Epoxy / Silicone Potting Material Removal for Greater Recovery of Circuit Boards

Final Report for REMADE Project: 18-01-RM-13

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The REMADE Institute Statement

This report documents research that was conducted by the Golisano Institute for Sustainability (GIS) at Rochester Institute of Technology (RIT), under a cost-shared subrecipient contract with the REMADE Institute.

The objective of this project was to investigate micro abrasion and laser ablation as potential cost effective methods for removal of epoxy and silicone potting material from printed circuit boards (PCB). The ability to cost effectively remove such PCB potting materials would improve PCB repair, remanufacture, and reuse opportunities.

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The REMADE Institute project number is 18-01-RM-13, SOPO Task Number 7.3

The REMADE Institute—a $140 million Manufacturing USA Institute co-funded by the U.S. Department of Energy—was launched in January 2017.

In partnership with industry, academia, trade associations, and national laboratories, REMADE will enable early-stage applied research and development of technologies that could dramatically reduce the embodied energy and carbon emissions associated with industrial-scale materials production and processing. The REMADE Institute is particularly focused on increasing the recovery, reuse, remanufacturing, and recycling (collectively referred to as Re-X) of metals, fibers, polymers, and electronic waste (e-waste).

By focusing our efforts on addressing knowledge gaps that will eliminate and/or mitigate the technical and economic barriers that prevent greater material recycling, recovery, remanufacturing and reuse, REMADE seeks to motivate the subsequent industry investments required to advance technology development that will support the U.S. manufacturing eco-system.

The REMADE Institute is committed to accelerating the adoption of sustainable innovations that will expand the circular economy.

The REMADE Institute - Accelerating the Circular Economy

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Rochester Institute of Technology Statement

Rochester Institute of Technology (RIT) conducted cost-shared research to investigate micro abrasion and laser ablation as potential cost effective methods for removal of epoxy and silicone potting material from printed circuit boards (PCB). The ability to cost effectively remove such PCB potting materials would allow improved PCB repair, remanufacture, and reuse opportunities.

Principal Investigators for the project were: Kristi Sisak (RIT) and subsequently, James Larrabee (RIT)

The Project Team included: Cesar Carbajal (Caterpillar, Inc.), Leslie Caviness (Caterpillar, Inc.), Everardo FriasRios (CoreCentric Solutions), and Ken Oda (CoreCentric Solutions).

Funding for this project was provided by the REMADE Institute with cost-share provided by Rochester Institute of Technology, Caterpillar, Inc., CoreCentric Solutions, and New York State Empire State Development under Grant #AC118.

Our industrial partners were Caterpillar Inc. (Peoria, IL) and CoreCentric Solutions (Carol Stream, IL).

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Acronyms, Abbreviations, and Definitions

Abbreviation/ Acronym / Term	Definition
Btu	British Thermal Unit. A measure of the heat content of fuels or energy sources. Used to compare energy sources on an equal basis. 1 Btu / minute ≈ 17.6 Watts.
cc	Cubic-centimeter. A measure of volume.
Conformal Coating	A thin (on the order of 0.005 inch) layer applied to electronic printed circuit boards to provide environmental protection such as anti-corrosion protection.
Hz	Hertz. The unit of frequency. Defined as one cycle per second.
IR	Infrared. A section of the electromagnetic spectrum with wavelengths longer than those of visible light, approximately 800 nm (nano-meter) to 1 mm (millimeter).
kg	kilo-gram, 10^3 grams
KHz	kilo-Hertz, 10^3 Hertz
Laser Ablation	Laser ablation or photo-ablation is the process of removing material from a solid (or occasionally liquid) surface by irradiating it with a laser beam.
M	"mega" or million, 10^6
Media Abrasion	Also referred to as media blasting, is a surface grinding or polishing method using high speed abrasive particles.
Micro Abrasion	Media abrasion performed with small sized abrasive media particles and typically higher abrasive material speeds.
nm	nano-meter, 10^{-9} meter.
PCB	Printed Circuit Board. A substrate (board), often an FR4 material, a fiberglass reinforced epoxy laminate, used to mount electronic components and make electrical connections between them, typically using photo-etched (printed) interconnects.
PCB Potting	A process of encapsulating printed circuit boards, generally with an epoxy or silicone material, used to provide environmental and mechanical protection and to hide implementation details.
PJ	peta-Joule, 10^{15} Joules
Solder Mask	Solder mask, solder stop mask or solder resist is a thin lacquer-like layer of polymer usually applied to the copper traces of a printed circuit board (PCB) for protection against oxidation and to prevent solder bridges from forming between closely spaced solder pads. Gives a PCB its color appearance and can be green, red, blue, black, yellow and other colors.
TBtu	"tera" or trillion Btu, 10^{12} Btus
µm	Micron or micrometer (international spelling), 10^{-6} meter.

Abbreviation/ Acronym / Term	Definition
μs	micro second, 10^{-6} second
UV	Ultra-Violet. A section of the electromagnetic spectrum with wavelengths shorter than those of visible light, approximately 10 nm (nano-meter) to 400 nm.
W	Watt. A unit of power or radiant flux. Equal to an energy transfer rate of 1 Joule per second.
YAG	Yttrium aluminum garnet. A crystalline material used as a lasing medium for solid state lasers, typically doped with neodymium.

Executive Summary

This exploratory project, "Epoxy/Silicone Potting Material Removal for Greater Recovery of Circuit Boards," evaluated printed circuit board (PCB) potting material removal methods to expose components for testing and repair. The goal of this study was to identify a PCB potting material removal method that would overcome cost constraints associated with current low-volume, time consuming methods, increasing the ability to test, repair, remanufacture, and reuse a larger volume and range of circuit boards. Epoxy and silicone potting materials were investigated. Methods for material removal evaluated were micro abrasion and laser ablation. While neither method evaluated proved to be a complete success, laser ablation was identified as a method potentially warranting further investigation, in particular for Epoxy based potting materials. Material removal rates were within project goals; however, the challenges of tight control of potting removal close to the PCB or near PCB components would require significant additional research and development to overcome.

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Epoxy / Silicone Potting Material Removal for Greater Recovery of Circuit Boards

REMADE Project: 18-01-RM-13

Introduction

Printed circuit boards used in appliance, automotive, marine, aerospace, outdoor lighting, photovoltaic, and military applications (among others) are often encapsulated with protective coating or potting materials. These materials provide physical (impact and vibration) and environmental (corrosion) protection to encapsulated circuit boards and their components.

There are three general families of PCB encapsulation methods.

1. Conformal coatings. Conformal coatings are typically clear, hard, thin coatings, on the order of 0.005 inch thickness. Conformal coatings are used primarily to provide environmental protection such as damage due to corrosion. Conformal coatings 'conform' to the shape of the PCB and underlying components, providing good coverage of delicate circuitries.
2. Epoxy potting. Epoxy potting materials are typically relatively hard coatings that can be significantly thicker than conformal coatings and that may be opaque. Epoxy potting, like conformal coating, is used to provide environmental protection. Thicker potting material depths can also provide physical protection such as increasing a PCB's tolerance to vibration for example.
3. Silicone potting. Silicone potting materials are typically soft, rubbery, and often clear. Like epoxy potting, silicone potting is typically significantly thicker than conformal coatings and can be used to provide both environmental and physical PCB protection.

While PCB conformal coating and potting materials provide circuit board protection, their use makes board repair difficult. It is typically a time consuming and therefore costly operation to remove these encapsulation materials once applied. While methods for removal of conformal coating material can be practical and cost effective in limited cases, such as low volume, high value circuit boards, general repair and remanufacture of encapsulated circuit boards is often not feasible. Due to the greater thickness of epoxy and silicon potting materials (10 to 25 times or more greater than conformal coatings), potting material removal presents a significant challenge to the repair, remanufacture and reuse of circuit boards so encapsulated, and generally applicable, cost-effective approaches for repairing potted boards do not exist.

The objective of this project was to identify and demonstrate in the laboratory, a proof of concept method allowing cost-effective repair, remanufacture and reuse of printed circuit boards encapsulated with epoxy and silicone potting materials.

Major challenges associated with this objective are the definition of material removal processes that are environmentally friendly, do not damage underlying PCB surfaces or fragile components, and that are cost-effective.

Two potting material removal methods, laser ablation and micro abrasion, were selected for evaluation. Since conventional media blasting or abrasion is an accepted method used to remove conformal coatings during PCB remanufacturing, micro abrasion was selected as it could have potential for reducing damage imparted to underlying PCBs by conventional media abrasion processes.[1] Laser ablation was selected as a process technique that might provide benefits with respect to the generally greater thickness of epoxy and silicone potting materials. Both methods offered the potential to be controllable, repeatable, automatable, and relatively potting material composition independent, and were experimentally tested for efficacy in removing epoxy and silicone circuit board potting materials.

The expected output of this project was identification of a cost-effective laser ablation or micro abrasion PCB potting material removal method with a technology development maturity level of TRL 3 to 4 that would warrant further development.

Project Objectives and Benefits

The goal of this exploratory project was to identify at least one cost-effective method to remove epoxy and silicone potting materials from printed circuit boards (PCBs) that would warrant further development. There are three general families of PCB encapsulation methods; conformal coating (clear, hard, thin coatings), epoxy potting (thick relatively hard coatings that can be opaque), and silicone potting (soft, rubbery, and often clear coatings). Current technologies for conformal coating removal operate on the scale of minutes for removal of 0.005" thickness; here, this project was targeting minutes for removal of potting material from a similar surface area, but with thicknesses that may be 10 to 25 times or more greater than typical conformal coating thicknesses. Baseline processes used by industry today for conformal coating removal manually operate on small local areas, with removal taking on the order of 10-30 minutes. Because of the time consuming nature of conformal coating removal processes, they are typically cost-effective only on very low volume repairs of high value components.

Remanufacturing of PCBs is currently limited by the ability to effectively remove potting material from the surface of the electronic circuit boards without damaging exposed components or other sections of the PCB. Strategically removing potting material from local regions on a PCB will allow specific components to be replaced or provide access to connections for board functional test and validation. This project addressed the REMADE identified barrier that a method for restoring components to "like-new" condition is not available, limiting the ability to reuse components. The REMADE defined knowledge gap states, "There are no cost-effective technologies for removing the conformal coating or potting from circuit boards, limiting the ability to repair and reuse circuit boards".

A cost effective method to remove potting material would allow for increased remanufacturing and reuse of circuit boards in heavy duty, appliance, and automotive industry service and repair

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[1] Methods currently employed to remove conformal coatings from PDBs include application of chemical solvents, thermal removal, scraping and grinding and micro abrasion. https://www.vaniman.com/ultimate-conformal-coating-removal-guide/#:~:text=How%20To%20Remove%20Conformal%20Coating%20Using%20A%20Micro,components.%203%20Procedure%20by%20CTR%20guide%20section%202.3.6

applications. Potted electronics are also used in marine, aerospace, outdoor lighting, PV (photovoltaic), communications, and military applications (among others).

To this end, the project objective was to develop and demonstrate, in the laboratory, a proof-of-concept method for removing potting material from a select portion of a PCB without damaging exposed components or remaining sections of the board. Two material removal methods, laser ablation and micro abrasion, were evaluated.

Caterpillar reported that approximately 25% of their electronics are potted, and that these units are not remanufactured due to a lack of a cost-effective potting removal process. Automotive electronics are similar in construction to heavy duty electronics but represent an even larger and growing market. Electronic components are approx. 0.2% of total vehicle weight[2], representing a volume of vehicle electronics of 62.7M kg annually (based on 17.25M annual US vehicle sales[3]. An estimated 15.7M kg of this volume could be realized for remanufacturing potential with an improved potting material removal process. When extrapolated through the heavy duty and automotive industries, using the Reman calculator in development at REMADE, the energy savings is approximately 50 TBtu.

In CoreCentric's appliance business, 10% of their current production is potted. A cost effective potting removal process would allow CoreCentric to double the number of potted boards that they remanufacture. Extrapolating across the industry approximately 4B kg of major appliances are replaced in the U.S. annually[4]. The percentage of electronics in refrigerators and washing machines is 0.17%, and 0.37% respectively[5]. Applying an average value, approximately 10.8M kg of appliance electronics enter the U.S. market annually. Applying CoreCentric's data, approximately 2.2M kg of this volume requires a potting removal solution for repair and reuse

Projected impact of improved PCB potting material methods applied across the many industries and applications mentioned shows a reduction in embodied energy of 53 PJ.

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[2] J. Tian and M. Chen, "Assessing the economics of processing end-of-life vehicles through manual dismantling," Waste Management, vol. 56, pp. 384-395, 2016.

[3] T. Lassa. (2018, 2018-01-04T07:55:05-07:00) U.S. Auto Sales Totaled 17.25-Million in 2017. *Automobile Magazine*. Available: http://www.automobilemag.com/news/u-s-auto-sales-totaled-17-25-million-calendar-2017/

[4] U. S. EPA, "Advancing Sustainable Materials Management: Facts and Figures 2013: Assessing Trends in Material Generation, Recycling and Disposal in the United States," vol. EPA530-R-15-002, ed, June 2015.

[5] T. Matsuto, C. H. Jung, and N. Tanaka, "Material and heavy metal balance in a recycling facility for home electrical appliances," *Waste Management,* vol. 24, pp. 425-436, 2004.

Project Approach

Roles and Responsibilities

Four test cases covering selected potting materials and removal processes were evaluated, as shown in Table 1.

Table 1. Test Cases

Process	Potting Material	
	Epoxy	Silicone
Micro Abrasion	Test Case 1	Test Case 2
Laser Ablation	Test Case 3	Test Case 4

Each test case was evaluated for potting material removal efficacy. Removal efficacy was measured in terms of ability to achieve material removal rates necessary to provide a cost effective removal process without causing damage to underlying PCBs or their components.

Rochester Institute of Technology (RIT) was responsible for developing and creating potting material samples for test, creating test plans, coordinating with vendors and analyzing test results. Industry partners, Caterpillar Inc. and CoreCentric Solutions identified test potting materials used on current product PCBs, and provided samples of potted PCBs and required process removal rates necessary to achieve cost effectiveness, see Figure 1.

Figure 1. Industry Partner Potted PCB Samples
An industry partner epoxy potted PCB is shown on the left and an industry partner silicone potted PCB is shown on the right.

Project Plan

Initial baseline or feasibility screening trials were defined and executed. The purpose of these screening tests was to identify the range of process operating conditions for each test case yielding the highest material removal rates, without imparting damage to underlying PCBs. Based on initial screening trial results, refined and optimized test trials were defined and executed.

Finally, based on refined trial results, process confirmation and demonstration using functional potted PCBs was planned. Figure 2 depicts the overall project plan.

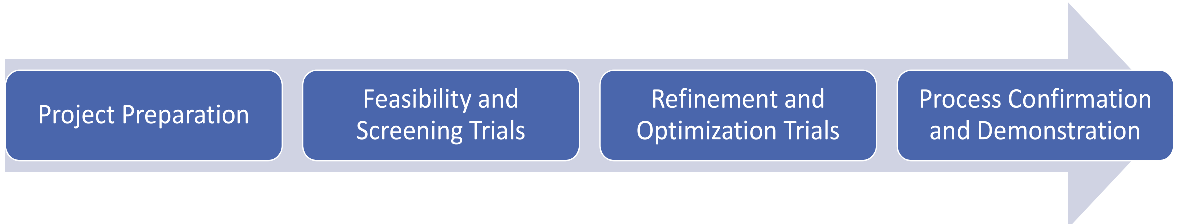

Figure 2. Project Plan

Defined test trials for the test cases shown in Table 1 included process parameters illustrated in Figure 3.

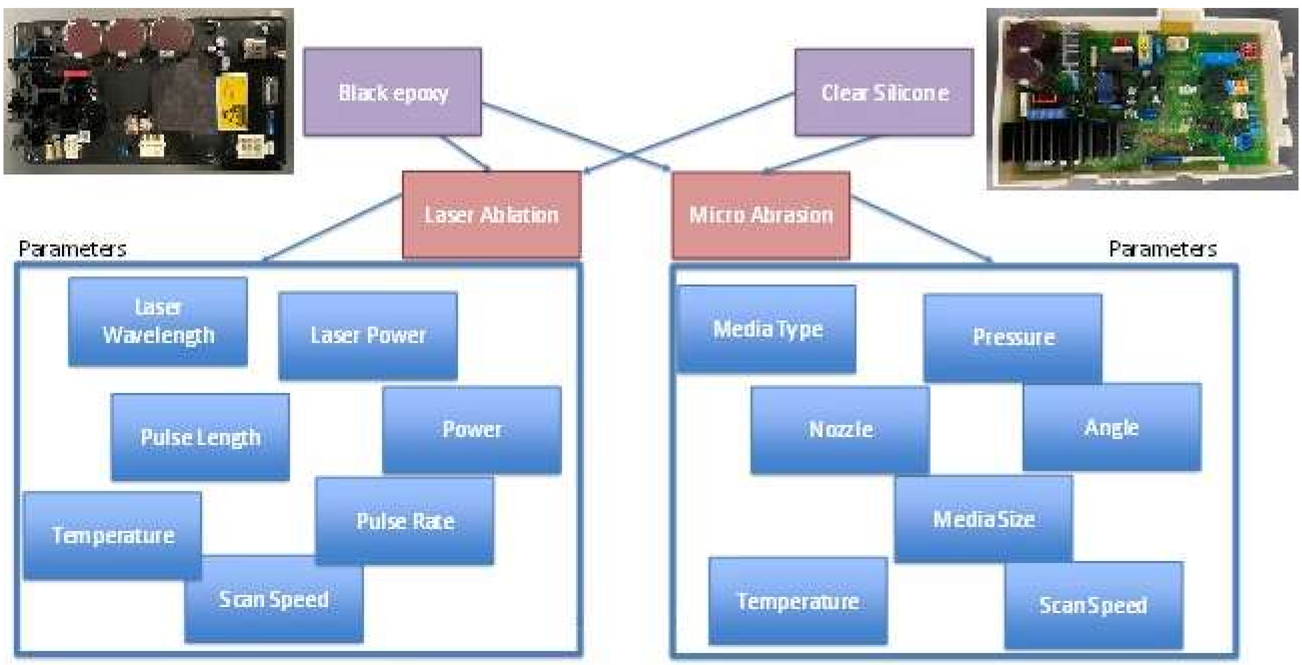

Figure 3. Screening Test Trial Process Parameter Definitions

Micro Abrasion Overview and Screening Trials

Media blasting or abrasion technologies use high pressure air to accelerate an abrasive media at a substrate. While conventional media blasting or abrasion is currently used for removal of conformal coatings, it is quite aggressive and has limited control over blast area, often resulting in unacceptable damage to underlying PCBs. Micro abrasion uses smaller nozzles and higher abrasive media speeds and has proven useful for a variety of very accurate material removal applications. Micro abrasion was selected for evaluation for this project due to its superior controllability. This project investigated effects on potting material removal rates based on type of media, nozzle pressure, nozzle design, and debris.

Ductile materials can be a challenge to remove via blasting, and brittle thermoset polymers are shown to have higher erosion efficiencies than ductile thermoplastics and elastomers[6]. Epoxies are brittle at room temperature, and erosion data on epoxy materials at very high media speeds[7] suggest that removal times of 1 minute for a 1-inch square section of potting material are possible. Silicone, in contrast, is ductile at room temperatures; however, removal rates of ductile polymers have been accelerated at low impact angles (approaching 30°)[8]. Erosion rates of ductile polymers have also been shown to be greatly accelerated at low temperatures (-35C), particularly for materials, such as silicone, with low glass transition temperature[9]. A simplified micro abrasion system is illustrated in Figure 4.

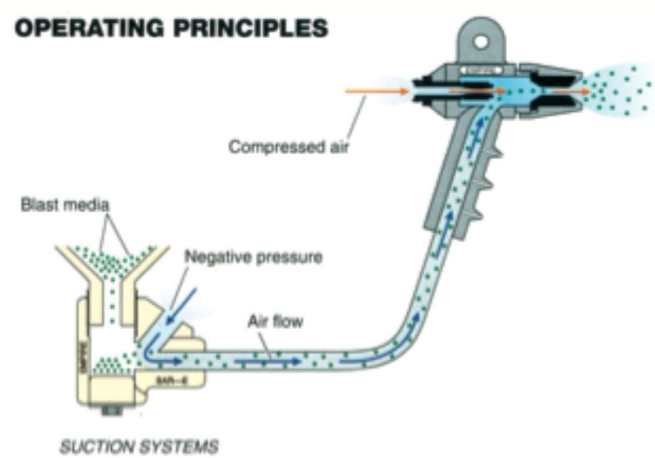

Figure 4. Typical Micro Abrasion System

All industrial blast systems have media delivery systems, containment systems, reclaim systems and dust collection systems.[10]

The goal of the micro blasting screening trials was to evaluate a range of process parameters and determine if material removal was high enough to warrant more structured designed experiment testing with a reduced set of process parameters. Parameters shown in Table 2 were controlled during micro abrasion screening trials.

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[6] S. Arjula and A. P. Harsha, "Study of erosion efficiency of polymers and polymer composites," *Polymer Testing,* vol. 25, pp. 188-196, 2006.
[7] G. P. Tilly and W. Sage, "INTERACTION OF PARTICLE AND MATERIAL BEHAVIOUR IN EROSION PROCESSES," *Wear,* vol. 16, pp. 447-465, 1970.
[8] N. M. Barkoula and J. Karger-Kocsis, "Processes and influencing parameters of the solid particle erosion of polymers and their composites," *Journal of Materials Science,* vol. 37, pp. 3807-20, 2002.
[9] K. Friedrich, "Erosive wear of polymer surfaces by steel ball blasting," *Journal of Materials Science,* vol. 21, pp. 3317-32, 1986.
[10] M. C. Finishing. “Blasting Technical Information”. http://mcfinishing.com/resources/blastingtech.pdf

Table 2. Micro Abrasion Screening Trial Test Parameters

Test Parameter	Test Values
Abrasion Media type and particle size	Silicon carbide, crushed glass, aluminum oxide, pumice and sodium bicarbonate
Nozzle Orifice	0.020 – 0.030 in.
Nozzle Angle	15 - 50°
Pressure	40 – 115 PSI

Laser Ablation Overview and Screening Trials

Laser ablation uses high energy levels to remove material in thin layers. This technology is sometimes used to remove conformal coatings; however, it has not been used for potting material removal, because the volume of material to be removed makes the process time too long. A primary investigation of this project was to determine the effect of increased laser power necessary to improve potting material removal rates, with respect to PCB and component damage.

Different laser technologies are used in industrial applications today for removing things like paint, oil, and other contaminants. Carbon dioxide (CO_2) lasers operate at an Infrared (IR) wavelength of (10.6µm). Yttrium aluminum garnet (YAG) lasers operate from near IR to ultraviolet (UV) wavelengths (1.06 µm -355nm), while excimer lasers operate from 193 to 351nm wavelengths and support short duration pulsing. Longer wavelengths apply deeper thermal effects, melting the target material, and generally allow for faster material removal than shorter wavelengths

At lower UV wavelengths, photons have higher energy and thus can break chemical bonds in polymers, allowing ablation directly to a gaseous state without melting. Lower wavelengths provide cleaner and more controlled material removal, and shortened pulse durations provide effective material removal with minimal heat transfer to surrounding materials.[11]

A simplified laser ablation system is illustrated in Figure 5.

[11] B. M. and A. C., "Fundamentals of Laser-Material Interaction and Application to Multiscale Surface Modification," *Laser precision microfabrication,* pp. 91-120, 2010.

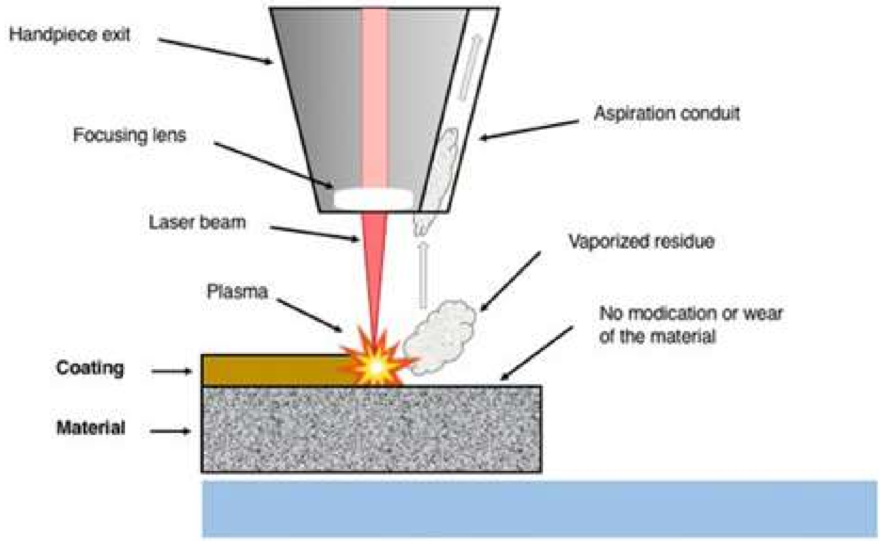

Figure 5. Typical Laser Ablation System

The goal of the laser ablation screening trials was to evaluate a range of process parameters and determine if material removal was high enough to warrant more structured designed experiment testing with a reduced set of process parameters. Parameters shown in Table 3 were controlled during laser ablation screening trials. Specific laser ablation screening trial controlled parameters were a function of equipment capabilities and resources available at particular laser testing contractors.

Table 3. Laser Ablation Screening Trial Test Parameters

Test Parameter	Test Values
Laser wavelength	UV (355 nm), Green (532 nm) and IR (1064 nm)
Pulse length / frequency	50 – 300 KHz
Focus spot size	Laser system optics dependent
Average Laser Power	Wavelength dependent

Test Material Selection and Target Removal Rates

Industry partners, Caterpillar, Inc. and CoreCentric Solutions, provided material removal rates necessary to provide cost effective removal processes with respect to PCBs of interest in their respective businesses.

Caterpillar Inc.	Epoxy Removal Rate	1.64 cc / min
CoreCentric Solutions	Silicone Removal Rate	2.73 cc / min

In general, the volumetric removal rate of potting material required to provide a cost effective process will vary with the value of the PCB impacted. The example PCB selected by Caterpillar represented a higher value assembly than the example selected by CoreCentric Solutions and thus a slower removal process was able to provide a cost effective solution.

One epoxy and one silicone formulation were selected by the industry partners based on example PCB usage.

Caterpillar Inc.	Epoxy	STYCAST 2850 FT
CoreCentric Solutions	Silicone	Sylgard 184

Identified materials were used to create material blanks approximately 2” x 2” x ¾” for use in initial screening trials. A sample of the blanks is shown in Figure 6.

Figure 6. Material Sample Blanks for Screening Trials
Epoxy sample blanks (left) and silicone sample blanks (right) were fabricated for initial process screening trials.

Results of initial screening trials were used to select processes warranting further refinement and investigation. The final goal was to validate selected processes on both industry partner supplied example boards and functional test boards developed at RIT.

Project Accomplishments

The starting goal and objective for the project was to identify at least one method to remove epoxy and silicone potting materials from printed circuit boards (PCBs) that would warrant further development. Successful attainment of this objective was defined as being able to define one of the two material removal methods being investigated, micro abrasion or laser ablation, as a process being capable of meeting material removal rates at an acceptable cost and that would be environmentally friendly. There was also an assumption that the defined process would not impart damage to boards being processed.

The initial assumption that one or both of the material removal processes selected for evaluation, micro abrasion or laser ablation, would be successful at removing both silicone and epoxy potting materials proved false. Neither material removal method proved efficacious with respect to silicone potting material. Laser ablation using a 532 nm laser source did show some success with silicone material, but due to project challenges, was not able to be thoroughly investigated.

Laser ablation did show promise as a potential method for the removal of epoxy potting material. While laser ablation was able to achieve the material removal rates necessary to provide a cost effective process, and would be significantly more environmentally friendly than current chemical based removal methods, laser power levels necessary to ablate and remove epoxy potting material were sufficiently high to impart damage to surrounding PCB surfaces.

Some preliminary investigation indicated that with appropriate sensing technology, control of the laser source at the potting material to PCB interface layer might be possible to allow ablation down to the board surface without damaging the board. A significant technology development effort, well beyond the scope of this project, would be required to pursue this investigation.

Project Results

The following sections of this report document the project results by Task as defined in the SOPO.

Task 1. Establish Experimental Test Plan, Prepare Test Samples, and Quantify Success Criteria for Removal of Epoxy and Silicone Potting Materials

Task 1. Objectives

This initial task will include the establishment of a screening test plan to evaluate the effectiveness of laser ablation and media blasting for removal of potting materials from PCB's. This initial test is not expected to identify the final solution, but will narrowing the parameters to the few key parameters with the greatest impact (Subtask 1.1). The key parameters will be used in the factorial DoE in Task 3. RIT will also prepare blank potting material samples to use for potting rate removal trials (Subtask 1.2). Based on input from Caterpillar and CoreCentric, RIT will design functional test boards that represent features and components likely to be damaged by either of the removal processes. These boards will be designed at RIT and fabricated by an approved RIT vendor. (Subtask 1.3) RIT, Caterpillar and CoreCentric will establish the feasibility cost threshold that the two processes must meet. The outcomes of this task will include the experimental test plan, test samples, and the feasibility cost threshold.

Task 1. Results

Screening trial test plans were established. Screening test plans and test plan parameter definitions were constrained based on available contractor equipment and resources. General Lasertronic Corporation was selected as the laser ablation contractor and Comco was selected as a micro abrasion contractor. Vendor access and equipment constraints due to COVID-19 caused schedule delays but had no material effect on the project results. Initial test materials were identified by the industry partners for the example PCBs, as follows:

Caterpillar Inc.	Epoxy	STYCAST 2850 FT
CoreCentric Solutions	Silicone	Sylgard 184

The industry partners provided the following removal rate metrics necessary to define a cost effective process with respect to their specific PCBs:

Caterpillar Inc.	Epoxy Removal Rate	1.64 cc / min
CoreCentric Solutions	Silicone Removal Rate	2.73 cc / min

Identified sample materials were used to create material blanks approximately 2” x 2” x ¾” for use in initial screening trials. See Figure 6.

Initial epoxy sample blanks created using STYCAST 2850 FT had a hardness 30 percent higher than industry partner sample boards and were determined to not be sufficiently representative of actual components. A new potting material was identified through a survey of commercial materials with a hardness value more closely matching that of industry partner example boards. The new selected material was Lord Thermoset EP-20 Resin.

Task 2. Conduct Laser Ablation and Media Blasting Feasibility Trials

Task 2. Objectives

RIT will conduct initial feasibility trials to investigate the effect that different process variables have on the maximum achievable potting removal rate. These trials will also evaluate way to tune the laser ablation and media blasting processes to achieve fine removal without imparting damage near the potting material/PCB board interface. There is a potential to utilize one set of parameters for the bulk of the potting material removal and a less aggressive set of parameters at the PCB surface. This will enable preliminary evaluation of each technology and identify the range of values for process control variables that achieve the highest removal rate with no board damage. The potting removal rate will be assessed by measuring sample weight loss and material removal depth. During feasibility testing, visual and micrographic analysis will be used as the primary measures of circuit board damage. The inspections will look for physical damage such as divots and cracks as well as heat related damage such as discoloration or melting. In addition to removal rate studies, a selection of unique potted circuit boards with different potting material formulations from Caterpillar and CoreCentric will be tested at the identified high removal rate processing conditions for each technology to determine whether the removal rates for other epoxy or silicone formulations are significantly different. Two potential contractors for laser removal trials (General Lasertronic Corporation and IPG Photonics) have been identified based on the wide range of laser technologies (across a range of wavelengths and pulse lengths) that are available in their application labs (e.g. Nd:YAG, Fiber, Solid State Diode), as well as each vendor's experience with conformal coating removal. The contractor will be selected based on RITs review of additional research on polymer removal by laser, and mapping of the range of technologies available at each potential contractor against the research findings. The outcome of this task will be a summary of the major findings from the feasibility trials including process operating conditions that yield the highest removal rates with no board damage and a comparison of the cost estimate for each removal technology with the feasibility cost threshold.

Task 2. Results

Based on test facility equipment capabilities, laser ablation designed experiments were conducted comparing average power vs. number of passes, pass spacing (beam overlap) vs. number of passes, and scan speed vs. number of passes or comparing irradiance, translation speed, number of passes and time between passes. Results are summarized in Table 4.

Table 4. Laser Ablation Screening Trial results

Potting Material	Laser Wavelength and Power (nm, W)	Maximum Ablation Rate Achieved (cc/min)	Test Facility
Silicone	532 nm (Green) 50 W	0.1	IPG Photonics
	1064 (IR) 500 W	Some transformation within the silicone observed but no material removal. Laser ablation with IR and UV lasers tested was determined to not be a feasible solution.	Lasertronics
	355 nm (UV) 40 W		Lasertronics
Epoxy	532 nm (Green)	1.0	IPG Photonics
	1064 (IR)	17	Lasertronics
	355 nm (UV)	0.1	Lasertronics

The best laser ablation result for silicone potting material was obtained using a 532 nm (green) laser with an achieved material removal rate of 0.1 cc/min. While slightly more than 27 times lower than the threshold removal rate determined by CoreCentric Solutions, and understanding that significant improvements would be required, it was decided to pursue use of the 532 nm laser for silicone potting material removal in subsequent optimization test trials.

The best result for epoxy was with a 1064 nm (IR) laser, which achieved a material removal rate of 17 cc/min, slightly more than 10 times higher than the threshold removal rate determined by Caterpillar Inc. in order to provide a feasible removal process.

While the 532 nm green laser also demonstrated positive performance for removal of epoxy potting material, it was dropped as a candidate for further investigation due to the more promising performance of the IR laser.

While laser ablation showed promise with respect to being a viable process for removal of PCB epoxy potting material, laser power levels employed effected the underlying PCB. Visual damage to non-potted test PCBs was clearly evident, as shown in Figure 7 and Figure 8.

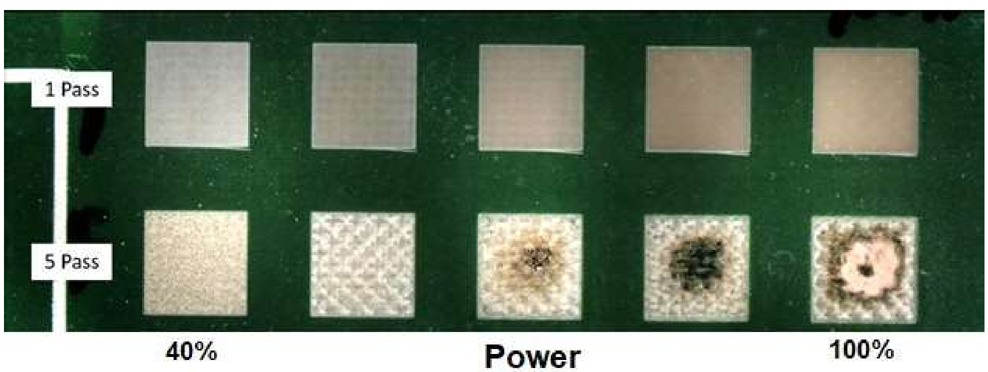

Figure 7. Non-potted PCB Surface Damage from Ablation Laser

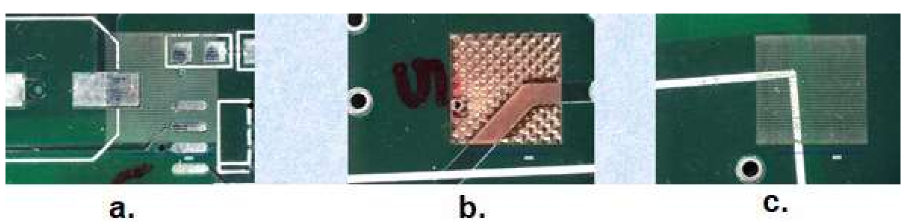

Figure 8. Non-potted PCB Trace and Pad Damage from Ablation Laser

PCB surface, trace, and pad damage greatly increased as laser power and number of passes increased. To be a viable potting removal process, a high level of process control will be required to prevent PCB and component damage at the potting material – PCB and potting material – component interfaces.

Media abrasion trials varied the pressure from 40 to 115psi, the blast angle from 15 to 45 degrees, and nozzle size from 0.025” to 0.030”. Sodium bicarbonate, pumice, aluminum oxide, and crushed glass media were tested. Results are summarized in Table 5.

Table 5. Media Abrasion Screening Trial results

Potting Material	Maximum Abrasion Rate Achieved (cc/min)	Test Facility
Silicone	0.004	Comco Industries
Epoxy	0.02	Comco Industries

Media micro abrasion material removal rates for both silicone and epoxy potting materials were significantly below the threshold removal rates determined by CoreCentric Solutions and Caterpillar Inc. for feasible processes. Micro abrasion was determined to not be a viable PCB potting material removal process and was excluded from further investigation.

Task 3. Refine Process Conditions for Laser Ablation and Media Blasting

Task 3. Objectives

Feasibility trials from Phase 1 will have narrowed the operating range of each process variable to be considered during this phase. Based on that information, a design of experiments (DoE) will be used to identify specific process parameters to apply during laser ablation and/or media-blasting removal of epoxy and silicone potting that achieve optimal potting material removal rates without damaging the boards. Sample weight loss (g/min) will be used to measure the material removal rate. Laser ablation and media blasting processes will be conducted using non-potted functional test boards to enable a more quantitative measure of board damage. RIT will analyze the results of the process refinement DoE. This data will be used to support a final process recommendation. The outcome of this task will include presentation of potting removal rates achieved using the optimized operating conditions for each technology and potting material combination.

Task 3. Results

Initial laser ablation screening tests using an IR laser source on epoxy potting material produced material removal rates significantly higher than that needed to provide a cost effective material removal process. While removal rates were positive, tests indicated that the laser system used lacked the required control of laser energy application to avoid PCB damage.

To address this issue, a highly controllable X-Y scanning system and improved laser optics and debris removal were implemented on the IR laser system. In addition, tests were conducted with surface recognition technology to investigate the ability to control laser power at the potting material – PCB boundary layer.

Tests similar to the initial screening tests were conducted using the IR laser on epoxy potting material sample blanks, where laser power, number of passes, and scan rates were varied. In general, test results indicated higher powered laser pulses, distributed over a broader area, successfully removed the potting material with lower bulk heating of the surrounding material compared with lower powered pulses.

No ablation occurred at a laser power level of 200 W. Rather, material samples softened, flowed and broke apart after cooling. While ablation occurred at a laser power of 300 W, material temperature increased to the point causing slight material softening. Laser power levels of 400 and 500 W produced clean ablation. Results tend to track typical ablation applications, where material removal rates increase approximately proportionately with average laser power once a threshold level is reached, and higher laser power and increased power density reduces thermal penetration into the material being ablated and therefore causes less material temperature rise. See Figure 9 and Figure 10.

While refinement of laser ablation applied to silicone potting material using a 532 nm (green) laser was intended per Task 2, the laser subcontractor with this equipment, IPG Photonics, did not quote on performing this work. Due to the amount of refinement necessary, ablation of silicon with this wavelength was not pursued using other avenues.

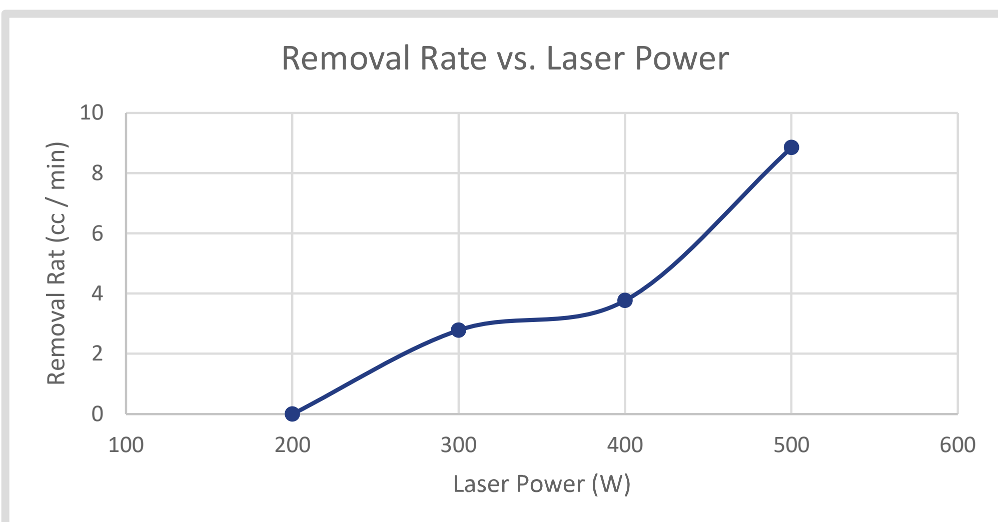

Figure 9. Material Removal Rate vs. Laser Power

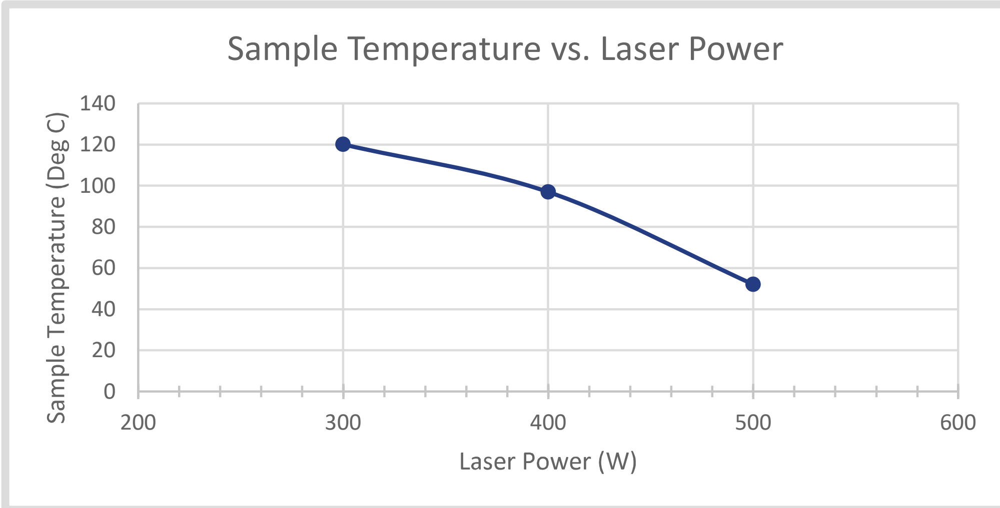

Figure 10. Sample Temperature vs. Laser Power

Figure 11 shows a material sample blank after ablation at a laser power level of 400 W. The material removal rate attained was 3.77 cc / min, approximately 2.4 times the rate necessary to be considered an economically viable process. Material ablation surface temperature rose to 97 °C.

As expected from initial screening trials, laser power levels required to achieve clean ablation of the epoxy potting material were high enough to produce damage of PCB surfaces. Typical damage at a laser power level of 300 W is shown in Figure 12.

Figure 11. Sample after Ablation
Ablation results using a laser power of 400 W.

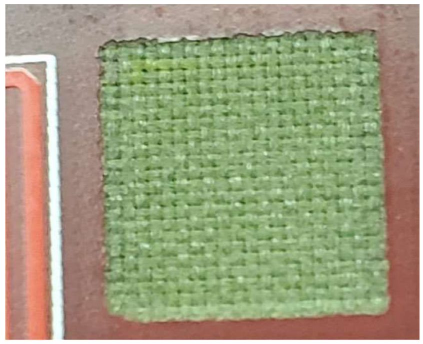

Figure 12. PCB Surface Damage at 300 W

The use of surface color sensing technology was investigated as a potential means to control laser power at the potting material to PCB surface boundary to prevent the type of damage shown above.

The IR laser system employed for testing used laser pulses with a nominal width of 100 ns and a repetition rate of 10 KHz or pulse separation time of 100 μs. The color sensor employed took 64 surface color measurement in the final 8 μs of the 100 μs pulse repetition window. The eight measurements were processed to produce a signal capable of providing laser control prior to firing the next pulse. Signal to noise ratio testing indicated an ability to detect dark red, bright red, and green PCB solder mask colors. Dark green and black solder mask colors were not reliably detectable with the color sensor employed.

Laser control tests with the color sensor were planned for potted PCBs, but were not conducted due to resource and other (COVID associated) constraints at General Lasertronic Corporation. (See Project Challenges below)

Task 4. Confirm the Performance of each Potting Removal Process by Conducting Process Demonstration Trials

Task 4. Objectives

In the final task, RIT will use the optimized process conditions for laser and media blasting to validate that process conditions produce repeatable performance by testing six (6) potted functional test boards (three of each of the two potting types), as well as the six high value core boards that were provided by the industry partners in Task 1. The outcome of this task will be a summary of the results from potting removal demonstration tests.

Task 4. Results

Laser ablation tests using potted industry partner and functional test boards developed by RIT were planned to demonstrate the ability to control laser power at the potting material to PCB surface boundary layer using the surface color detection sensor. These tests were not conducted due to the complexity and cost of the controls that would be needed. This activity would require a larger budget and more time than available within the exploratory project.

Other Project Products

There were no other products developed under this project award and technology transfer activities.

Project Conclusions and Recommendations

The goal of this exploratory project was to identify material removal processes for silicone and epoxy PCB potting materials that were economically viable, environmentally friendly, and presented no threat of damage to underlying PCBs. Laser ablation and media abrasion were selected as the processes to investigate.

Neither laser ablation nor micro blasting proved to be a viable removal process for silicone potting materials. Laser ablation testing on Silicone showed some material removal in screening tests with a 532 nm green laser; however, attempts to increase removal rates were not actually able to achieve ablation (versus burning of the silicone). (See Recommendation for Future Work below)

Screening tests of micro blasting on epoxy resulted in material removal rates below the threshold target value and further development was not conducted. In laser ablation screening of Epoxy potting, both 532 nm (Green) and 1064 nm (IR) lasers generated ablation; however, ablation with the IR laser was much higher. Additional development indicated that the IR laser could achieve the minimum removal rate defined as a project economic feasibility threshold. However, at these process conditions, the laser power was high enough to impart significant damage to PCB surfaces. The initial economic feasibility criteria were based primarily on labor costs and do not include amortization of needed equipment (See Appendix A for estimated equipment costs).

In order to complete the planned testing on real functional circuit boards, a means of detecting the PCB and PCB component boundary would be required in order to reduce laser power and prevent board damage. Developing the controls needed to achieve this were beyond the scope of the project (budget and timing) and this was therefore not undertaken.

Project Challenges

A number of modifications were required during execution of this project in response to various project impacts. The ability of RIT and vendor labs to execute project testing was greatly impacted due to the COVID-19 pandemic. Both RIT and vendor labs experienced various levels of restrictions, ranging from complete closure to highly restricted work forces. Travel planned to coordinate and manage testing was not possible, and all testing coordination had to be done remotely. Certain tests planned based on results of initial screening trials had to be canceled due to vendor lab closures and work force restrictions. The ability to implement vendor equipment modifications to perform enhanced test trials was reduced due to vendor work force challenges and supply chain issues.

Recommendations for Future Work

Removal of PCB epoxy potting material using laser ablation showed promise as a potential method of removing relatively thick layers of potting material in a timely, i.e. cost effective manner.

Unfortunately, laser power levels necessary for material removal were sufficient to impart damage to surrounding PCB surfaces. While some initial investigation indicated that it may be possible to control the laser source using sensing technology to prevent board damage at the potting material to PCB surface boundary layer for certain colors of solder mask, additional work is necessary to develop this technology.

The initial sensing technology investigated was based on sensing the color difference between the dark epoxy material and the color of the underlying PCB solder mask. Using PCB CAD models, it may be possible to generate a “depth map” indicating where component and PCB surfaces lie under the potting material, and control the ablation process based on depth instead of color. This would alleviate the issue of being able to detect the difference between the dark potting material and board integrated circuit devices, which are often housed in black packages.

It should be noted that only *overall* ablation material removal rates were studied as part of this exploratory project, not *average* rates. Through further analysis, if it is found that average ablation rates are well controlled for a given potting material, an approach based on depth mapping based on PCB CAD models might prove to be quite effective.

Appendix A: Laser Ablation System Cost Estimate

While laser ablation achieved defined material removal rates for epoxy potting material necessary to indicate a cost effective process, capital equipment costs to perform potting material ablation is significant and could affect viability. A cost estimate to duplicate the IR laser system employed by General Lasertronics Corporation to perform laser ablation tests on PCB epoxy potting material is outlined below.

Table 6. Laser Ablation System Cost Estimate

Item	Quantity	Description	Cost
1	1	1000i 500W Laser Ablation System	$480,000.00
2	1	Model D Color-Selective Work head	$90,000.00
3	1	10-meter umbilical and test bed, pre-assembled and tested	$4,000.00
4	1	Remote Safety Box	$5,000.00
5	1	Integrated HEPA Waste Collection System	$20,000.00
		Total:	$599,000.00

A service contract to provide warranty support past the initial one year warranty period was quoted at $10,000.00 per year.