Non-Explosive Actuator Simulator

A Senior Project

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The CubeSat group at California Polytechnic State University, San Luis Obispo discovered the need for a new piece of ground test equipment. Previous testing of the non-explosive actuator has been very expensive and is not repeatable; two undesirable traits. The analysis of the fuse as well as the design and test of the simulator concept and final article is discussed. The simulator has already seen real use and its entire build and operation cost is much less than the cost of one test of the actual hardware. Performance of the simulator based on burn time and reset time is acceptable while other requirements are not yet fulfilled.

Nomenclature

```
= specific heat capacity, J/(kq - K)
d
            = diameter, m
Ι
            = current, A
            = length of fuse wire, m
P
            = power, W
Q
            = heat energy, J
\dot{Q}
            = radiated heat, W
R
            = resistance, \Omega
            = resistance per lineal foot \Omega/ft
R_0
            = reference resistance, \Omega
            = specific resistivity, \Omega - CM/F
R_{sp}
            = radius of fuse wire, m
            = time, s
            = temperature, K
T_{melt}
            = reference temperature, K
T_0
V
            = voltage, V
\alpha
            = temperature coefficient of resistance, \Omega/K
            = permittivity of free space, F/m
            = emissivity
            = density, kg/m^3
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I. Introduction

Cubesat is a student group at the forefront of the emerging field of low-cost access to space. They have a need for a device to help with certain testing and have created the requirements for a testing device. The group manufactures a standardized picosatellite launcher called the Poly Picosatellite Orbital Deployer. One of the primary features of the launcher is a non-explosive actuator that allows the door to open. There have been some issues with practicality on testing the actuator so a device has been created to help reduce cost and increase the usefulness of the tests.

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A. Background

An understanding of the requirements will be aided by a summary of the interested party as well as the space-rated system where the actuator is relevant.

1. CubeSat

The CubeSat name gets used in many ways. There is the CubeSat Project throughout the world, the CubeSat group at Cal Poly, and the small satellites they launch are called CubeSats.

The CubeSat group at California Polytechnic State University, San Luis Obispo (Cal Poly) is the customer for the requested test hardware. The student-run organization is the hub of the multinational and widely recognized CubeSat Project. The Project is "an international collaboration of over 40 universities, high schools, and private firms developing picosatellites containing scientific, private, and government payloads". Groups often choose to build CubeSats because of their relatively low launch cost. One of the primary roles for the CubeSat group is to act as the interface between launch providers and the satellite builders.

The satellites created for the CubeSat Project must conform to the CubeSat standard. Satellites that conform to the Standard are cube-shaped and ten centimeters on a side. Because of this constraint they are in a general class of satellites called picosatellites, or "picosats." Satellites following the standard also may not be more than one kilogram in mass and also conform to certain interface requirements. Satellites that meet the size, mass, and interface requirements are then eligible to be launched into space through the organized efforts of the CubeSat group.

When CubeSats are selected for a particular launch they are not just placed into the launch vehicle fairing in a random way. The CubeSats are loaded into a deployment device called a P-POD which allows for a controlled release of the satellites at a particular time.

2. Poly Picosatellite Orbital Deployer (P-POD)

This standardized deployment device is designed and assembled by CubeSat and a computer model of it can be seen in Fig. 1. The goal is to "provide a standard, reliable, and flight proven deployment system". Up to three CubeSats can be placed in this device and then it can be attached to a preselected location on the launch vehicle within the payload fairing. This unobtrusive method utilizes mass margin and available room leftover from the primary payload. By utilizing this small extra capability, CubeSats have allowed relatively affordable access to space for universities and other organizations. After the primary payload has moved away from the launch vehicle for minutes to hours, the P-POD door is allowed to open and eject the CubeSats by way of a large internal spring.



Figure 1. P-POD Computer Model¹

3. Non-Explosive Actuator (NEA)

The door on the P-POD is held closed by a NEA. This is a safe way to contain the P-POD contents during launch and then release them without dangerous explosive charges that could interfere with the primary payload. The device operates by burning a metal fuse that holds together a split fastener nut. The P-POD door has a bolt in it that is secured into the split bolt in the NEA which is mounted to the P-POD. Upon burning the fuse the nut separates and the bolt comes out of the NEA allowing the spring-loaded door to open.

The NEA has two circuits internally to allow for system redundancy.

4. Testing Issues

The primary issues that led to the request for the simulator were high test cost and no reset ability.

Before each mission, the launch vehicle's wiring harness must be verified. In at least one specific case, many P-PODs were tested as part of a single mission and an intermediate box was also tested. CubeSat's involvement with this procedure is to ensure that the signal sent to the NEA is sufficient to cause the fuse to burn and allow the door to open. Real tests are the most reliable way of testing the harness but it is also a very expensive procedure because each time a NEA goes through this test it must be refurbished by the manufacturer. As with many other aerospace procedures, it is strictly controlled, very reliable, and very expensive. Further, the test is not easily reset. The combination of high cost and limited reset ability has led to the need for an apparatus that can replace the NEA during these repeated tests.

B. Objectives

The test device to be created must fulfill certain requirements in order to be used in place of real space hardware for tests. In general, the device must behave like a real NEA as seen by the launch vehicle electrical harness but also have features that make it more amenable to regular testing. These qualities include fast system reset, easy use, and low cost. Wiring harness variations must also be accounted for in each test.

1. Requirements

The informal requirements given at the start of the project as well as the derived technical meaning and success criteria are further detailed in Table 1.

Table 1. Customer Requirements and Distillation

Explicit Requirement	Implied Requirement
Reduce Test Cost	Recurring test cost shall be at least 50% less than current test cost
Easy to Use	The device shall not require special training
Transportable	The device shall be no larger than airline carry-on and easy to contain
Easily Resettable	The device shall not require specialized tools for resetting
Door Open Switch	The device shall communicate a door-open signal to the Launch Vehicle
Burn Confirmation	The device shall have a clear visual indication that the fuse has burned
Nominal Burn Time	The device shall burn within a 50% time margin from the nominal
Resistance Matching	The device shall be adjustable to $1.5 \pm 0.2 \Omega$ for every test
Monitor Test Data	The device shall be compatible with a Data Acquisition method
Fuse Calculations	Determine the variables most important to predicting burn time
Many Launch Vehicles	The device shall be able to use any likely Launch Vehicle connector
Safety Device (late add)	The device should be physically isolated from test personnel during test
Appearance (late add)	The device should appear to be of quality design and manufacture

II. Apparatus and Instrumentation

Proof-of-concept tests utilized a number of different electronic devices. An Agilent 54622A Oscilloscope is used for measuring burn time and voltage drops. An Astron RS-35M power source provided the primary circuit power. The IRF7530 MOSFET gate is actuated by an Agilent E3631A Triple Output DC Power Supply.

A. Initial Testing and Design Phase

To begin the investigation into how the real NEA works and to begin developing a new test device to emulate it, there were only four items items to start with. These items were the the fuse is (1) made of stainless steel, (2) 0.045" in diameter, (3) 0.375" long, and (4) modeled by equations in a proprietary spreadsheet which was provided.

The nominal fuse burn times on the spreadsheet were first evaluated by an Electrical Engineering student. The student recommended fast-acting 20mm 315mA fuses based on their burn characteristics. The first test box was also built at this time to be compatible with these fuses. Initial test burns were far too slow. This prompted further analysis of the spreadsheet to determine what options existed for replacing the fuse with small wire. Initial tests of the new fuses made in-house with small-diameter wire were still too slow but an improvement from the fuse. Finally, a 0.003" diameter wire was used and it came to be satisfactorily similar to the nominal burn time of the NEA. Wire diameters up to 0.006" were used and custom wire was quoted at prices near \$150. The box was redesigned to use the 0.003" wire as a fuse.

B. Testing Setup and Procedure

The initial circuit for testing fuse concepts is show in Fig. 2. The Astron power supply provides that primary circuit power for burning the fuse. A MOSFET gate keeps the primary circuit open until power is supplied via the Agilent power source. Using the MOSFET removes much of the transient response when turning the Astron power supply on because the power Astron is already on when the gate is opened.

The procedure described below is the method used with the circuit to obtain burn times from the wire fuse.

- 1. Load a fuse into the holder and ensure that the holder is properly places in the circuit
- 2. Use an ohmeter to measure the resistance across the fuse and the rheometer together. Adjust until $1.5 \pm .2\Omega$ is read. Remove the ohmeter.
- 3. Pre-set the gate power supply output to the value desired for the gate but ensure that the output is off.
- 4. Use the oscilloscope to scope across the fuse and the rheometer together.
- 5. Turn on the primary circuit power supply.
- 6. Set a falling trigger on the oscilloscope to capture the voltage drop and the duration of the burn on the display.
- 7. Turn on the gate power supply until the fuse burns than then turn of immediately.
- 8. Turn off the the primary circuit power supply.
- 9. Calculate current through fuse from the resistance measured before the burn and the voltage drop during the burn.
- 10. Repeat. Use the same setup or change the coil resistor to vary the current running through the fuse.

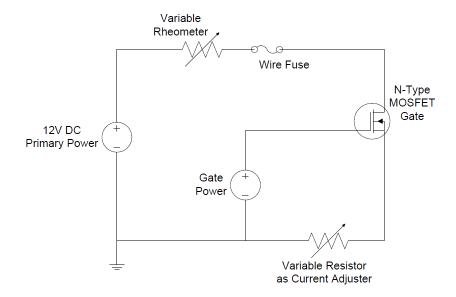


Figure 2. Testing Circuit Diagram

C. Test Box Build Procedure

The box is built by first laying out the desired dimension and layout on the project enclosure's extra metal backplate to the project enclosure. From these marks it is recommended to drill small holes through the metal plate in order to enable re-use as a template. A drill press is used for all drilling and is highly recommended for future box manufacturing. The metal piece is placed over the top of the project enclosure and a drill bit of the same size as the pilot holes are used to extend these holes through the project enclosure wall. After these holes are drilled then the template is removed and the holes are opened up to the desired hole size depending on the piece of hardware that will be placed there. This method increases the reproducibility of the box and also improves the outward appearance of the box. The D-sub connector opening was created by placing small holes in the side of the box with a drill press as needed.

Copper strips with adhesive backing are placed on the inside of the box to connect all components to a common ground. It is necessary that each component secured to the box is in contact with this strip at the mounting interface. After placing the copper strip then attach all components to the box except the D-sub connector. Continue by soldering in 20-gauge wire to complete the necessary circuit connections shown in Fig. 3. Make sure to leave sufficient length to route all wires through the D-sub connector hole and be able to solder into the connector outside of the box. After routing the wires through the connector hole then solder the wires to the proper pins as shown. A complete box is shown in Fig 4.

Two toothless alligator clips, a banana jack jumper, and some epoxy are used to make the fuse holders. For this test box the alligator clips were simply affixed to the banana jack connector with epoxy. Tape can be used to help secure the clips while the epoxy sets. The clips are attached so that they point outward from box when placed in the banana jacks it is intended for. The fuses are placed so the fuse wire strung between them is 0.375" long. A small wire is run from the end of each alligator clip into a small hole on its side of the banana jack jumper and secured in order to complete the electrical connection. The fuse holder is shown in Fig. 5.

D. Characterization Testing

Both completed boxes were tested with each of four different fuse holders that were created. This helped to find a combination and secondary combinations in order to get burn times with both boxes as similar as possible.

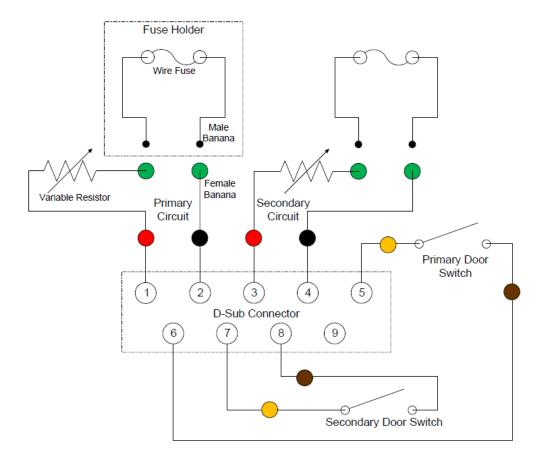


Figure 3. NEA Simulator Electrical Diagram. Colors relate to actual box components in Fig. 4

E. Test Box Field Use Procedure

When the box is completely built the procedure for using it is rather simple. The box has a umber of different interfaces but the colors, labeling, and arrangement allow for a manageable task. To begin, it is necessary to have the test box, an appropriate adapter for the launch vehicle interface, and a collection of pre-cut fuse wires approximately 1" to 1.5" long. Make sure that the fuses are contained or otherwise controlled since they are easy to lose they could pose major problems for electronics it misplaced.

Make sure the both mechanical switches are down and in the "off" position and remove the fuse holder from the test box. Connect the launch vehicle adapter cable to the box and the vehicle harness in whatever order is most convenient. When the box is electrically connected to the launch vehicle through the cable then the fuse holder can be put into the green banana plugs once a fuse has been placed between the two toothless alligator clips.

If desired, an ohmeter can scope between the red and black banana jacks to measure the resistance of the circuit. The rheometer knob for each circuit can be rotated until the desired resistance is achieved. The ohmeter should be removed at this point but, if desired, an oscilloscope can be attached to the same points in order to monitor and record the voltage during the test.

When the launch vehicle sends the signal to release the P-POD door it is in fact burning the fuse within the NEA. The same will happen on the test box. Once the fuse has burned the operator must flip the switch on the test box to "on" which will indicate to the launch vehicle that the door has opened and the deployment was a success. If desired, the voltage across the switch can be scoped with the orange and brown pair of banana plugs to confirm that the circuit has closed.



Figure 4. Photo of an NEA Simulator Box.

III. Analysis

The burn time of the fuse can be predicted using some basic properties of the fuse wire. The first property is volume

$$V = \pi r^2 l \tag{1}$$

because the wire as a whole will be able to contain an amount of heat energy directly proportional to volume. The actual heat storage capacity of the wire is described as

$$Q = \rho c_p V T_{melt} \tag{2}$$

where it not only takes into account volume, but heat capacity of the material. Next, it is important to find the power put into the fuse from the electrical resistance and the rate at which the fuse radiates heat to the environment. Resistance of the fuse has to be found before the power input because it is reliant on resistance. The resistance per unit length is found by

$$R_{lf} = \frac{R_{sp}}{(2r1000)^2} \tag{3}$$

which converts a standard resistance measurement in "ohms per cubic mil foot" or $\Omega - CM/F$ to resistance per length of wire. The resistance of the actual fuse can easily be found using

$$R = R_{lf}l \tag{4}$$

which just uses the length of the wire to find the resistance. The resistance in then used in the equation for electrical power



Figure 5. Photo of a Fuse Holder.

$$P = I^2 R (5)$$

to find the heat generated within the fuse from current running through it. To find the other part of heat transfer in this system, we consider the equation for radiation

$$\dot{Q} = (\epsilon_0 \pi 2rl) [\epsilon (T_{melt} + T_0)^4 - T_0^4] \tag{6}$$

based mainly on temperature and wire surface area. Finally, we can gauge the fuse burn time by

$$t_{rad} = \frac{Q}{P - \dot{Q}} \tag{7}$$

which finds the difference in heat generated to heat radiated to find the time it will take to melt the wire. The wire is expected to burn when it has filled with enough heat to take it to the melting temperature and the fuse breaks.

The author does not follow the complete logic of the rest of the analysis but it is presented for subsequent discussion. The time to burn is given as

$$t_{burn} = 0.53 \frac{Q}{P} \tag{8}$$

to give seconds of time to burn. The fraction determines the amount of time it would take to burn the fuse if it did not radiate any energy while being heated and then taking 53% of the time to be the real burn time. This seems odd because radiation cooling should cause the burn time to be longer than if there was no radiation and that would require a percentage higher the 100% instead of 53%. The author also discovered that 0.53 is the ratio of $\frac{t_{rad}}{t}$ as current goes to very large values.

that 0.53 is the ratio of $\frac{t_{rad}}{t_{nominal}}$ as current goes to very large values.

When calculating the resistance of the real NEA fuse and comparing to the custom fuse there was some discrepancy and it may be based on the resistance change with temperature. The relation is given

$$R = R_0 + \alpha * T \tag{9}$$

as it varies by temperature. Good results were achieved when using a temperature near the melting point.

IV. Results and Discussion

The fast-acting fuses used in the original design of the test box were too slow to satisfy the burn time requirement. Once the fuse was replaced with the small diameter wire the burn times moved much closer to the trend predicted by the manufacturer's calculations.

Some discrepancy between the predicted burn times and the burn times found in our lab are likely caused by the fact that the real NEA fuse is under tension. This conclusion was deduced from information suggested by the manufacturer.

Figure 6 shows all of the analysis done for this investigation. It is interesting to note that the preliminary fuse data follows the predicted curve shape very closely but the tests with the final test setup varied much more. The connection to the fuses is suspected as the cause of this because the preliminary tests used strong, screw-on connections for the fuse but the NEA simulator box used toothless alligator clips. Further, the resistance on the final NEA simulator box was not variable so in fact all of the variability observed is from a single set point for overall resistance and also a constant voltage.

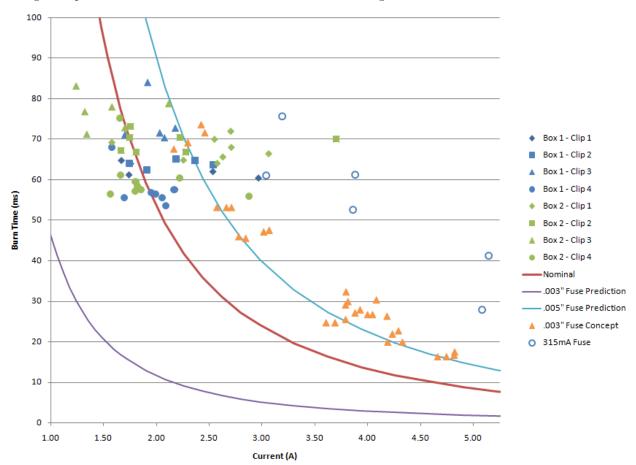


Figure 6. Theoretical and Actual Actuation Curves

The simulator box did not meet every requirement set out for it but it did fulfill enough of them to become a useful piece of testing hardware. A summary of the requirements can be seen in Table 2.

Table 2. Requirements Fulfillment

Explicit Requirement	Success	Description
Reduce Test Cost	Yes	No appreciable reset cost; price of all supplies less than one real test
Easy to Use	Yes	Requires a stable hand, scissors, and (optional) oscilloscope
Transportable	Most	Not 100% contained but simple, robust, and easy to pack
Easily Resettable	Yes	Less than 30 seconds is possible with no special equipment
Door Open Switch	Yes	Not automatic but it does fulfill the requirement
Burn Confirmation	Most	No indicator lamp but otherwise obvious
Nominal Burn Time	Most	Approximately 25% from set point, no actual variability of resistance
Resistance Matching	Yes	Adjustable resistance with simple knob
Monitor Test Data	Yes	Banana jacks allow optional, external monitoring
Fuse Calculations	Yes	Details provided in "Analysis" section
Many Launch Vehicles	Yes	Set of D-Sub connectors tied to vehicle-specific connectors
Safety Device (late add)	No	Limited to ad hoc safety procedures; not obviously hazardous
Appearance (late add)	Most	Hobby materials, some gluing, clean construction, precise placement

V. Conclusion

As with many projects, the unknown unknowns can amaze, educate, and seriously delay a project. This project was no exception but the results overall were successful. The device will likely evolve in the future to take into account even more improvements. Besides learning about difficulties with hardware there is also the effect of changing requirements as the project develops. Once the interested parties become more interested in the success of the device and future potential, the number of desired qualities of the device grow. Fortunately, compared to the money savings possible with such a device, the improvements are well-justified.

After several weeks of searching for an ideal fuse material we found out that the burn time requirement was much more lax than previously thought. This changing requirement was one of the main sources of unnecessary time lost that could have been spent on other manufacturing improvements.

The first demonstration of the test box with a launch vehicle gained positive feedback in the form of confirmation that the box did perform as an acceptable replacement for a real NEA in a ground test. Further, the box is fast and easy to reset during a test, to the agreement of the launch vehicle provider. Despite the success, there is also a list of changes that both external parties would like to see as will as the CubeSat group internally.

The variation in fuse length between each fuse holder is hoped to be reduced in the future. One idea for this is to use a machine available with some CubeSat partners at SRI to bond the fuse wires to a harness of some sort. The process seems to be flexible and very effective at mass-producing pieces. Even if a custom fuse holder design must be used it will be easy to make it consistently and cheaply. This method should also reduce errors in reading the resistance of the fuse from internal electrical reflections.

The rheometers in the second version of the test box somehow became ineffective after just a couple uses. We believe that the momentary, but high, power spikes damaged it somehow. They were replaced with basic high-power resistors for the first set of tests since the resistance in the system is consistent enough to allow for acceptable results even if it cannot be adjusted for each test. High-power rheometers that are much more effective at the desired resistance range have already been ordered and will be incorporated into the next design.

Grounding and safety have also come up as issues to address. The past box used copper strips and a connecting wire to place all the components on a common ground but future designs would be better if they could use the box as a grounding device. The device will need development in the area of safety in order to preserve the reliability of space hardware and safety of test personnel. One of the ideas is to use a small plastic cover to enshroud the fuse. This will prevent electric shock of any handler and contain the debris and any hot metal from the fuse. Small pieces of hot fuse do commonly leave the area of the fuse holder although there were few implications in the lab in which it was tested.

The D-sub connector that is currently used proved to be mostly sufficient but the CubeSat group has decided it would be worth the extra money to use real launch vehicle connections to interface with the box. There will still be an adapter from the box connector to the launch vehicle connector. The reasoning is that the box is relatively light while the harness from the launch vehicle is stiff enough to cause the box to move when not held down. Even if the box is held down, the D-sub connector does not provide enough grip on the connector to ensure that it will never be pulled out by the harness. The new connectors, probably D-38999, have a positive lock through a screw-on collar. This new connector will also allow the rest of the box to use 20-gage which is the same size as used in the harness.

An LED indicator of the fuse burning and one for the door open switch would be a small but appreciated addition to the box. An initial attempt to implement this was scrapped when it was decided that an automatic door switch was not feasible in the time allowed because of the power spikes in the circuitry. An automatic switch would also be a good improvement but for now seems to be impractical. An LED for the manual door switch, however, is likely not out of reach.

After spending a weekend selecting parts online I decided there are few things as receiving \$200 of shiny things in a box with your name on it.

Appendix

A. Sample Calculations

1. Experimental Values

Given the fundamental relationship

$$V = IR \tag{10}$$

and arranging it to solve for current

$$I = V/R \tag{11}$$

we can use the measured voltage and resistance to determine current. The current and burn time are used to plot the data. The first data point from Table 3 is calculated below.

$$I = \frac{8.25V}{1.71\Omega} \tag{12}$$

$$I = 4.85A \tag{13}$$

2. Nominal Burn Curve

The curve is generated with many data points but the case of I=1A is presented here.

$$I = 1A \tag{14}$$

$$l = 0.375in * (\frac{.0254m}{1in}) \tag{15}$$

$$d = 0.0045(\frac{.0254m}{1in})\tag{16}$$

$$\rho = 7900 \frac{kg}{m^3} \tag{17}$$

$$c_p = 460 \frac{J}{kg - K} \tag{18}$$

$$V = l(\frac{d}{2})^2 \pi \tag{19}$$

$$= (0.00953m)(\frac{0.00011}{2})^2\pi \tag{20}$$

$$V = 9.77x10^{-11}m^3 (21)$$

The resistance for the nominal fuse is based on a resistance constant based on area and is shown below. The custom fuse resistance calculations are based on length.

$$R = \frac{1.24x10^{-8}W - m^2}{d^2/4} \tag{22}$$

$$=\frac{1.24x10^{-8}}{0.00011^2/4}\tag{23}$$

$$R = 1.207\Omega \tag{24}$$

$$P = I^2 R \tag{25}$$

$$= (1)^2 (1.207) \tag{26}$$

$$P = 1.207W \tag{27}$$

$$T_m elt = 1371.11^{\circ}C \tag{28}$$

$$Q = \rho c_p V T_{melt} \tag{29}$$

$$= (7900)(460)(9.77x10^{-11}(1399)$$
(30)

$$Q = 0.487J \tag{31}$$

$$\dot{Q} = (\epsilon_0 \pi 2rl) [\epsilon (T_{melt} + T_0)^4 - T_0^4]$$
(32)

$$= (0.5669x10^{-8})(\pi dl)[(1371 + 273)^4 - (273)^4]$$
(33)

$$t_{rad} = \frac{Q}{P - \dot{Q}} \tag{34}$$

$$=\frac{0.487}{1.27 - 0.2823}\tag{35}$$

$$t_{rad} = 526.5ms \tag{36}$$

$$t_{burn} = 0.53 \frac{Q}{P} \tag{37}$$

$$=0.53\frac{0.487}{1.207}\tag{38}$$

$$t_{burn} = 213.8ms \tag{39}$$

3. Custom Fuse Resistance

The resistance for our in-house fuses was calculated based on "ohms per cubic mil foot."

$$R_{lf} = \frac{R_{sp}}{(2r1000)^2} \tag{40}$$

$$=\frac{420}{(2*.003*1000)^2}\tag{41}$$

$$=46.67 \frac{\Omega}{ft} \tag{42}$$

$$R = R_{lf}l \tag{43}$$

$$=46.67 \frac{\Omega}{ft} (0.375in) (\frac{12in}{1ft}) \tag{44}$$

$$R = 1.46\Omega \tag{45}$$

B. Raw Data

Table 3. Raw Data Table 1

Voltage	Milliseconds	Resistance	Amps
8.25	17.6	1.71	4.82
7.88	16.4	1.69	4.66
7.88	16.4	1.66	4.75
8.00	16.8	1.66	4.82
7.19	20.0	1.66	4.33
7.13	20.0	1.70	4.19
6.31	24.8	1.71	3.69
6.31	24.8	1.75	3.61
6.72	28.0	1.71	3.93
6.41	25.6	1.69	3.79
6.56	27.2	1.69	3.88
6.72	26.8	1.68	4.00
7.03	22.0	1.66	4.23
7.34	22.8	1.71	4.29
6.41	30.0	1.68	3.82
6.56	29.2	1.73	3.79
6.72	32.4	1.77	3.80
6.86	30.4	1.68	4.08
7.03	26.4	1.68	4.18
6.88	26.8	1.70	4.05
4.84	46.0	1.74	2.78
5.31	47.6	1.73	3.07
4.84	45.6	1.70	2.85
5.16	47.2	1.71	3.02
4.22	73.6	1.74	2.43
3.91	69.2	1.70	2.30
4.06	71.6	1.65	2.46
3.75	67.6	1.73	2.17
4.53	53.2	1.67	2.71
4.53	53.2	1.76	2.57
4.53	53.2	1.70	2.66

Table 4. Box 1 with All Fuse Holders

Resistance Across Current Adjuster (Ω)	Avg Voltage Across Fuse (V)	Current (A)	Burn Time (ms)	
Box 1 - Clip 1	0.141	0.184	2.97	60.4
Box 1 - Clip 1	0.194	0.200	1.74	61.2
Box 1 - Clip 1	0.193	0.190	1.67	64.8
Box 1 - Clip 1	0.150	0.180	2.54	62.0
Box 1 - Clip 1	0.193	0.200	1.75	64.0
Box 1 - Clip 2	0.180	0.193	1.91	62.4
Box 1 - Clip 2	0.166	0.190	2.18	65.2
Box 1 - Clip 2	0.158	0.187	2.37	64.8
Box 1 - Clip 2	0.188	0.190	1.74	64.0
Box 1 - Clip 2	0.150	0.180	2.54	63.6
Box 1 - Clip 3	0.171	0.187	2.03	71.6
Box 1 - Clip 3	0.169	0.187	2.08	70.4
Box 1 - Clip 3	0.165	0.188	2.18	72.8
Box 1 - Clip 3	0.165	0.165	1.92	84.0
Box 1 - Clip 3	0.187	0.184	1.70	71.2
Box 1 - Clip 4	0.183	0.203	1.95	56.8
Box 1 - Clip 4	0.204	0.212	1.70	55.6
Box 1 - Clip 4	0.177	0.213	2.17	57.6
Box 1 - Clip 4	0.185	0.218	2.06	55.6
Box 1 - Clip 4	0.182	0.215	2.09	53.6
Box 1 - Clip 4	0.187	0.215	1.99	56.4
Box 1 - Clip 4	0.192	0.178	1.58	68.0

Table 5. Box 2 with All Fuse Holders

Main Resistance (0.067)	Avg Voltage (V)	Current (A)	Burn Time (ms)	
Box 2 - Clip 1	0.216	0.309	2.26	64.8
Box 2 - Clip 1	0.269	0.300	1.58	69.2
Box 2 - Clip 1	0.190	0.300	2.70	72.0
Box 2 - Clip 1	0.192	0.306	2.71	68.0
Box 2 - Clip 1	0.177	0.300	3.06	66.4
Box 2 - Clip 1	0.199	0.306	2.55	70.0
Box 2 - Clip 1	0.199	0.309	2.58	64.0
Box 2 - Clip 1	0.200	0.318	2.63	65.6
Box 2 - Clip 2	0.216	0.312	2.28	66.8
Box 2 - Clip 2	0.262	0.321	1.75	73.2
Box 2 - Clip 2	0.263	0.322	1.75	70.4
Box 2 - Clip 2	0.223	0.320	2.22	70.4
Box 2 - Clip 2	0.259	0.300	1.67	67.2
Box 2 - Clip 2	0.160	0.300	3.70	70.0
Box 2 - Clip 2	0.250	0.309	1.81	66.8
Box 2 - Clip 3	0.269	0.300	1.58	78.0
Box 2 - Clip 3	0.257	0.303	1.70	72.8
Box 2 - Clip 3	0.305	0.303	1.34	71.2
Box 2 - Clip 3	0.306	0.300	1.32	76.8
Box 2 - Clip 3	0.313	0.290	1.24	83.2
Box 2 - Clip 3	0.216	0.290	2.12	78.8
Box 2 - Clip 4	0.268	0.350	1.85	57.6
Box 2 - Clip 4	0.278	0.331	1.66	61.2
Box 2 - Clip 4	0.268	0.312	1.65	75.2
Box 2 - Clip 4	0.268	0.340	1.80	57.2
Box 2 - Clip 4	0.228	0.331	2.22	60.4
Box 2 - Clip 4	0.194	0.331	2.88	56.0
Box 2 - Clip 4	0.300	0.346	1.57	56.4
Box 2 - Clip 4	0.266	0.340	1.82	58.4
Box 2 - Clip 4	0.266	0.337	1.80	59.6

Table 6. 315 mA Fuse

Voltage	Resistance	Amps	Time (ms)
6.56	1.69	3.88	61.2
6.56	1.70	3.86	52.6
5.42	1.70	3.19	75.6
5.16	1.70	3.04	61.0
8.75	1.70	5.15	41.2
8.59	1.69	5.08	28.0

Table 7. Nominal Fuse Curve

Current	Power	Milliseconds	Radiation Milliseconds
1.00	1.21	213.8	526.5
1.06	1.36	190.3	453.4
1.12	1.51	170.4	395.2
1.18	1.68	153.5	348.2
1.24	1.86	139.0	309.4
1.30	2.04	126.5	277.0
1.36	2.23	115.6	249.7
1.42	2.43	106.0	226.3
1.48	2.64	97.6	206.2
1.54	2.86	90.1	188.7
1.60	3.09	83.5	173.4
1.66	3.33	77.6	160.0
1.72	3.57	72.3	148.1
1.90	4.36	59.2	119.5
2.08	5.22	49.4	98.6
2.26	6.17	41.9	82.8
2.44	7.19	35.9	70.5
2.62	8.29	31.1	60.8
2.80	9.46	27.3	53.0
2.98	10.72	24.1	46.7
3.30	13.15	19.6	37.9
3.62	15.82	16.3	31.3
3.94	18.74	13.8	26.4
4.26	21.91	11.8	22.5
4.58	25.32	10.2	19.4
4.90	28.99	8.9	17.0
5.22	32.89	7.8	14.9
5.54	37.05	7.0	13.2
5.86	41.46	6.2	11.8
750.0	6.79E + 05	0.0	0.0

Table 8. Expected 0.003" Fuse Curve

Current	Power	Milliseconds	Radiation Milliseconds
1.00	2.72	46.4	94.6
1.16	3.05	41.3	83.5
1.12	3.41	37.0	74.2
1.18	3.78	33.4	66.5
1.24	4.18	30.2	59.9
1.30	4.59	27.5	54.2
1.36	5.02	25.1	49.4
1.42	5.48	23.0	45.1
1.48	5.95	21.2	41.4
1.54	6.44	19.6	38.1
1.60	6.95	18.1	35.3
1.66	7.48	16.9	32.7
1.72	8.04	15.7	30.4
1.90	9.81	12.9	24.8
2.08	11.75	10.7	20.6
2.26	13.87	9.1	17.4
2.44	16.17	7.8	14.9
2.62	18.65	6.8	12.9
2.80	21.30	5.9	11.3
2.98	24.12	5.2	10.0
3.30	29.58	4.3	8.1
3.62	35.59	3.5	6.7
3.94	42.17	3.0	5.7
4.26	49.29	2.6	4.8
4.58	56.98	2.2	4.2
4.90	65.22	1.9	3.7
5.22	74.01	1.7	3.2
5.54	83.37	1.5	2.9
5.86	93.27	1.4	2.6
750.00	1.53E + 06	0.0	0.0

Table 9. Expected 0.005" Fuse Curve Curve

Current	Power	Milliseconds	Radiation Milliseconds
1.00	0.98	358.4	1029.4
1.06	1.10	318.9	866.4
1.12	1.23	285.7	742.0
1.18	1.36	257.4	644.4
1.24	1.50	233.1	566.1
1.30	1.65	212.0	502.0
1.36	1.81	193.7	448.8
1.42	1.97	177.7	404.1
1.48	2.14	163.6	366.0
1.54	2.32	151.1	333.3
1.60	2.50	140.0	305.0
1.66	2.69	130.0	280.3
1.72	2.89	121.1	258.5
1.90	3.53	99.3	207.0
2.08	4.23	82.8	169.7
2.26	4.99	70.2	141.9
2.44	5.82	60.2	120.5
2.62	6.71	52.2	103.7
2.80	7.67	45.7	90.2
2.98	8.68	40.4	79.2
3.30	10.65	32.9	64.1
3.62	12.81	27.3	53.0
3.94	15.18	23.1	44.5
4.26	17.75	19.7	38.0
4.58	20.51	17.1	32.8
4.90	23.48	14.9	28.6
5.22	26.64	13.2	25.1
5.54	30.01	11.7	22.3
5.86	33.58	10.4	19.9
750.00	5.50E + 05	0.0	0.0

Table 10. Stainless Steel 303/304 Properties

Property	Value
Specific Resistivity	$420 \Omega - CM/F$
Thermal Coefficient of Resistance	$0.00085~\Omega/K$
Density	$7.93 \ q/cm^3$

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References

 $^{^1\}mathit{CubeSat}$ in the News. Web. 06 Dec. 2009. http://cubesat.org