Sterilization of Spacecraft Components by Laser Ablation and Plasma Generation. C. B. Dreyer[1], J. R. Spear[1], K. L. Lynch[1], and A. J. Bauer[2], [1]Colorado School of Mines, Golden, CO 80401, cdreyer@mines.edu, [2]Applied Research Associates, 7921 Shaffer Parkway, Littleton, CO 80127.

Introduction: In the coming decades spacecraft will travel to destinations that may harbor evidence of past or present life. A Mars sample return mission will likely return samples to Earth from an area of Mars that will be thought to have been habitable in the ancient past. Such missions increase the need for new planetary protection (PP) methods. We are investigating the use of focused laser beams to ablate the surface of spacecraft surfaces and any contaminating materials. The method can be applied such that the ablated material is heated to a plasma, making it a LIBS (laser induced breakdown spectroscopy) approach. As with traditional LIBS, the plasma emission can be analyzed and used to determine if the ablated material is from the known spacecraft material or a foreign component. The method could be use in-transit or on the martian surface. It can also be applied to the exterior of sample return canisters and is amenable to other surface missions, such as a landing on one of the moons of Jupiter or Saturn.

Sterilization with focused laser beams: Focused laser beams have been used to kill microbes inside the mouth and in wounds [1] [2] using low irradiance laser beams (~1 W/cm^2). Ablation of most materials requires laser irradiance above a threshold on the order of tens of MW/cm^2 [3]. An irradiance level well above the ablation threshold will cause a plasma to form. A plasma that can be analyzed by the principles of LIBS requires irradiance on the order of 10 GW/cm^2 [4]. Laser irradiance below the ablation threshold can weaken cell membranes causing loss of membrane integrity. Oxidative species that destroy enzymes and DNA can also be generated by this plasma. High irradiance laser beams can sterilize surfaces by ionizing the entire surface and all contaminating materials. Under the right conditions the plasma emission generated by high irradiance beams can be used to determine the elemental composition of the ablated material.

Laser Sterilization Concept: Figure 1 shows a concept of how laser sterilization may function in practice. A robotic arm with several degrees of freedom is used to raster scan the laser across the surface of a part, i.e a sample container. The part may be held fixed or translated in concert with the robotic arm. Emission from a LIBS plasma is collected by a spectrometer mounted on the robotic arm, as shown, or placed off the RA and light collected by optical fiber. The particular means of implementing the laser ablation sterilization method will depend on several factors including the shape of the part and mission objectives.

The range of laser irradiance need to implement the laser sterilization method is likely to be from about 1 MW/cm^2 to 10 GW/cm^2, depending on whether the objective is sub-ablative sterilize, ablation of the surface without plasma or generation a LIBS plasma. The laser irradiance has important implications for setting the laser power consumption, laser spot size at the surface, raster scanning rate, and time for sterilization.

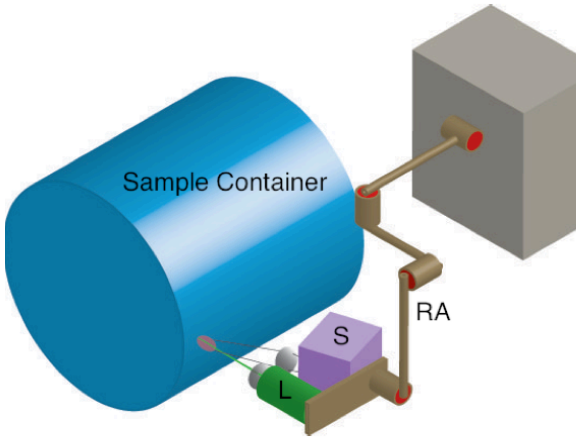

Figure 1: *Schematic of the laser sterilization concept treating a large part. L: laser and focusing optics. S: miniature spectrometer. RA: Robotic arm. Cameras would also be used to position the RA (not shown).*

The rate at which the untreated surface is removed by ablation is:

$$\frac{\mathrm{d}a_u}{\mathrm{d}t} = -a_l f \frac{a_u}{A}$$

integration yields:

$$a_u = Ae^{-t/\tau_s}; \quad \tau_s = \frac{A}{a_l f}$$

Where a_u is the total untreated surface area, a_l is the area treated by the laser per laser shot, A is the total area of the part, and f is the laser repetition rate. The expression is an exponentially decreasing function with time constant τ_s. Full surface treatment is approached after several times constants of treatment (99.3% of the surface is treated after 5τs).

In Table 1 the relationship between laser focal spot diameter, laser pulse energy, and laser repetition rate is shown for a fixed surface area of $1m^2$. Laser input power of 10W with 25% conversion to optical power is assumed as this a reasonable value for a spacecraft instrument. Laser irradiance is sufficient to produce a LIBS plasma on every laser pulse. These parameters yield a sterilization time constant τ_s = 22.2 hours for all spot diameters. A low repetition rate laser with a high pulse energy would be needed for focusing with a large spot diameter. A tightly focused laser beam would require very low pulse energy but very high repetition rate. A moderately focused beam (100 μm) would require a few mJ per pulse and a few KHz repetition rate, such a laser is common for diode pumped Nd:Yag and Nd:YLF lasers. At lower than 10 GW/cm^2 irradiance, either in sub-ablation sterilization or non-LIBS plasma forming ablation achieved by defocusing, sterilization could be achieved more rapidly with intermittent LIBS measurements to verify surface condition.

Table 1: Relationship between spot size and laser repetition rate at 10W laser power (25% efficiency), 10 GW/cm^2 irradiance, 2 ns pulse, total sterilization area $1m^2$. With these parameters τ_s is 22.2 hours.

Spot diameter (μm)	Pulse Energy (mJ)	Repetition Rate (Hz)
1500	353.4	7.1
1000	157.1	15.9
500	39.3	63.7
100	1.57	1591.5
50	0.393	6366.2
10	0.016	159154.9

LIBS plasma emission can be used to classify the type and amount of contaminants that were present before sterilization. LIBS spectra can be categorized according to known surface material, material of biological origin, material of mineralogical origin or unknown material. Plasma temperature decreases below 1 torr due to cooling by adiabatic expansion of the plasma expanding into vacuum, which causes a reduction in lifetime and emission intensity, however, emission is known to be observable and relatively constant below 0.1 torr ambient pressure [5] [6].

Conclusions: Laser sterilization of spacecraft components by ablation of the surface and contaminating material appears to be a plausible planetary protection method. The method has several advantages:

- Direct measurement of the sterilized surface. As the LIBS spectra of the man-made surface will be well known, deviations will be easily detected, and the contamination level determined.
- The surface and contaminating material are destroyed. The method can be operated to ionize the surface material. No known microbe can survive a direct hit by a high irradiance laser beam.
- The sterilization system can also double as an *in situ* instrument for scientific investigations.

The method could be useful in several potential PP mission scenarios such as:

- In-space sterilization of a Mars sample return canister. This scenario offers ample time for sterilization before returning samples to earth by performing sterilization in Mars orbit or on a Mars-earth trajectory.
- Sterilization of hardware on the Mars surface for manned and robotic missions. Hardware removed from a zone with high biological potential could be sterilized before entering a human habitation zone or a PP safe zone.
- Forward contamination, particularly missions in which in-space sterilization is needed to reduce the bioburden after launch, such as landed missions to the moons of Jupiter and Saturn.

Future work: Areas of future work are:

- How physical processes couple with microbe biological transport processes during sterilization. Atmospheric LIBS forms a shockwave that could induce transport of microbes and mineral dust near to the intense laser focus, while in a vacuum the shockwave is much reduced as it can only be formed from ablated material.
- The survivability of microbes due to a near miss of the ablation beam must be examined. Does a LIBS ablation pulse effectively sterilize a larger area than the ablated area?
- Operational and technical considerations: What is the best combination of laser focal spot size, pulse rate, and pulse energy? What scanning system is optimal? Can the method reach into crevices and into corners? Does the efficacy of the method vary with surface material? What is the surface finish of a laser sterilized part?

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