discuss below. At the high intensity end of the graph, there is some overlap of data points, which indicates a small difference in efficiency at different intensities. This result is related to the

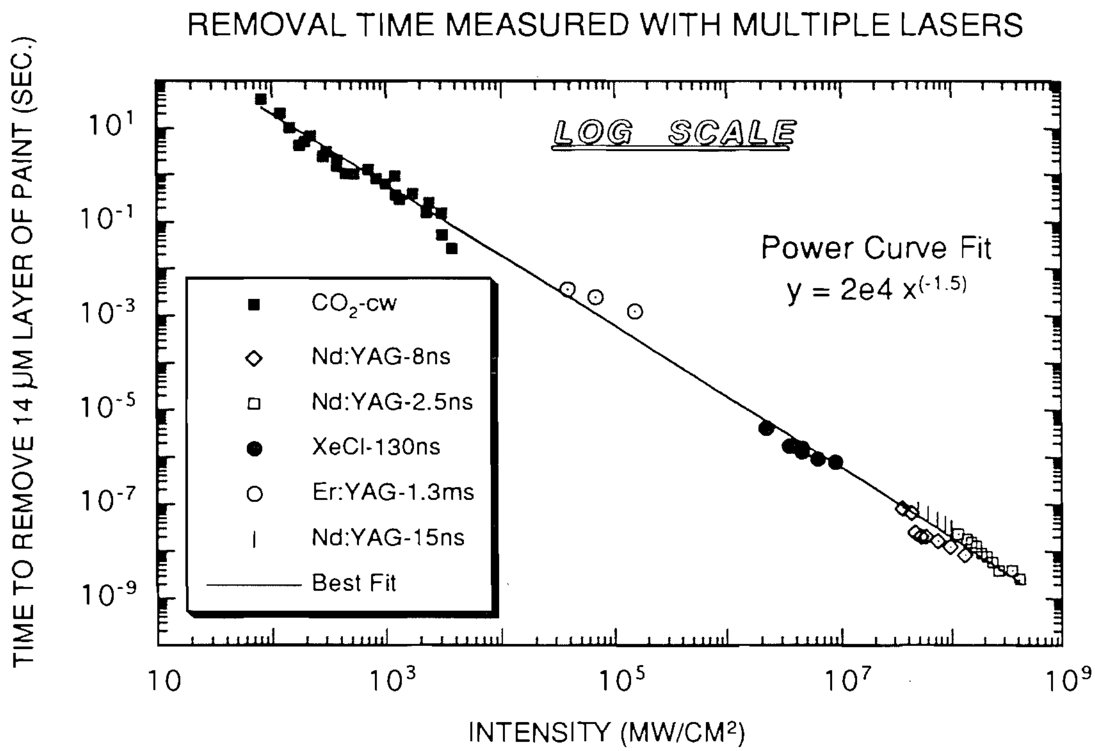


Figure 7. Exposure time required to removed 14 mm of paint from concrete, measured with multiple lasers, listed in the insert. All data fit a power law, shown on the graph.

characteristic pulse width we mentioned in Chapter 2 and will be discussed further with more analysis below.

B. Efficiency as a Function of Beam Size and Pulse Width

There are two questions we answer here: i) assuming a given amount of energy uniformly distributed in one second (constant power), how many cm^2 of paint can be removed with this amount of energy using different beam sizes? ii) assuming a given amount of energy uniformly distributed in one cm^2 (constant fluence), how many cm^2 of paint can be removed with this amount of energy using different total pulse widths (the pulse width is the time period which contains the total amount of the energy)? We evaluate the total area of paint which can be removed in both of these cases based on the curve fit function obtained from the data shown in Fig. 7, i.e.

(Time required to remove ~ 14 μm paint off concrete block)

$$\approx 2 \times 10^4 \times (\text{Beam intensity in W/cm}^2)^{(-1.5)} \qquad (1)$$

Since a larger area of paint which can be removed in these cases is equivalent to a higher efficiency of the paint removal process, we calculate the total area as the indication of efficiency.

For the first question, assuming a fixed amount of energy, the total area of paint removed in 1 sec. can be calculated as follows:

$$\text{Total Area} = \frac{\text{One Second}}{\text{Time for the Beam Area}} \times \text{Beam Area}$$

$$= \frac{\text{One Second}}{2 \times 10^4 \times \left[\frac{\text{Total Energy}}{(\text{One Second})\ (\textit{Beam Area})}\right]^{(-1.5)}} \times \textit{Beam Area}$$

where the *Beam Area* is the variable, and Time for the Beam Area is the time required for removing paint of the area of the beam. Fig. 8 illustrates the behavior of the total area removable (i.e. efficiency) vs. beam size as the answer to the first question, assuming the total energy is 1000 J uniformly distributed in 1 second. Clearly the beam area should be as small as is practical. The could be done with a focused, raster scanned system.

For the second question, considering the pulse width dependence of the fluence per unit time, the total area of removed paint can be calculated as follows:

$$\text{Total Area} = \frac{\text{Pulse Width}}{\text{Time for the One cm}^2} \times \text{One cm}^2$$

$$= \frac{\textit{Pulse Width}}{2 \times 10^4 \times \left[\frac{\text{Total Energy}}{(\text{One cm}^2)\ (\textit{Pulse Width})}\right]^{(-1.5)}} \times \text{One cm}^2$$

where the *Pulse Width* is the variable, and Time for the One cm^2 is the time required for removing paint of the area of the beam, i.e. 1 cm^2 in this case. Fig. 9 illustrates the behavior of the total area removable (i.e. efficiency) vs. pulse width as the answer to the second question,

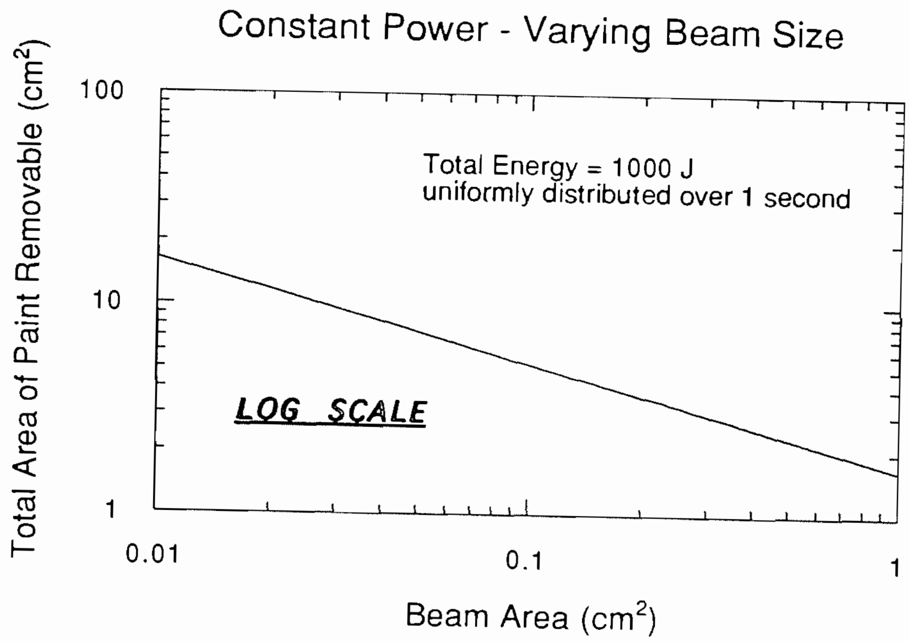


Figure 8. Total area removable vs. beam size, assuming the total energy is 1000 J uniformly distributed in time over 1 second.

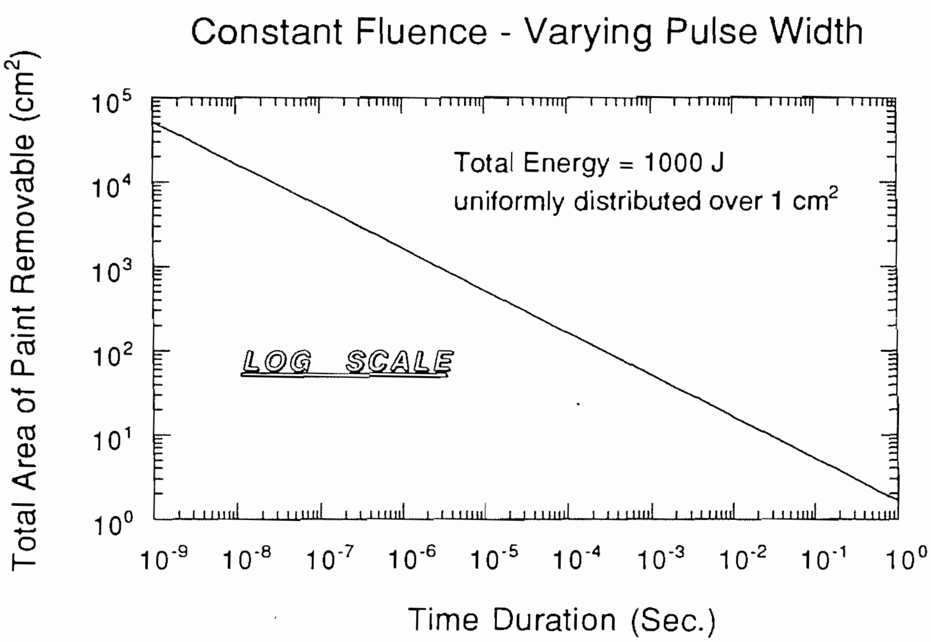


Figure 9. Total area removable (i.e. efficiency) vs. pulse width, assuming the total energy is 1000 J uniformly distributed in 1 cm^2 (also assuming square pulse shape).

assuming the total energy is 1000 J uniformly distributed in 1 cm^2 and the pulse shape is square. Clearly the shorter the pulse the better.

From the above two calculations, we conclude that we should try to focus the beam to a small area and reduce the pulse width without sacrificing the total energy whenever we can to obtain the highest efficiency for removing paint.

C. Characteristics of Paint Removal Efficiency in Terms of Laser Parameters

Although the efficiency of paint removal increases as the beam size or pulse width decreases, there is a limit to how small we should focus the beam and how short the pulse width can be without reducing the total energy. The former issue is related to the ablation quality. The spatial profile of a laser beam is often Gaussian. When it is focused to a small spot, the energy density increases very quickly from the edge to the center of the beam. This makes removing paint uniformly over the beam area very difficult and tends to burn the middle of the beam area. In other words, it is more difficult to control the paint ablation quality when working on a large area. For the latter issue of reducing the pulse width without sacrificing average power, it is often a laser problem. Due to the properties of laser media, having high energy per pulse and short pulse width normally results in a reduced average power. However, the pulsed mode may still be more energy efficient than the cw mode when using a laser for removing paint. Therefore, we have to consider all laser parameters such as pulse width, energy per pulse and pulse repetition rate when designing a laser to operate in a pulsed mode instead of in the cw mode.

Assuming a practically reasonable beam area of 1 μm^2, we illustrate the paint removal efficiency as a function of average power at different pulse width and repetition rate in Fig. 10. As with Fig. 6, this plot is based on the curve fit function (1). Here, however, the average of the results from all lasers is included. The calculation is shown as follows. Assume an average power, Po, a beam size with area A, a pulse width tp, a pulse repetition rate f, then the beam intensity during the pulse-on time is given by $I = \frac{Po}{ftpA}$. Using the curve fit function (1), we obtain the total pulse-on time required for removing paint of ~ 14 μm thick in a beam area of A:

$$\Delta t_{abs} = 2 \times 10^4 \left(\frac{Po}{ftpA}\right)^{-3/2},$$

and the total elapsed time for removing paint of ~ 14 μm thick in a beam area of A:

$$\Delta t_{total\ elapsed} = \frac{\Delta t_{abs}}{ftp} = 2 \times 10^4 \left(\frac{Po}{A}\right)^{-3/2} (ftp)^{1/2}.$$

We then assume a beam area of 1 mm^2 and scale Δt_{total} to a target area of 1 m^2 to obtain

$$\Delta t_{total\ for\ 1\ m^2} = 2 \times 10^4 \left(\frac{Po}{1\ mm^2}\right)^{-3/2} (ftp)^{1/2} \left(\frac{1m^2}{1\ mm^2}\right),$$

which is illustrated in Fig. 10. This graph provides us a guideline on how to choose laser parameters, such as average power, pulse width, and pulse repetition rate, to obtain the highest energy efficiency for removing paint. It is expected that this curve is valid for all lasers, for removing 14 μm paint from concrete.

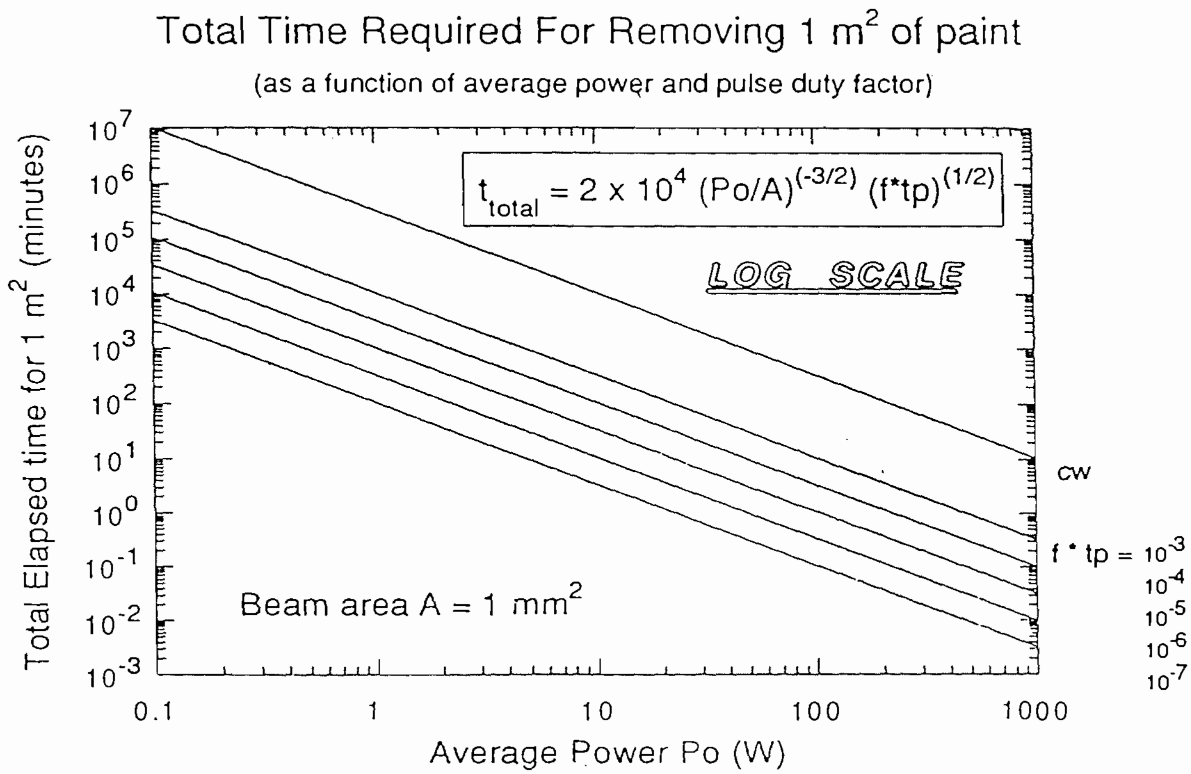


Figure 10. Total elapsed time required for removing paint from 1 cm^2 as a function of average power at various values of duty cycle, f*tp, where f is the repetition rate of the laser pulses and tp is the pulse width. This curve is based on the data in Fig. 7, assuming a beam area of 1 mm^2. The power law which was used to generate these curves is shown in the inset.

Figure 10 has included all major laser parameters except for wavelength. During the derivation of (1), we did not consider laser wavelength dependencies (we do not expect any because of the use of black paint). Furthermore, our measurements of the paint absorption spectrum of colored paints is relatively flat, without any distinctive features. Finally, our measurements of paint removal efficiency (Fig. 7) show a very consistent characteristic even though the data was collected using lasers with a large wavelength difference (from UV to far IR). Basically, we do not think the paint removal efficiency is very much wavelength dependent.

Another factor not included in Fig. 10 is the possibility of damaging the substrate. Our measurements showed that the concrete block studied here damaged at an intensity I > 400 MW/cm^2. Chapter 6 below contains a discussion of how to analyze the results shown in Fig. 10 while taking this factor into account.

CHAPTER 4

MATERIAL STUDIES

A. Characteristic Pulse Width

As discussed above, we believe that there exists a characteristic pulse width related to the efficiency of paint removal. When the pulse duration is longer than this characteristic pulse width, the paint removal efficiency is higher at higher intensity. When the pulse duration is shorter than this characteristic pulse width, however, the important parameter is not the peak intensity any more but the total energy of the pulse. Assuming that the paint and its substrate have a particular response time to the laser beam, this response time is one of the factors contributing to the characteristic pulse width. For example, increasing the intensity by narrowing the pulse width (while keeping the energy/pulse constant) will not increase the paint removal efficiency when the pulse width is shorter than this material response time. Therefore, the characteristic pulse width is associated with the material response time. It can also be associated with the concept of the threshold in fluence for paint removal.

To see this effect experimentally, we measured the paint removal efficiency vs. pulse fluence using lasers with different pulse width. Figure 11 shows the result. There is little difference in paint removal efficiency between the 2.5 ns and 8 ns pulses, although the beam intensities of 2.5 ns pulses are more than 3 times higher than the beam intensities of 8 ns pulses. However, there is a large difference in paint removal efficiency between the 8 ns and 130 ns pulses when the energy/pulse is the same. The data for pulse width of 15 ns was taken with a different sample (the same paint and the same substrate but the paint thickness is somewhat different), so we do not want to use this data here to determine the characteristic pulse width but only to show it for reference. In any event, we can at least say that the characteristic pulse width in this case for the particular paint and substrate as described in Chapter 3 is between 8 ns and 130 ns.

B. Paint Removal From Different Substrates

In the preliminary experiments, we noticed some differences in paint removal efficiency while the paint was on different substrates. The substrate material affects the paint removal efficacy, presumably due to the thermal conductivity, surface reflection, and other parameters of the material. In the following, we discuss the difference in paint removal from various substrates due to the thermal conductivity of the substrate.

Efficacy of removing paint from different substrates, such as brick, concrete, glass, and metals, were qualitatively examined using a cw CO_2 laser and a pulsed Nd:YAG laser. As a result, using the cw CO_2 laser, the relative paint removal efficiency is ordered for various substrate materials as (from high to low):

fire brick -> red brick -> concrete block (cinder block) -> steel -> aluminum.

We used the same power for different substrates, but varied the intensity by varying the beam size. In the case of fire brick, the beam was expanded and in the case of aluminum, the beam had to be focused to a small spot. The difference in the beam diameter from fire brick to aluminum is about one order of magnitude. Paint removal from substrates of wood and Plexiglas was unsuccessful using the cw laser. The laser beam burned the substrate at the same time as

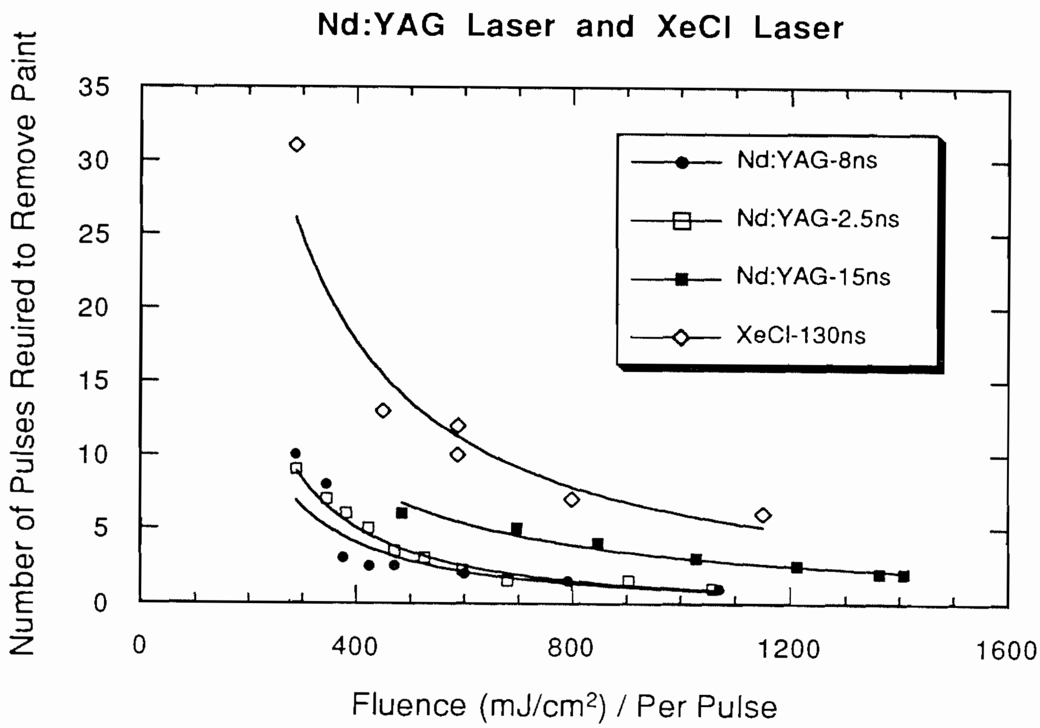


Figure 11. Measurement of paint removal efficiency vs. pulse fluence using different lasers with different pulse widths. Paint removal efficiency is defined as the number of pulses required to remove the paint, normalized to the same fluence per pulse.

removing the paint. The paint used for this test was the KRYLON Quick Dry Gloss Black and the thickness of the paint on each substrate may not be the same but is similar.

Using the pulsed Q-switched 8 ns Nd:YAG laser, however, there was almost no difference between different substrates. An unfocused beam (~ 0.7 cm diameter) was used and number of shots required to remove paint was counted for each substrate. It took 2 - 2.5 shots for all the substrates, which included fire brick, red brick, concrete block, steel, aluminum, and wood. What we mean by 2.5 shots is that two shots are a little bit short and three shots are a little bit too much. The samples used here are the same pieces as used in the CO_2 laser test as described in the last paragraph. Paint removal only worked with longer pulses (~ 100 μs) for glass and was unsuccessful for producing a smooth surface on Plexiglas.

What we learned from these two tests is the importance of the thermal conductivity of the substrate material. While using the cw CO_2 laser, it takes less time to remove paint from materials (substrates) with low thermal conductivity than from materials with high thermal conductivity. This is expected, because the fast heat diffusion in good thermal conductors acts as an energy loss for heating up and eventually burning off the paint. In this regard, whether the laser beam is cw or in very short pulses should play a very important role. If the pulse duration is shorter than the velocity of heat transfer in the paint, then the heat will basically not get to the substrate before the paint is burned off. This is exactly what we have seen in the test using the Q-switched Nd:YAG laser - the substrate did not affect the paint removal efficiency when the pulse width was 8 ns.

We have also examined a situation where paint is to be removed from a steel substrate (relatively good thermal conductor). Compared to the results on concrete, the difference between using the cw CO_2 laser and using the pulsed Nd:YAG laser is much bigger. The pulsed Q-switched laser beam removed the paint of ~ 20 μm layer at the first shot, but the cw laser required several seconds to achieve the same result. The total energy consumed to remove the paint is several orders of magnitude less using the pulsed Nd:YAG laser than using the cw CO_2 laser. In the extreme case of an aluminum substrate, the pulsed laser beam removed the paint in one shot but the cw beam would not even make a mark for a long time.

C. Efficacy of Removing Paint of Different Colors and Different Brands

In order to find out if there is a big difference in removing paint of different colors and different brands, we tested six colors of paint by KRYLON and black paint of three brands with our cw CO_2 laser and pulsed Q-switched Nd:YAG laser. We only did the measurements in a qualitative way, which is to compare the paint removal speed among the different kinds of paint.

While using the CO_2 laser, we expanded the beam to a size of 1.5 cm in diameter, used a power of ~ 300 W, and measured the beam-on time duration required to remove each kind of paint. The result is listed below in the order from fast to slow:

		Time Duration
KRYLON	True Blue	Fastest (~ 1 second)
KRYLON	Banner Red	.
KRYLON	Gardena Green	.
KRYLON	Pasenda Pink	.
KRYLON	Gloss Black	.
GREAT DAY	Gloss Black	.
ILLINOIS BRONZE	Flat Black	Slowest (~ 3 x 1 second)

It can be seen that all paints essentially behaved the same, within a factor 3. This is not surprising, because the binder material that holds the paint together is completely opaque to the 10.6 μm wavelength laser beam.

While using the Nd:YAG laser, we used an unfocused beam of ~ 0.7 cm in diameter with 8 ns pulses. At a sufficiently high intensity, all the different kinds of paint were mostly removed at the first shot and the difference between the threshold intensity for different paint is small. The unusual phenomenon is that the size of the paint removal spot is different for different paints, and increasing the number of shots fired on the paint does not change the spot size very much. The spot size is largest for black paint. The result is shown as follows:

		Diameter (cm)
KRLYON	Gloss Black	0.7
GREAT DAY	Gloss Black	0.7
KRYLON	Gloss White	0.6
KRYLON	True Blue	0.55
KRYLON	Banner Red	0.45
KRYLON	Gardena Green	0.4
KRYLON	Pasenda Pink	0.3

Again, within a factor of two all colors behave the same. However, clear black is more efficiently removed, since a larger diameter spot has paint removed.

The main difference between the results from the two lasers is the black. In terms of removal efficiency, the black color paint is lower compared to other colors with the CO_2 laser, but is higher with the Nd:YAG laser, probably due to the wavelength difference. As a summary, it appears that the difference in removal efficacy of different kinds of paint is not very large, within factor of three among the paints we have tested.

CHAPTER 5

SPECIAL ISSUES IN TREATING FREEWAY SIGNS

We have performed preliminary tests of laser treating graffiti on freeway High Intensity signs. The surface of these signs is much more delicate and sensitive to heat than the other substrates we have tested and studied, which makes the problem of removing paint much more complex and laser parameters more critical. Although efficacy and surface quality of laser treatment are still under investigation, we have obtained some very promising results and have defined a range of laser parameters which might work for the problem. We summarize our preliminary study in the following aspects.

A. Construction of the Signs

The high intensity signs are made by 3M, and consist of several elements as listed below:

aluminum sheet as the substrate;
layer of very small glass beads on top of the aluminum for high reflection;
plastic-like film on top as the surface of the sign and the cover for the layer of glass beads;
commercial paint on top of the plastic layer in places with no writing, providing the background for the sign.

Aluminum is a very good thermal conductor and not sensitive to local heating. Its smooth surface is highly reflective to all wavelengths from near UV to IR. Therefore, we do not have to worry about damaging this material when using a laser to treat the graffiti on signs. The glass beads could be damaged or heated to melting when the laser energy is sufficiently high and pulse width is too short or too long. However, it is also possible to avoid this happening by using relatively well controlled pulses, since the layer is, after all, not immediately next to the graffiti. The tough task is to remove graffiti paint without damaging the other two layers - the plastic-like film and the background paint. Plastic-like materials normally have low melting point and are very susceptible to thermal damage. The background paint is basically the same kind of material as the graffiti paint we want to remove, which makes discriminated removal extremely difficult. The most likely way to work is to use very well controlled pulses, ablating the graffiti paint in a very small depth with each pulse and stopping the ablation when reaching the surface of the background paint.

B. Results of the Preliminary Experiment

In the case of paint removal from signs, the background paint layer, the plastic-like film and glass beads are all parts of the substrate. In dealing with substrates like concrete and bricks, it is easy to remove the layer of the paint and recover the original substrate surface. What we have been working on in that area is to find out the most energy efficient way of accomplishing the task. In dealing with signs, however, before we worry about efficiency, we have to concentrate on the question of whether we can remove the graffiti paint without damaging the sign.

Due to the substrate's sensitive reaction to heat, we anticipated that a pulsed laser would be required and the pulse width would need to be relatively short, to eliminate the heating damage to the substrate. Our experiments did show that the result from a short pulse laser is better than a long pulse laser. We have tested a graffiti painted high intensity sign with quite a few different lasers. They are:

Nd:YAG laser	1.06 μm	8 ns pulses
DYE laser	504 nm	1.5 μs pulses
XeCl laser	308 nm	130 ns pulses
CO_2 laser	10.6 μm	cw output
Nd:YAG laser	1.06 μm	100 μs pulses
Nd:YAG laser	1.4 μm	250 μs pulses
Er:YAG laser	2.94 μm	250 μs pulses
Cr:Er:glass laser	1.53 μm	1.5 μs pulses

The differences among these lasers are not only their wavelength, but also more importantly their pulse width. In this preliminary experiment, we have concentrated on removing graffiti paint from the plastic film substrate (high reflection areas), since this is easier than removing graffiti paint from the commercial paint as substrate. In addition, it is more critical to find solutions for treating the high reflection areas, because the painted areas may always be repainted.

The result of this study was that all lasers caused damage. We found it was important to look at the non-specular reflection, i.e. that which comes from the glass beads, in order to properly test for damage. The least damaging laser was the 8 ns Nd:YAG. After irradiation with this laser, we found flakes of paint on the table, indicating that the paint was removed by a laser-induced shock wave. Our results indicate that very careful control of laser intensity is needed to succeed in removal of graffiti off highway signs, unless some other tricks are used.

As a result of our research, we have come to believe that grazing incidence may be the best angle at which to use the laser. This is because paint absorption is independent of angle, but reflectivity increases rapidly with angle. It may be possible to keep the laser light from entering the sign and causing damage if we use grazing incidence reflection. We did not have time to carry out this experiment, however.

We also found that successful removal of graffiti could be achieved by combining laser and chemical treatments. This is discussed in the next section.

C. Combined Use of Laser and Chemical Treatments

We were able to somewhat recover the original high reflection surface with a treatment combining the laser irradiation and a chemical graffiti remover (mild solvent). We were not able to use any of the above lasers alone to recover the original shiny surface, presumably because the melted paint always leaves some residue on the surface. Wiping off that residue with solvent after laser treatment seems to be necessary for the recovery of high reflection. The amount of the solvent and the labor needed to treat the residue, however, is by far much less than what would be needed to treat graffiti paint with the solvent only.

Short pulses such a 8 ns showed the best surface quality after such a treatment, not perfect but near satisfactory. The laser beam damaged some of the glass beads, but surprisingly enough that did not reduce the surface reflection very much. The dye laser at 504 nm with 1.5 μs pulses also worked pretty well. The XeCl laser at 308 nm with 130 ns pulses damaged glass beads quite bit and really reduced the surface reflection compared to the original surface. We suspect that the damage in this case is due to the laser's short wavelength which is absorbed by the glass beads. The cw CO_2 laser burns the paint and the substrate at the same time, and melts the paint and the substrate together. All other lasers with pulse width from 100 μs to 1 ms have a similar problem, which makes a lot of cracks on the plastic-like film, presumably due to heating. The surface became dull after the laser treatment. The microscopic results clearly show what each laser does to the surface.

As for the background areas commercially painted by Caltrans, we were able to use the laser to remove the graffiti paint without removing the substrate paint very much. However, the substrate paint would loose the originally very smooth and relatively shiny surface. It is the future task to determine whether this is tolerable.

D. Further Studies on Graffiti Removal From High Intensity Freeway Signs

Extensive trial and error experiments were carried out to determine the laser parameters for the best surface quality after graffiti removal, to understand the substrate material in an attempt to avoid underlying surface damage. Finally, we carried out a comparison of laser treatment and chemical graffiti removal.

In an attempt to remove graffiti paint, we performed extensive tests using the method of trial and error to obtain the laser parameters which give the best surface results for the both cases of the plastic-like substrate and background paint substrate. We tried as many short pulse lasers as we could to understand the laser removal process to obtain better surface quality. We considered high power optical fibers. They have the advantage of scrambling the laser modes to achieve a more uniform beam and hopefully better surface quality after the laser treatment. For any attempt to recover the original substrate surface without using any solvents after the laser ablation, a beam with very uniform spatial profile is essential. However, the laser power must be reduced in order not to damage the fiber. For this reason, we decided that higher repetition rate cw pumped Q-switched lasers are best for use with fibers.

We acquired some real graffiti samples and found that it is much harder to remove paint from older signs. Our intention is to compare the treatment using the present method of chemical graffiti remover with the treatment using laser or laser/chemical combination treatment. Preliminary results on signs with fresher paint seem promising.

The criterion was to compare the laser treated signs with the signs treated by the SO SAFE chemical graffiti removers currently being used in Los Angeles County. For graffiti signs made by solvent based paint and when the paint is fresh, SO SAFE works relatively well and shows a satisfactory result, but freshly painted surfaces are a small number and require absolutely immediate attention. For other kinds of paint and especially when the paint has been out there for longer than several days, SO SAFE is not able to take the paint off and the combination of laser and SO SAFE will probably be an advantage.

For all the lasers we tried, the laser alone was unable to completely remove the paint uniformly without causing some damage to the sign. The shortest pulses (8 ns) caused the least damage. Flakes of paint were found under the sign after exposure, indicating the ablation occurred without any heating of the substrate. That is, the shock of the short laser pulse caused the paint to "flake off". However, the strong shock also tended to cause the surface of the sign to separate from the glass beads below the surface. We believe that a 100 nsec pulse would work with less damage to the sign, but that the laser cannot be UV. The XeCl laser with 130 nsec pulses caused considerable damage because it is so strongly absorbed at the surface of the sign. Again, cw pumped Q-switched high repetition rate lasers appear to be the most suitable for this application.

CHAPTER 6

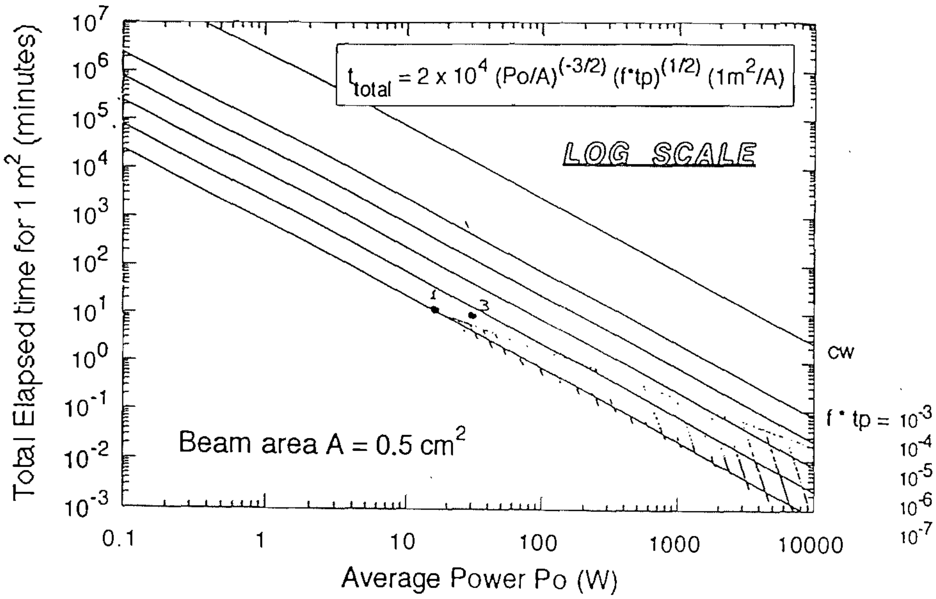
DETERMINATION OF THE MOST EFFECTIVE LASER

We have made some conclusions about what kind of laser is the "better" laser in terms of paint removal efficiency, ease of use, low cost and convenience for delivering the beam.

Determining the correct paint removal efficiency requires examination of the characteristic curve shown Fig. 10, adding the requirement that $I < 400$ MW/cm^2. Above this intensity, the beam burns the substrate; this limits the minimum spot size which will be useful. Taking this into account we have analyzed the total time required for removing 1 square meter of paint from concrete, as a function of average power and pulse duty factor available from commercial lasers. Inclusion of the damage threshold limit means that there are different curves analogous to Fig. 10 for different size beams. Examples of our results are shown in Figures 12. The data are presented as the total elapsed time to remove 1 m^2 of paint as a function of the time-averaged laser power. The lines designated by f*tp (the fraction of time that the pulses are present) correspond to different duty cycles. The damage threshold limits the minimum time possible, depending on available average power and beam area. The regions which will cause damage are cross-hatched to show that they cannot be included. In all cases, however, we found that pulsed Q-switched lasers had faster paint removal times than CW lasers. Thus, our first conclusion is that a CW laser is not the optimum.

The decision on the "better" laser is made first on the pulse length. We investigated kinds of lasers which are available commercially. Appendix 1 outlines these lasers, listing their specifications and their price, identifying them by number. Table 1 is a synopsis of this data, with each laser listed by the same number as in Appendix 1. The graphs in Fig. 12 show numbered data points representing each of the available lasers, individually located on the proper duty cycle line and at the proper average power. Understanding that the fastest operating conditions will be just under damage threshold, we have designed the minimum spot size possible, although arbitrarily deciding to stop with 1 mm^2 spot size, since aligning smaller spot sizes would be difficult. From the analysis it can be seen that lasers 1,3,4,7,8 will remove 1 m^2 of paint in approximately 10 minutes. These are all Q-switched lasers and are either pulsed pumped (1,3,4) or CW pumped (7,8). We have also imagined creating our own laser (9,10), with a high power CW-pumped commercially available laser and a Q-switch added. If a suitable Q-switch could be found, this is expected to remove 1 m^2 in less than 2 min., but such a laser needs to be properly designed; none are commercially available. Finally, a new high-power pulsed Q-switched laser came out recently, much more expensive, but able to remove 1 m^2 paint in only a few minutes (11-13).

Based on the commercially available lasers shown in Table 1, it appears that there are pulsed pumped and CW pumped lasers which have comparable removal times; about ten minutes for 1 m^2 (approximately a square yard). Based on going for the least expensive laser which operates in a reasonable time, the "best" laser would appear to be the Continuum laser, which we designated as # 4. It operates 50 Hz, with 300 mJ/pulse. This laser is similar to the one we have in our laboratory and with which we have been making measurements to date. The suggestion is that the laser be operated with an area of 0.1 cm^2. This high power laser will require a beam scanning system, since it will probably damage the end of a fiber if the full power is focused into it.



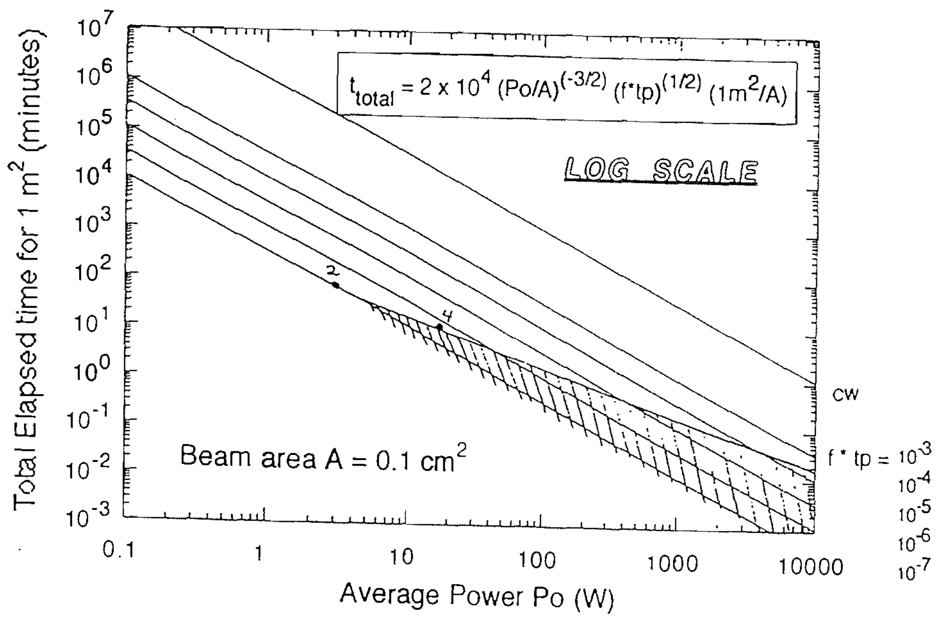
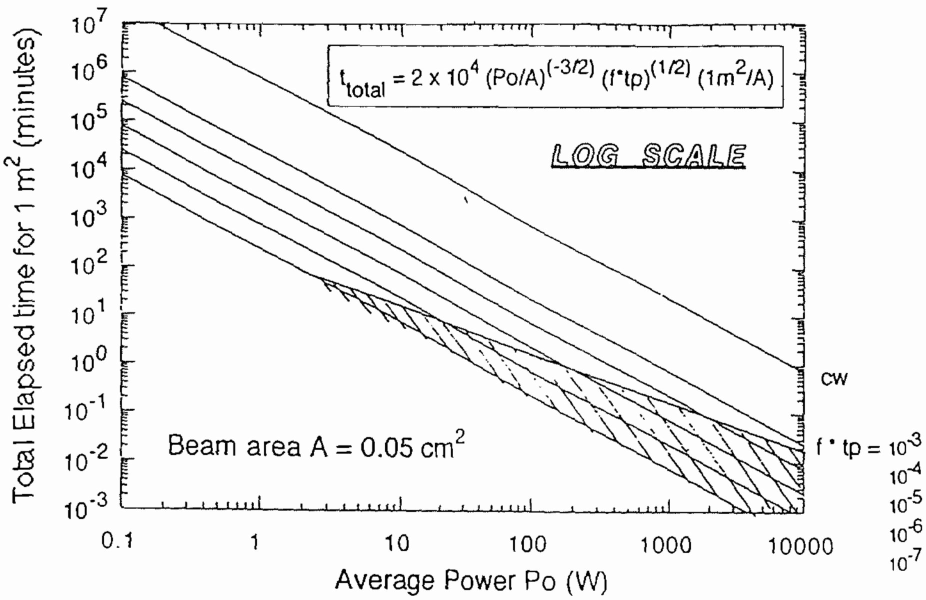


Figure 12. Total time (in minutes) required to remove 1 m^2 of paint 14 μm thick as a function of average laser power, for different duty cycles. The four figures are for laser beams focussed to different areas. The equation is a phenomenological fit to experimental data. The parameter f*tp represents the duty cycle. Numbers inserted on the graph represent enumerated lasers from Table 1.



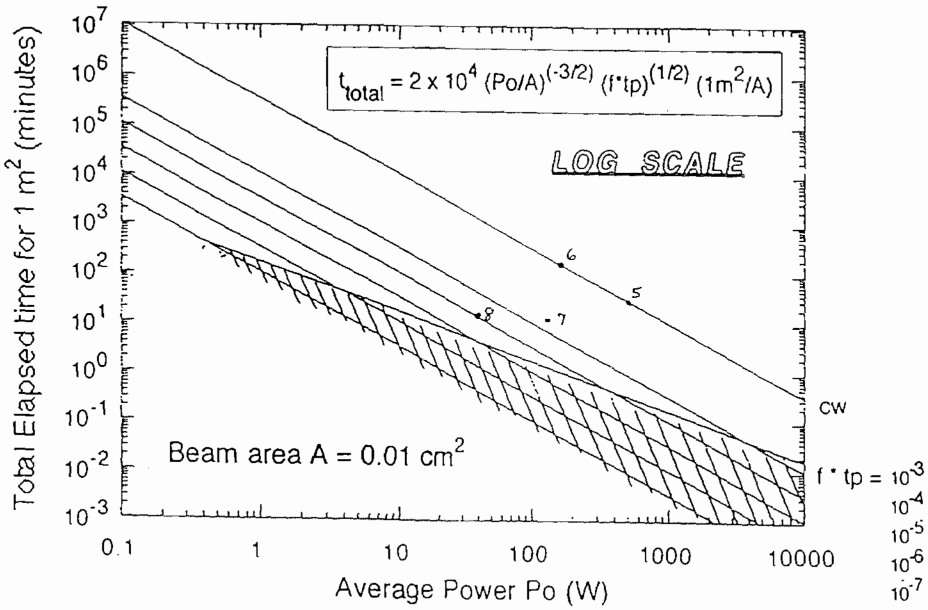


Figure 12. Total time (in minutes) required to remove 1 m^2 of paint 14 μm thick as a function of average laser power, for different duty cycles. The four figures are for laser beams focussed to different areas. The equation is a phenomenological fit to experimental data. The parameter f*tp represents the duty cycle. Numbers inserted on the graph represent enumerated lasers from Table 1.

TABLE 1
Parameters for possible Nd:YAG lasers, their projected graffiti removal rates and cost

Laser Number	Rep. rate Hz	Energy per pulse Joules	Pulse Width nsec	Average Power Watts	Minimum Spot Size cm^2	Removal Time minutes	Price $
1	10	1.5	8	15	0.47	11	77,500
2	10	0.45	8	4	0.12	42	19,500
3	40	0.8	7	32	0.29	5	75,000
4	50	0.3	7	15	0.11	11	25,000
5	CW			500	0.01	30	47,500
6	CW			150	0.01	181	21,500
7	10,000	0.012	250	120	0.01	13	35,650
8	1,000	0.04	125	40	0.01	15	35,650
9	10,000	0.045	250	450	0.01	1.7	47,500+QS
10	1,000	0.2	125	200	0.01	1.3	47,500+QS
11	100	0.32	8	32.5	0.12	5	79,950
12	50	1	8	50	0.4	3	99,950
13	10	2	8	20	0.8	10	87,950

Notes on table:
*Slow repetition (rep.) rates are pulsed pumped; fast rep. rates are CW pumped.
*Minimum spot size is that calculated to give damage threshold: $I = 400\ MW/cm^2$
*The smallest allowable spot size is chosen to be 0.01 cm^2, for practical reasons.
*Removal time is based on 1 m^2 from concrete, calculated from a model fit to our measurements of removal of a layer of paint of thickness 14 μm .
*Price is list, 1993. QS represents adding a Q-switch to a commercially available CW laser. It is unclear what kind of Q-switch is availableor what its cost would be.

It would appear that a more practical alternative is to use #7, a Lee Laser, which is a 120 W laser Q-switched at 10 kHz. We have not been able to test such a laser in our laboratory, so this is an engineering prediction. This laser should be able to be used with a fiber, although we have not been able to try it. We have a high power laser such as this in our laboratory, but it is not Q-switched and is not applicable without our acquiring a Q-switch. This may be a direction to explore in follow-on research. We will solve the problem of high duty-cycle heating, by using a high speed optical scanner.

CHAPTER 7

COST-BENEFIT ANALYSIS

A. Requirement for a "Better" Laser

Based on the results of our study so far, Q- switched lasers, either cw pumped or pulse pumped, give higher paint removal efficiency compared to cw lasers. We believe that in principle the most energy efficient laser is a cw pumped Q-switched laser and the wavelength of the laser does not appear to be very important. CW pumped Q-switched lasers produce relatively short pulses at a high repetition rate so that the average power would not be reduced very much. Pulsed pumped Q-switched lasers can produce short pulses with very high energy per pulse so that each pulse is very powerful; however, the repetition rate is normally low which results in a very low average power. CW lasers have high average energy, but the intensity is low due to the fact that the total energy is uniformly distributed over time. Among the commercially available high power lasers, CO_2 and Nd:YAG are the most common and more efficient lasers. A cw pumped Q-switched Nd:YAG laser should be a good candidate because it is solid state, easy to operate, simple to maintain, convenient to move around, available in high power, and can use optical fibers as a beam delivery medium.

B. Cost - benefit Analysis

We think that the first important issue in a cost-benefit analysis is the speed of removing paint using a laser compared to other conventional methods. Based on the graph shown in Fig. 10 we can calculate how many minutes it takes to remove graffiti paint of 1 m^2. Let us look at an example: a pulse pumped Q-switched Nd:YAG laser from CONTINUUM with 300 mJ per pulse, pulse width 7 ns, and pulse repetition rate 50 Hz would take ~ 2 minutes to remove 1 m^2 of paint. This speed is comparable to the conventional method of paint-over. Very high power cw pumped Q-switched lasers are not commercially available, presumably because there is not as much need for them as for the pulse pumped ones.

The cost for the above mentioned pulse pumped Q-switched Nd:YAG laser in a graffiti removal system is ~ $50000. We estimate its lifetime of 2 shifts (8 hours a shift) in 5 years; then the cost per hour for the equipment is $2.50/hour. If, using the conventional method of paint-over, we estimate the setup and take down time is ~ 2 hours out of 8 hours and $20/hour for labor, then the excess cost per hour for painting is ~ $40/8 hours = $5/hour. Since this is still a preliminary estimate, we only want to say that the laser removal technique appears to be not any more expensive than the conventional method. Comparing the expenses in electricity for using a laser to the paint, brushes, etc. needed for paint-over, the costs in the two cases are relatively comparable. Labor cost are also expected to be comparable.

However, there are a number of benefits to using a laser to remove graffiti. Compared to conventional methods such as paint-over, sand blasting, chemical, etc., laser removal of graffiti gives a clean surface so that it is less inviting for new graffiti, is environmentally friendly, is not labor intensive, has no setup and takedown time, and has no supplies needed.

C. Summary of Conventional Methods for Removing Graffiti

i) Category

Walls and bridges - paint over (brush, spray, etc.), sand blast, water blast, cement slurry.
Signs - chemical, protective coating, replace.

ii) Effectiveness and problems of different methods

paint over - easiest and fastest; but paint builds up; not always possible to paint over.

chemical - works sometimes; harsh on surfaces and workers; removes surface of sign and concrete; not 100% effective.

protective coatings (mostly from 3M?) - intensive labor to apply and maintain; expensive; not fully protect. (one district claimed that Seibulite coating during manufacturing performs extremely well.)

sand blasting - use on walls, etc., if originally not smooth surfaces; in summary either ineffective or harmful to structure.

water blasting - use on smooth and metal surfaces; hard to reach many places since it needs long hoses which results in low water pressure; consumes much water.

iii) Removal rate and cost of the conventional methods

Cost in the area combining L.A. and Ventura County - estimated $6000/day, 20 people dedicated to clean graffiti.

We made a visit to the highway department of Caltrans in Los Angeles to see how they cover over graffiti with paint. We found out that if it is possible to use a paint sprayer, this is much cheaper than any laser system would be. However, we found that in special cases, painting over is undesirable. In that case Caltrans might want to contract with a company to provide laser removal of graffiti, as long as it is cost-effective.

D. Comparison of Paint Removal Technologies

A comparison was made of the time required to remove 1 m^2 of paint with the competitive techniques. The analysis is outlined below. It will show that the actual cost for removal of 20 m^2 of paint is estimated to be roughly $100. Comparison between laser and conventional methods turns out to be comparable in terms of cost.

However, using a laser has many benefits such as 1) ability to remove any graffiti; 2) much more superior surface quality after treatment in terms of removing graffiti but not damaging the underlying material; 3) friendly to structure, workers, and environment; no harm to any of the above; 4) not labor intensive.

Our analysis is outlined as follows:

i) Laser cost - using one particular laser system as an example

The pulse pumped Q-switched Nd:YAG laser from CONTINUUM with 300 mJ per pulse, pulse width 7 ns, and pulse repetition rate 50 Hz.

Takes ~ 11 minutes to remove 1m^2 of paint.

Cost for the laser, a generator, and accessories is ~ 25,000 + 4,000 + 1,000 = ~ $50,000.

Estimate its lifetime of 5 years with 2 shift (8 hours a shift), then the cost per hour is $2.50/hour.

For removing 20 m^2 of area fully covered by paint, it takes ~ 4 hours laser work. Assuming price/hour includes the laser ($2.50/hr.), the labor ($20/hr.),and gasoline to run the generator ($1hr.), then the cost for 20 m^2 is ~ $100.

The only other cost is replacement of flash-lamp, which costs $500 every six months.

ii) Conventional methods (see below) - chemicals and sand blasting

Commercially available services for removing graffiti are mostly using methods of chemicals or sand blasting. The prices range from- $100 to $400 for treating 20 m^2 of brick wall, sometimes including a protection coating to seal the surface of bricks.

If we assume the prices include 100% profit, then the actual cost is~$50-$200.

The result of this analysis is that laser removal is comparable to sand-blasting or water-blasting in cost, but not to painting over. The base cost (not including profit) is projected to be roughly $100 to remove 20 m^2 of paint.

E. Additional Considerations in the Cost-benefit Analysis

Other considerations may affect the cost-benefit analysis in the future:

i) A "better" laser?

Types of lasers - are there any other kind besides CO_2 and Nd:YAG? What about flash-lamp pumped dye lasers? What about using a flash lamp directly?

Efficient lasers - energy efficiency (electrical - optical - ablation rate); some applications will want the most efficient regardless of price.

Other factors - user friendliness; convenient beam delivery; maintenance, lifetime, safety issues, etc.

Comparison between different systems - example: between one high power laser system and a multiple lower power laser system with the same removal rate in terms of beam quality, lifetime and price

ii) Cost

Electrical power - cost of electrical power generator
Laser - start-up, lifetime, and maintenance.
Accessories - beam delivery and safety equipment

iii) Benefits compared to conventional methods such as paint-over, sand blasting, and chemical remover.

- speed and cost?
- cleanness of the surface which makes it less inviting for new graffiti
- environmentally friendly
- not labor intensive, no setup and take down time, and no supplies needed.

CONCLUSIONS AND RECOMMENDATIONS

It was found that all lasers lie on the same log-log plot of exposure time vs. laser intensity. This allows predictions for the minimum time needed for graffiti removal, based on practical laser system capabilities. It was shown that the minimum removal time is achieved with a Q-switched Nd:YAG laser at a rate between 1 and 10 min for 1 square meter. A cost-benefit analysis was performed that showed the laser removal process is comparable in cost to sand-blasting and is expected to be less environmentally and structurally damaging.

It was also found out that brick, unpainted wood and metal followed the same engineering process model as did concrete block, as long as Q-switched lasers were used. However, it was found that high intensity highway signs are much more tricky and may need aditional approaches. The first is a careful control of the laser intensity. Four others we identified are: 1) using grazing incidence reflection; 2) quantifying the combined use of lasers and chemical solvents; 3) using a 100 nsec pulse; and/or 4) using other spectral wavelenghs (red or green).

We suggest a two year follow on program which will allow additional tests to be performed on highway signs, leading to the development of a practical removal process for this application. We suggest, based on our engineering design model, that this program should use a CW-pumped Q-switched Nd:YAG laser. We estimate that the removal rate will be comparable to that of a pulse-pumped Nd:YAG laser. In addition, the pulses will be longer, which may cause less damage during highway sign irradiation. Furthermore, the peak pulse energy will be lower, ensuring that a fiber delivery system can be used. Finally, the cw-pumping is presently done with a lamp, but in the future may be done with long-lived laser diodes.

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APPENDIX I
Available Nd: YAG Laser Systems for Graffiti Removal

A few examples of commercially available Nd: YAG laser systems are listed asfollows (time required for removing 1 m^2 of paint is from the calculation described in Chapter 6, or inferred from Figure X. The results shown here are also shown in Table 1. The question marks indicate systems which are not available yet, but may possibly be developed.

Continuum

(1) Pulsed Q-S, 10 Hz, 1.5 J/pulse, 8 ns; Po=15 W, $f^*tp=0.8x10^{-7}$;
Beam Area for I < 400 MW/cm^2=0.5 cm^2; Removing 1 m^2 takes ~ 11 minutes; ~ $77,500.

(2) Pulsed Q-S, 10 Hz, 400 mJ/pulse, 8 ns; Po=4 W, $f^*tp=0.8x10^{-7}$;
Beam Area for I < 400 MW/cm^2=0.13 cm^2; Removing 1 m^2 takes ~ 42 minutes; ~ $19,500.

(3) Pulsed Q-S, 40 Hz, 800 mJ/pulse, 7 ns; Po=32 W, $f^*tp=2.8x10^{-7}$;
Beam Area for I < 400 MW/cm^2=0.3 cm^2; Removing 1 m^2 takes ~ 5 minutes; ~ $75,000.

(4) Pulsed Q-S, 50 Hz, 300 mJ/pulse, 7ns; Po=15 W, $f^*tp=3.5x10^{-7}$;
Beam Area for I < 400 MW/cm^2=0.1 cm^2; Removing 1 m^2 takes ~ 11 minutes; ~ $25,000.

Lee Laser

(5) CW; Po=500 W cw; Removing 1 m^2 takes ~ 30 minutes; $47,500.

(6) CW; Po=150 W cw; Removing 1 m^2 takes ~ 180 minutes; $21,500.

(7) CW Q-S, 120 W, Q-S of (6); 10 KHz, 12 mJ/pulse, 250 ns; Po=120 W, $f^*tp=2.5x10^{-3}$;
using a reasonable beam area 0.01 cm^2; Removing 1 m^2 takes ~ 13 minutes; $35,650.

(8) CW Q-S, 40 W, Q-S of (6); 1 KHz, 40 mj/pulse, 125 ns; Po=40 W, $f^*tp=1.25x10^{-4}$;
using a reasonable beam area 0.01 cm^2; Removing 1 m^2 takes ~ 15 minutes; $35,650.

Artificially designed systems

(9) CW Q-S, assumed Q-S of (5) Po=450 W; 10 KHz, 45 mJ/pulse, 250 ns; f*tp=2.5×10^{-3}; using a beam area 0.01 cm^2; Removing 1 m^2 takes ~ 1.75 minutes; $47,500 + Q-S device??

(10) CW Q-S, assumed Q-S of (5) Po=200 W; 1 KHz, 200 mJ/pulse, 125 ns; f*tp=1.25×10^{-3}; using a beam area 0.01 cm^2; Removing 1 m^2 takes ~ 1.3 minutes; $47,500 + Q-W device??

Should we use CW Q-switched or pulsed Q-switched? Very high power cw pumped high repetition rate Q-switched lasers are not commercially available, presumably because there is not as much need for them as for the pulse pumped ones. However, they are more suitable to fiber delivery.

Continuum's new line of high energy Nd:YAG lasers

Continuum has a new line of pulsed Q-S lasers with higher repetition rate which came out at CLEO '93. However, the prices are much higher than we were quoted for the older systems listed above. The new ones are listed as follows:

(11) Pulsed Q-S, 100 Hz, 325 mJ/pulse, 8 ns; Po=32.5 W, f*tp=0.8×10^{-6}; Beam Area for I < 400 MW/cm^2=0.12 cm^2; Removing 1 m^2 takes ~ 5 minutes; ~ $79,950.

(12) Pulsed Q-S, 50 Hz, 1 J/pulse, 8 ns; Po=50 W, f*tp=0.4×10^{-6}; Beam Area for I < 400 MW/cm^2=0.4 cm^2; Removing 1 m^2 takes ~ 3 minutes; ~ $99,950.

(13) Pulsed Q-S, 10 Hz, 2 J/pulse, 8 ns; Po=20 W, f*tp=0.8×10^{-7}; Beam Area for I < 400 MW/cm^2=0.8 cm^2; Removing 1 m^2 takes ~ 10 minutes; ~ $87,950.