Space Debris Mitigation Utilizing Laser Ablation

Bret Silverstein,[1] Travis Brashears,[2] Philip Lubin,[2]
[1]*Academy of Allied Health and Science, 2325 Heck Avenue, Neptune City, NJ 07753*
e-mail address: bretsilverstein@gmail.com
[2]*Department of Physics, UC Santa Barbara, CA 93106, USA*

Space debris poses an increasingly serious threat to satellites and spacecraft. Our project will aim to mitigate this problem using an array of kilowatt-class lasers, powered by photovoltaics. An experiment was implemented to study this using a directed energy system to completely vaporize or propel space debris out of Earth's orbit. Common materials found in space debris were tested using a $60MW/m^2$ laser to simulate mission level flux. We vaporized samples in a low thermal conductive sample holder inside a vacuum chamber. The difference in the reflection of a measurement laser aimed at a mirror on the torsion balance correlated with success of vaporization/ablation. Applications of this system include diminishing or propelling space debris, which can result in reduced risk of collision.

Keywords: Space debris mitigation, laser ablation, directed energy, vaporization, Kessler syndrome

I. INTRODUCTION

Space debris is currently a serious impediment to the operation and deployment of Earth orbiting technology. Currently, there are more than 500,000 pieces of space debris being tracked with millions more too small to be accounted for. These pieces can travel to extreme speeds of up to 17,500 mph. At these speeds even a small segment of debris can cause damage to a satellite or spacecraft in a collision [1]. As debris collides with these satellites, more debris is created, increasing the likelihood of future collisions. This scenario is called Kessler syndrome, named after the NASA astrophysicist, Donald J. Kessler, and is a significant issue [2]. There are about 1300 satellites in the area of the atmosphere known as low-Earth orbit, between 160 and 2000 km above Earth. Space debris traveling at high speeds in this area can damage spacecrafts or satellites, and potentially endanger the lives of astronauts [3].

Fairly recently, incidents involving space debris have increased the amount of debris in orbit and detailed the larger problem that will arise if this debris continues to accumulate. Most recently, in February of this year, an American weather satellite exploded, due to a faulty battery. In 2007, China intentionally destroyed their own spacecraft while testing an anti- satellite weapon [3].

On February 10, 2009, the inoperable Russian satellite Cosmos 2251 collided with the American satellite Iridium 33 destroying both satellites and creating over 500 large pieces of debris along with many smaller ones [4].

A number of solutions have been suggested to deal with the problem [3][5]. Use of nets and tethers have been suggested to capture debris, as well as the use of lasers, both in space, or ground based. Future satellites might even be designed to self-destruct after a designated lifespan [3].

The Japanese research institute RIKEN suggests the use of a laser directed at debris by a telescope in the International Space Station. It would be equipped with an energy efficient system to reduce the high electrical needs of the laser [5].

Previously proposed laser systems have limitations in their usefulness. Ground based lasers could inadvertently endanger objects in their path. A laser as proposed by RIKEN that was part of the ISS is a plausible solution but would not be powerful enough to vaporize large pieces of space debris. The system we suggest is called DE-STAR, for Directed Energy System for Targeting of Asteroids and exploRation and is outlined in detail in [6] [7] [8] [9]. This system consists of an orbiting modular array of kilowatt-class lasers powered by photovoltaics. If the array was of sufficient size, it would be able to ablate the surface of pieces of space debris causing a reactionary thrust and propelling it out of orbit. In some cases, the array would be able to completely vaporize the debris. DE-STAR was originally designed for the deflection of asteroids coming towards Earth but is a plausible solution to the problem of space debris.

The current experiment sought to clarify the characteristics of materials amenable to vaporization and the degree of thrust produced using a 60MW/m2 laser on samples with different ranges of thermal conductivities, including aluminum, titanium, carbon fiber, and stainless steel, though it is noteworthy that the theoretical models proposed suggested that vaporization can occur on materials of any thermal conductivity if the laser is powerful enough [9]. By calculating the size of the material able to be completely vaporized with our laser, a coupling coefficient can be determined that will correlate size of the debris with the Watts required to vaporize it. The laser power required to vaporize actual space debris can be evaluated by scaling up this coefficient. Assessment of the laser's success in these scenarios, as well as calculation of power needs, are critical to predictions for its long term practical application to address this significant and increasingly troublesome problem.

II. METHODS

The questions posed above required an experimental framework to respond to. We developed and used a system composed of a 60 MW/m^2 laser, a vacuum chamber, and a torsion balance for the testing of samples. Experiments were structured to measure the thrust produced at different levels of laser power.

The laser operates at a wavelength of 808 nm and is attached to a set of thermoelectric coolers. The laser feeds through a 810 micron diameter fiber optic cable connected to an anti-reflection coated lens that is aimed into the vacuum chamber through a quartz window at the sample.

We machined a torsion balance to measure the thrust the sample produces when it is ablated. It includes two adjustable counterweights to ensure the entire balance is level in both the horizonal and vertical directions. The balance has a sample holder one one end and a mirror on another used to refelect a measurement laser. The thrust created through ablation is measured using the measurement laser in conjunction with the torsion balance. It reflects back from the mirror diffferently when the sample is ablated and thrust is produced. A 10 mm x 10 mm Silicon 2D position sensitive centroid detector (PSD) captures the change in the position of the measurement laser and is converted to micronewtons of thrust. A laser-line band pass filter and a long-wave band pass filter are used to recieve the most accurate data possible. The laser-line filter only allows light in the 405 nm wavelength to pass through, the wavelength of the measurement laser used. The long-wave filter blocks light in the infrared spectrum. This reduces the leakage of light from the directed energy system. We place the torsion balance inside of the vacuum chamber and hang it from a 1.64 mm stainless steel fiber used for centering the measurement laser on the centroid detector. We placed a copper disc on the bottom of the balance and is used in conjuction with a rare eath magnet placed below it. This uses eddy-current

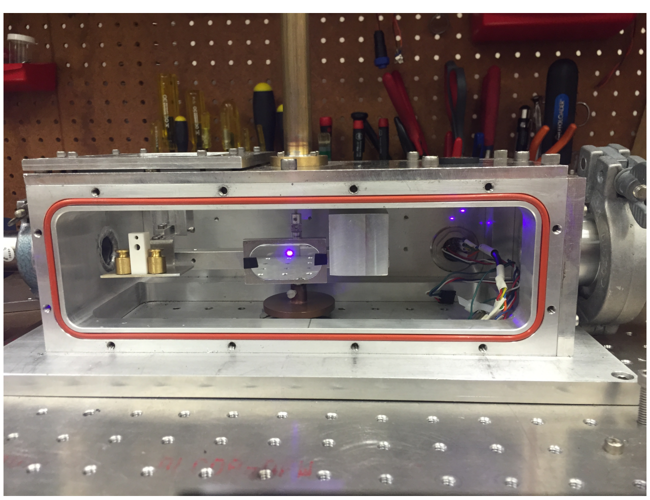

Figure 1. Front view of the torsion balance inside of the vacuum chamber. The purple measurement laser can be seen hitting the mirror in the center. The left side holds a sample of space debris inside of a macor holder.

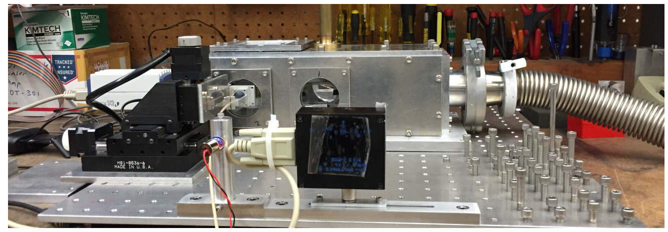

Figure 2. View of the vacuum chamber, laser, measurement laser, and centroid detector. Attached to the chamber, the vacuum tube can be seen on the right and a cathode pressure gauge on the left.

dissipation to reduce the amount of natural oscillations of the balance (**Figure 1**).

A container that could reach as low of a pressure as possible was constructed to simulate the space environment. A dual pump system including a roughing pump and a turbo molecular pump was used to achieve this. A disparrity of pressure exists between the area of the chamber nearest the pump and the far side of the chamber. This problem limits the pressure which can be achieved to a maximum of about 10 mTorr. A hot cathode pressure gauge was used to measure pressure and was located on the far end of the chamber (**Figure 2**).

The laser passes first through a quartz window, then through a quartz blast shield. The blast shield protects the outer window from damage caused by the high speed ejecta. Another quartz window is found in the middle of the vacuum chamber and allows the measurement laser to pass through (**Figures 2-3**).

A 2.54 cm x .95 cm holder was machined out of macor to hold space debris samples including carbon fiber, aluminum, ceramic paint, stainless steel, and titanium. A hole in the top of the piece allowed a small piece of debris to be inserted. Two other holes including a hole for a set screw and a hole for the laser to pass through were also made. The macor holder provides a low thermally conduc-

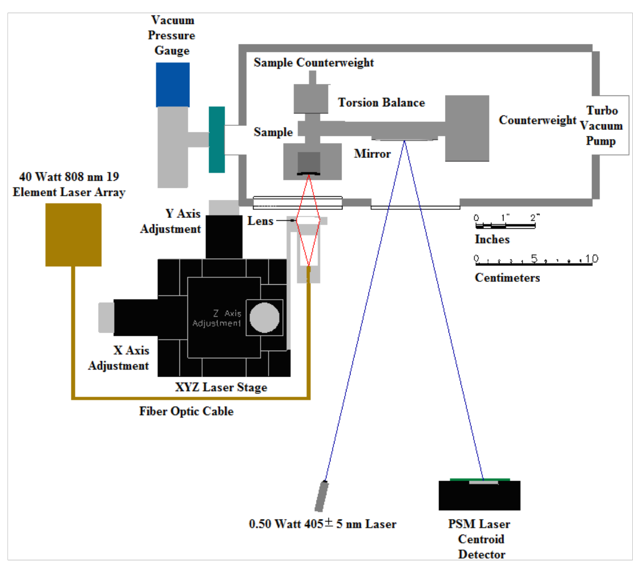

Figure 3. Top view of the entire setup. The torsion balance lies inside the vacuum chamber, the laser shines in through the quartz window onto the sample, and the measurement laser reflects off the mirror on the torsion balance.

tive environment for the sample in order to keep as much heat on the debris as possible.

The testing of samples of space debris is accomplished using the following lab procedure. First, the sample is placed in the macor holder and on the torsion balance. The balance is suspended in the air and balanced using the adjustable counter weights. Next, we place the balance in the vacuum chamber and attach it to the torsion fiber. The measurement laser is centered on the centroid detector and the side of the vacuum chamber is screwed on. Then, the pressure is reduced from 750 Torr to 10 Torr using a roughing pump at which point a turbo molecular pump further lowers the pressure to around 10 mTorr. When the chamber is at a sufficiently low pressure, the test can begin. For each test we collect one minute of noise data, then one minute with the laser on, and another minute of noise date. The results we report on are results of a series of power tests. The materials were tested at 15, 20, 25, 30, and 35 amps of laser current.

III. RESULTS AND DISCUSSION

Prior experimentation in this laboratory has resulted in a body of work detailing the success of the DE-STAR system as a potential solution for asteroid or comets threatening a collision with Earth. Directed energy laser ablation has been shown to exert an ejection plume on the asteroid, imparting thrust, and thereby allowing the asteroid itself to act as the deflection propellant. The current experiments sought to expand on the success of the DE-STAR system as a potential solution to mitigate the threat of space debris in Earth's orbit. As the amount of debris is likely to increase exponentially given the creation of new debris with every impact, this is a considerable threat. The aim of these experiments was to demonstrate the ability of DE-STAR to cause a reactionary thrust on the debris that might propel it out of orbit, and safely out of risk to spacecraft, satellites, and human astronauts. In some cases, DE-STAR is predicted to totally vaporize the debris. Samples of different thermal conductivities were tested to assess the degree of thrust and success in total vaporization of the space debris [10].

We completed five main experiments. The first being ablation of the reinforced polymer which makes up carbon fiber-reinforced polymer (CFRP) or simply carbon fiber. Carbon fiber squares 20 mm x 20 mm x .5mm were ablated and only the fibers of carbon which form the majority of the sample remained in the area in contact with the laser. The reinforced polymer which makes up the other component of carbon fiber and holds the fibers together was vaporized. This experiment was conducted at various laser amplitudes including 15 amps, 20 amps, 25 amps, 30 amps, and 35 amps. Estimations of the corresponding optical power in Watts was calculated. **Figure 4** shows that the laser has 0 wattage until it reaches 10 amps. 15% of the power is lost by passing through the 4 sides of the quartz windows. About 50% is also lost due to a buildup of material on the inner quartz window. The data for the two trials display very similar measures of thrust across all power levels (**Figures 5 and 7**). The specific polymer in the sample tested is polymethylpentene. The results show that despite the different power levels, the same amount of polymethylpentene was ablated each test and similar thrusts were produced. Only polymethylpentene was ablated because of the extremely high heat of vaporization of carbon. Carbon requires 715 kJ/mol to vaporize, an amount of energy unable to be delivered by our laser [11]. While the fibers of carbon can not be vaporized themselves, the polymethylpentene and other types of polymers can be and so a thrust is still produced. The material vaporizes very quickly and at low flux so it is difficult to maximize the amount of ablation with a thin piece of material. The thrust created has the ability to remove a piece of space debris containing carbon fiber from Earth orbit while not requiring high amounts of energy to do so. An average coupling coefficient relating force produce to energy was calculated to be 19.2 μN/W.

The second experiment tested ablation of aluminum at the five different power levels. The aluminum was

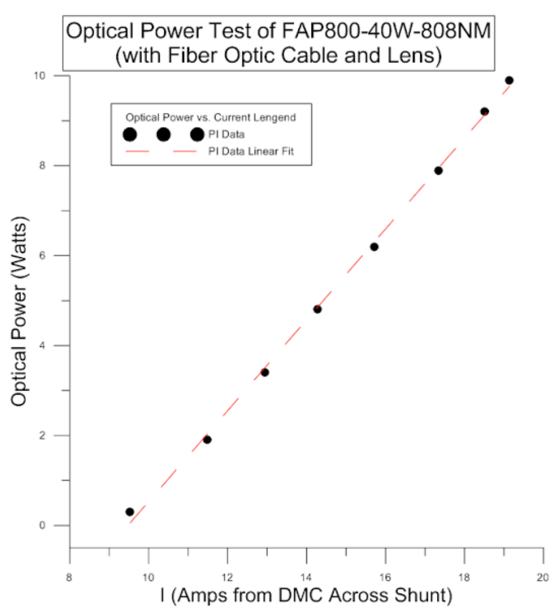

Figure 4. Results of an optical power test which corrolates the power of the laser to the current. The relationship between the two are extremely linear. The maximum power measured is 10 watts for our laser. This is limited by the power meter.

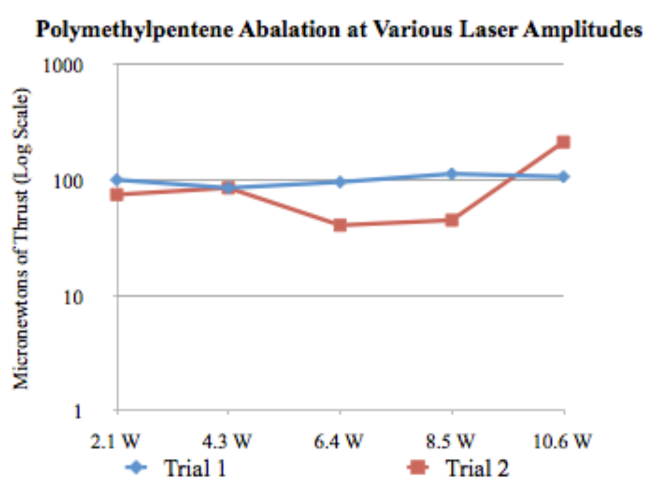

Figure 5. Ablation of polymethylpentene, the polymer in a sample of carbon fiber. This data shows similar thrust measurements regardless of how much laser power was used.

cut into pieces of dimensions 13 mm x 9 mm x .64 mm. Aluminum produced the largest amount of thrust of the tested materials with the max thrust being 212.3 μN (Figures 6 and 7). This material had the most thrust because of its properties of having a high thermal conductivity, 237 W/m·K, and a low heat of vaporization, 293 kJ/mol [11][12]. The average of the coupling coefficients was calculated to be 10.4 μN/W. It conducts heat throughout and does not require a large amount of energy to vaporize.

A sample of ceramic paint, a paint of low thermal conductivity which is used in space missions, was ablated. It produced a large amount of thrust and proves to us that even if a piece of space debris has a layer of paint, ablation can still occur.

The fourth and fifth experiments were ablation tests for stainless steel and titanium at high laser powers. Both materials were cut into pieces 17 mm x 8mm. The stainless steel was .305 mm thick and the titanium was .406 mm thick. The metals had very low measurements of thrust. The low thermal conductivities of both stainless steel and titanium make them more difficult to reach the required temperatures to ablate and as a result, less thrust was produced (Figure 7). Stainless steel and titanium have thermal conductivites of 15 W/m·K and 180 W/m·K respectively [12]. In addition, titanium has a high heat of vaporization, 425 kJ/mol, making it require more energy [11]. The high luster of both materials also reflect the photons the laser is firing at them. Therefore, testing these materials at lower amperage would result in results that were too small to be measured with accuracy considering the noise levels.

These preliminary tests support the usefulness of the DE-STAR laser in ablating aluminum and to some extent carbon fiber. Testing on stainless steel and titanium were less successful. Many more testing sequences should be run to confirm these results. Future work will also be needed to find amperage requirements that might be more successful for these samples, though with more amperage, energy needs and resultant cost increases might be limiting factors.

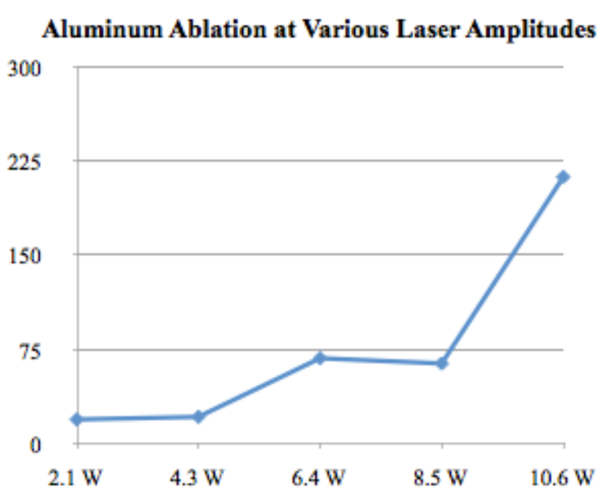

Figure 6. Ablation of aluminum at amplitudes of 15, 20, 25, 30, and 35. An upward trend can be seen which varies directly with the increase in laser power.

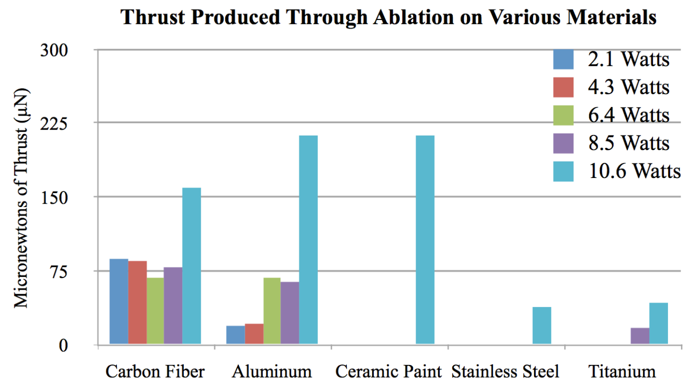

Figure 7. Results of ablation tests of materials at 15, 20, 25, 30, and 35 amps. The resultant thrust is displayed on the y-axis. At max power, aluminum produced the greatest thrust while stainless steel and titanium produced very little thrust. Carbon fiber remained relatively constant in terms of thrust.

IV. CONCLUSION AND FUTURE WORK

Space debris is a problem which will continue to plague Earth orbit for generations to come unless something is done about it. The results found in this paper strongly suggest that space debris consisting of carbon fiber and aluminum would be easily ablated and removed from orbit while remaining energy efficient. Stainless steel and titanium would still be capable of ablation, they would just use more energy. There were problems with our system which will need to be addressed in the future. First, the macor holder machined to contain the pieces of space debris was giving incorrect data. This could possibly be a result of forcing the plume of vaporized material to go in strange directions. Second, the fiber optic cable was subject to accidental displacement by the person focusing the laser. This in turn knocked into the measurement laser, causing large spikes of noise. This problem could be solved by developing an automated focusing system where a computer controls the laser. Third, the vacuum chamber is not capable of becoming a complete vacuum. In order to simulate space better, it would be best to use a system which can reach the lowest possible pressure. A vacuum chamber using a diffusion pump is currently being assembled and is expected to reach pressures of under 10^{-4} Torr. Future work regarding this research will help reach the larger goal of deploying an array of lasers able to mitigate the threat of space debris. This will include testing more materials with many trials to receive the most accurate data, doing tests at higher flux levels, launching a CubeSat which could be used to test in space, and tracking debris to determine where to focus the lasers. The bigger picture of this research is certainly a long term goal but is necessary in order to protect our satellites, spacecraft, and in some cases, human lives.

V. REFERENCES

[1] "Space Debris and Human Spacecraft," *NASA*, National Aeronautics and Space Administration, Sept. 26, 2013. [Online]. Available:http://www.nasa.gov/mission_pages/station/news/orbital_debris.html [Accessed: July 12, 2015].

[2] La Vone, Michelle, "Kessler Syndrome," *Spacesafety-magazine,* Space Safety Magazine, 2014. [Online]. Available:http://www.spacesafetymagazine.com/space-debris/kessler-syndrome/ [Accessed: July 12, 2015].

[3] K., A. A., "The Trouble with Space Junk," *Economist,* Economist Newspaper, May 10, 2015. [Online]. Available:http://www.economist.com/blogs/economist-explains/2015/05/economist-explains-11 [Accessed: July 12, 2015].

[4] Iannotta, Becky, and Tariq Malik, "U.S. Satellite Destroyed in Space Collision," *Space*, Purch, Feb. 11, 2009. [Online]. Available:http://www.space.com/5542-satellite-destroyed-space-collision.html [Accessed: July 12, 2015].

[5] "Char Wars", *Economist,* Economist Newspaper, Apr. 23, 2015. [Online]. Available:http://www.economist.com/news/science-and-technology/21649443-how-clean-up-space-shooting-down-bits-junk-char-wars [Accessed: July 12, 2015].

[6] Lubin, P., Hughes, G.B., Bible, J., Bublitz, J., Arriola, J., Motta, C., Suen, J., Johansson, I., Riley, J., Sarvian, N., Clayton-Warwick, D., Wu, J., Milich, A., Oleson, M., Pryor, M., Krogen, P., Kangas, M., and O'Neill, H. "Toward Directed Energy Planetary Defense," Optical Engineering, Vol. 53, No. 2, pp 025103-1 to 025103-18 (2014).

[7] Kosmo, K., Pryor, M., Lubin, P., Hughes, G.B., O'Neill, H., Meinhold, P., Suen, J., C., Riley, J., Griswold, J., Cook, B.V., Johansson, I.E., Zhang, Q., Walsh, K., Melis, C., Kangas, M., Bible, J., Motta, Brashears, T., Mathew, S. and Bollag, J. "DE-STARLITE - a practical planetary defense mission," Nanophotonics and Macrophotonics for Space Environments VIII, edited by Edward W. Taylor, David A. Cardimona, Proc. of SPIE Vol. 9226 (Aug, 2014).

[8] Hughes, G.B., Lubin, P., Griswold, J., Bozinni, D., O'Neill, H., Meinhold, P., Suen, J., Bible, J., Riley, J., Johansson, I.E., Pryor, M. and Kangas, M. "Optical modeling for a laser phased-array directed energy system (Invited Paper)," Nanophotonics and Macrophotonics for Space Environments VIII, edited by Edward W. Taylor, David A. Cardimona, Proc. of SPIE Vol. 9226 (Aug, 2014).

[9] Johansson, I.E., Tsareva, T., Griswold, J., Lubin, P., Hughes, G.B., O'Neill, H., Meinhold, P., Suen, J., Zhang, Q., J., Riley, J. Walsh, K., Brashears, T., Bollag, J., Mathew, S. and Bible, J. "Effects of asteroid rotation on directed energy deflection," Nanophotonics and Macrophotonics for Space Environments VIII, edited by Edward W. Taylor, David A. Cardimona, Proc. of SPIE Vol. 9226 (Aug, 2014).

[10] Zhang, Q., Walsh, K.J., Melis, C., Hughes, G.B., Lubin, P. "Orbital Simulations for Directed Energy Deflection of Near-Earth Asteroids," *Procedia Engineering*: Vol. 103, pp. 671-678, 2015.

[11] "Heat of Vaporization of the Elements," *Periodic Table,* Wolfram Research, Sept. 2, 2013. [Online]. Available: http://periodictable.com/Properties/A/VaporizationHeat.an.html [Accessed: July 26, 2015].

[12] "Thermal Conductivity of Common Metals, Alloys and Materials," *Engineers Edge*, Engineers Edge, 2015. [Online]. Available:https://www.engineersedge.com/heat_transfer/thermal-conductivity-metals-alloys.htm [Accessed: July 26, 2015].

VI. ACKNOWLEDGEMENTS

Special thanks to NASA for their funding from the NASA California Space Grant. My mentor, Travis Brashears, Lina Kim, Ross Melczer, and the Deep Space Laboratory: Philip Lubin, Travis Brashears, Payton Batliner, Jonathon Madajian, Aidan Gilkes, Jana Georgieva, Olivia Sturman, Kenyon Prater