A Nichrome Burn Wire Release Mechanism for CubeSats

Adam Thurn*, Steve Huynh*, Steve Koss*, Paul Oppenheimer*, Sam Butcher*,
Jordan Schlater** and Peter Hagan+

Abstract

The nichrome burn wire release mechanism uses a nichrome burn wire which when activated heats up and cuts through a Vectran tie down cable allowing the deployable on the satellite to actuate. The release mechanism was designed from scratch with the goals to make it small, inexpensive, simple, reliable and easy to use by anyone including student-run University CubeSat projects. The release mechanism, shown in Figure 1, utilizes a two saddle design with compression springs to apply a spring stroke and force to the nichrome wire to thermally cut through the Vectran cable when heated. Through a test program and using a design of experiments (DOE) approach it was determined that the applied current to the nichrome wire and the diameter of the nichrome wire were the key parameters governing successful performance. To activate the nichrome wire a constant current of 1.60 ± 0.05 amps is applied to ensure a successful and reliable cut. The tight tolerance constant current source is necessary in order to reliably: 1.) thermally cut the cable and 2.) prevent overheating failure of the nichrome wire to allow the mechanism to be reusable for many actuations without replacing the nichrome filament. The tight tolerances on the current prevent failure of the nichrome wire from overheating under too much current in a vacuum while also providing adequate thermal margin to cut through the Vectran tie down cable in air which requires more current than in vacuum. The burn wire release mechanism has been tested in air at room temperature and in vacuum at temperatures as low as -50°C and as high as 70°C on two different Vectran cable thicknesses. The release mechanism has shown to have cut times ranging from 2.4 to 7.2 seconds under these operating conditions. The burn wire release mechanism has 400 firings in component and system level testing without a single failure. The mechanism has been qualified for flight on the TEPCE (Tether Electrodynamic Propulsion CubeSat Experiment) program to release two carpenter tape deployments and a stacer and tether deployment system.

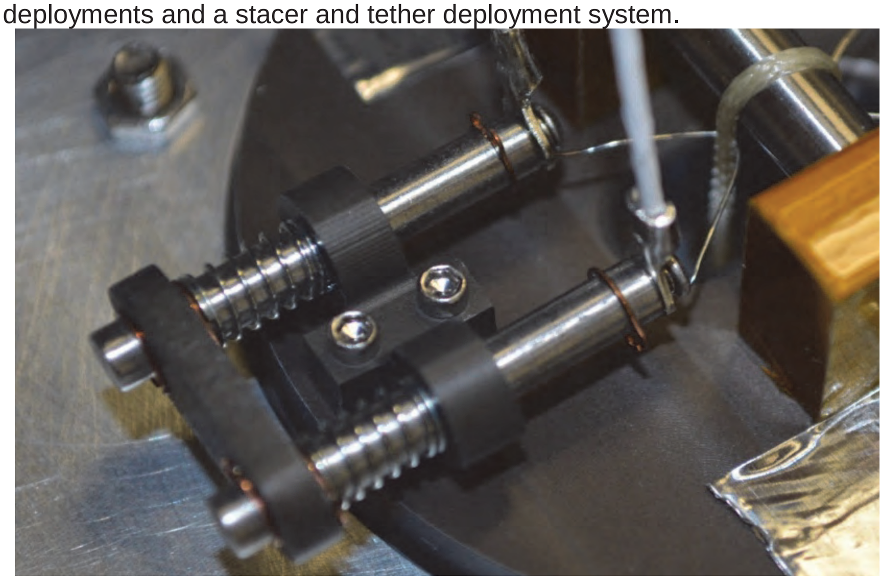

Figure 1. Assembled burn wire release mechanism

---

* Naval Research Laboratory, Washington DC
** NRL Co-op Student from the University of Cincinnati, Cincinnati, OH
+ NRL Co-op Student from Northeastern University, Boston, MA

Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18, 2012

Introduction

CubeSats have grown into a class of satellites which are rapidly introducing new, inexpensive technologies in space. This ever increasing complexity and functionality in a small package brings rise to numerous mechanisms and deployables necessary in order to meet mission requirements. Release mechanisms often add significant development cost to a satellite program and in the world of small satellites, such as CubeSats, the need for simple, reliable, and inexpensive release devices can be critical to the success of the program. The ability for a single mechanism to accomplish many of these releases is a desirable trait among CubeSat users. Whether the mechanism be used to release antennas, solar arrays, deployable doors, etc.; an inexpensive, simple and reliable release mechanism would help to further promote the class of small satellites throughout the community. Since there are currently no standard commercialized CubeSat class release devices on the market, one was developed at the Naval Research Laboratory (NRL) via internal fellowship funding, since these programs are never funded sufficiently to develop one with program funding.

A spring-loaded nichrome burn wire solution was selected because it: 1.) could be actuated with standard CubeSat bus power and fairly simple, low cost electronics, 2.) was simple enough that University students could build and use it, and 3.) was inexpensive enough that CubeSat funding levels could afford it. With few moving parts, simply machined components and the majority of the hardware able to be purchased through low cost commercial suppliers such as McMaster-Carr, the nichrome burn wire release mechanism would allow CubeSat programs, including Universities, to keep down cost and complexity and ensure a high level of reliability for the release mechanisms needed for successful satellite operation.

Design

The release mechanism, utilizes a compression spring system in order to apply a force and a stroke to the nichrome burn wire. When a constant current is applied to the nichrome wire, it will thermally cut through a Vectran tie down cable allowing it to release the deployable it had secured. The nichrome wire used on the mechanism is 30 AWG type Chromel C with an allowable free length ranging from 10.0 (0.4") to 32 millimeters (1.25"). The free length of the nichrome wire is configured into a V shape with the apex in the V being the primary area for cutting through the tie down cable (See Figure 1). The nichrome wire free length range is determined by the minimum length which will avoid problems with heat sinking the nichrome wire to the rest of the mechanism. At a free length of at least 10 mm the apex in the V of the nichrome wire will be sufficiently far enough away from the mechanism heat sinks to avoid heat loss and ensure a successful cut. The maximum length of the nichrome wire is limited by the free length which causes the wire to lose structural stability when heated. At a free length greater than 32 mm the apex of the nichrome wire when heated becomes very hot and the resulting loss in tensile strength can cause necking of the wire which would impact further use of the nichrome wire. Using this free length range the resistance of the nichrome wire as measured from the screw head to screw head of the release mechanism is in the range of 0.4 to 0.9 Ω. When selecting the free length of the nichrome wire it is critical that the release mechanism has ample spring stroke to cut through the Vectran cable with the allowable deflection of the Vectran cable. Particularly in vacuum where convective heating cannot be taken advantage of, the nichrome wire must completely stroke through the Vectran cable in order to ensure a successful release. If the spring stroke on the wire is lost before the entire cable is cut then it is possible for the nichrome wire to remain stuck in the Vectran cable without severing it enough to have a successful cut. Therefore the tension on the Vectran cable must be enough that it does not allow for large, sagging bends in the cable which would allow for the springs on the mechanism to lose their preload and cutting stroke.

The compression springs are held between two saddles which are positioned on a pair of stainless steel dowel pins using retaining rings. The saddles are machined from 6061 aluminum which has been hard anodized to prevent electrical shorting (See Figure 1). The dowel pins have a tapped hole on their upper end where a #0-80 button head screw threads into. The head of the #0-80 screw attaches the nichrome wire to a ring terminal which is connected to two flying leads and provides the electrical connection to the release mechanism. The nichrome wire is secured between the ring terminal and the underside of the head of the #0-80 screw (See Figure 2). The ring terminals which can be purchased cheaply with tin plating will need to be stripped by a plating manufacturer for a small cost, approximately $1 per ring terminal. The #0-80 screw is secured into the tapped hole of the dowel pin using 3M Scotch-Weld™ 2216 B/A on the threads of the screw to prevent the screw from backing out and losing the secure connection of the nichrome wire. Figure 3 shows CAD models of the nichrome burn wire release mechanism in the deployed and stowed states.

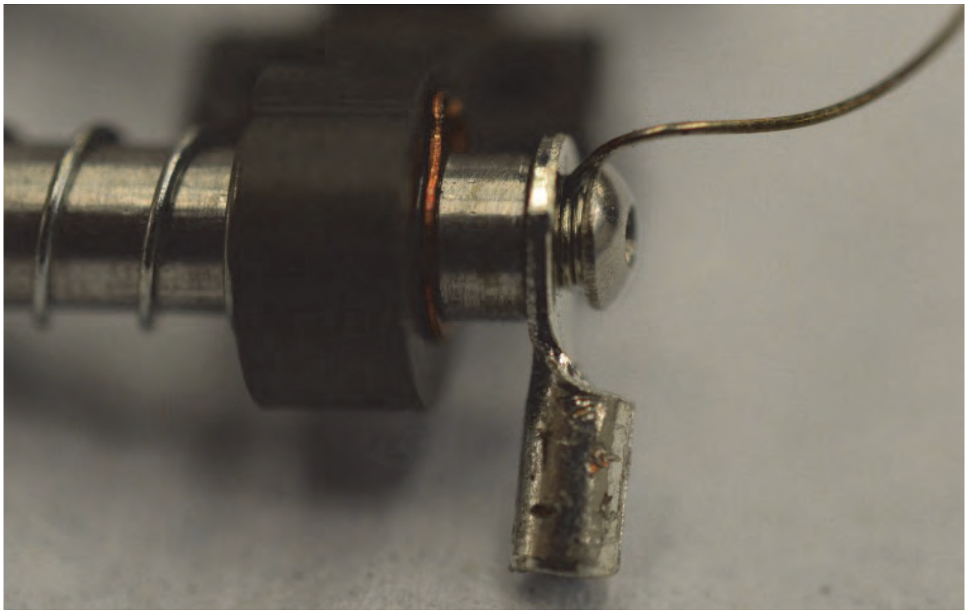

Figure 2. Nichrome wire secured between the button head screw and ring terminal

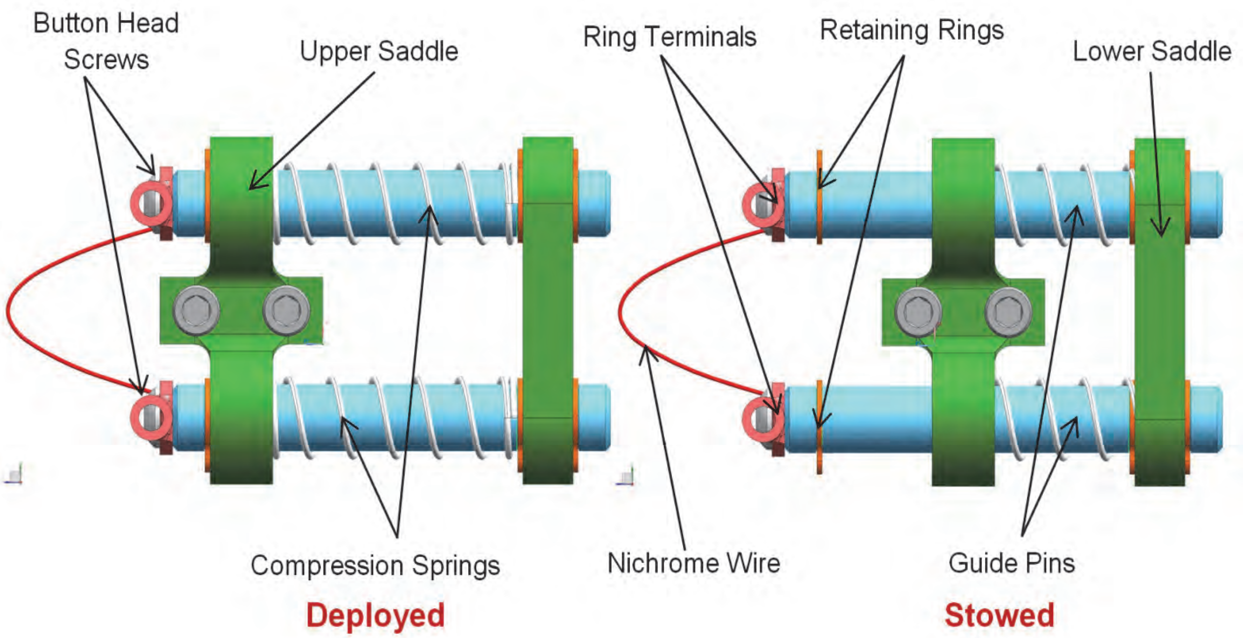

Figure 3. Nichrome burn wire release mechanisms in the deployed and stowed configurations.

The mechanism was designed to thermally cut through two different deniers of Vectran cable. Both Vectran cables were 12 strand tubular braids with either 200 or 400 denier strands and were manufactured without an oil finish for low outgassing. The 200 denier Vectran cable has a tensile breaking strength of 300 N and the 400 denier Vectran has a tensile breaking strength of 600 N. Vectran cable was selected as the primary tie down cable due to its low creep over time, its relative strength to other materials, and its resistance against self-abrasion.

The entire burn wire release mechanism once assembled has dimensions of approximately 32-mm (1.25”) long by 16.5-mm (0.65”) wide by 11.5-mm (0.45”) tall. Figure 4 shows two, redundant burn wire release mechanisms stowed on the TEPCE tether deployment system. Due to the small size, assembly and workmanship, inspection is best done with the aid of magnification such as a stereo microscope.

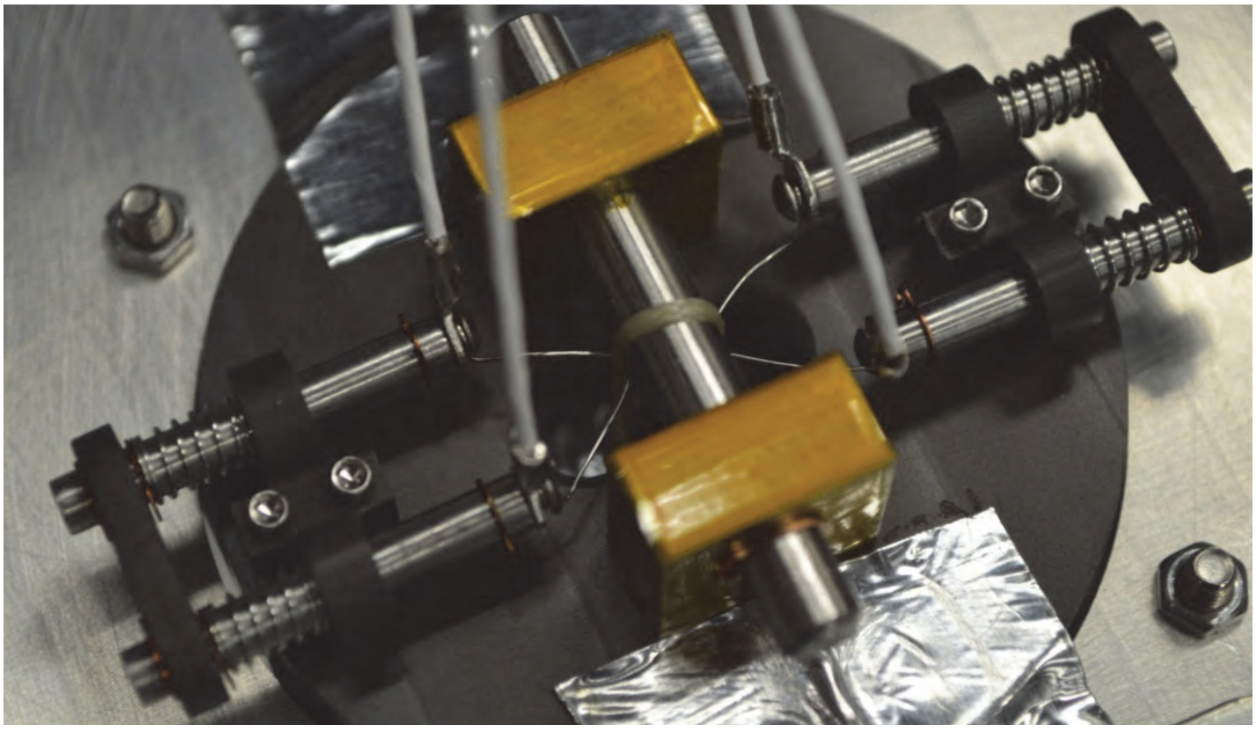

Figure 4. Release mechanisms on Vectran tie down cable for TEPCE tether deployment system

Testing

The goals established for a generic CubeSat class release mechanism were: 1.) to be simple enough to replicate the build and assembly by all CubeSat users (including Universities), 2.) be inexpensive, 3.) reliably release in a few seconds but rugged enough to survive for a 30 second timer for each actuation, 4.) have a design life at least 50 actuations, 5.) work at the same power draw in both air and vacuum and 6.) fit into as small a volume as possible. A burn wire based release device was selected based on a trade study between numerous miniature actuators including bolt releases, pin pullers, and linear and rotary actuators. Then the parameters associated with the burn wire, the compression springs and the tie down cable were investigated. Since a large number of parameters needed to be tested in order to find the optimal design of a nichrome wire system, a design of experiments (DOE) approach was taken in order to test multivariable changes in the minimum number of experiments. The parameters chosen to test were the nichrome spring stroke and force applied, the nichrome wire diameter, the free length of the nichrome wire and its corresponding resistance, the tie down cable, the tension on the tie down cable, the current supplied to the nichrome wire, the number of actuations (life) for each nichrome wire, the performance in air and vacuum and the effect of the environmental temperature. Additionally, minimizing the cut time of the Vectran tie down cable was a goal. Using the JMP Statistical Discovery software a DOE test matrix was designed and tests were conducted and important factors in the design were determined.

Through the DOE analysis in JMP, it was found that the most important factor for successful cut times in both air and vacuum was the supplied current to the nichrome wire. As long as the compression springs supplied spring stroke all the way through the Vectran tie down cable and the nichrome wire had enough current to thermally cut through the tie down cable then the release mechanism would successfully release. The diameter of the nichrome wire was then based on that which provided a large enough electrical current margin to reliably release in air balanced against not failing in vacuum due to overheating the nichrome wire. An electrical circuit was designed to supply a constant current to the nichrome wire independent of the resistance of the wire and the voltage available from the spacecraft. As long as the minimum required power (0.9 W) was available from the spacecraft then the electrical circuit would supply a constant current to the nichrome wire.

It was found that the 30 AWG nichrome wire provided an acceptable margin relative to overheating in vacuum versus failing to thermally cut in air. Since the design envelope for the two failure modes was not large, the constant current source was kept to tight tolerances. The minimum amount of current needed to reliably cut through the tie down cable in air (worst case) was 1.40 amps. The supplied current to the nichrome wire that would cause a failure due to overheating in vacuum (worst case) was 1.90 Amps. Therefore a constant current requirement of 1.60 ± 0.05 amps was selected to provide margin on either side of the failure modes and was used to design the electrical circuit. This allowed the mechanism to successfully operate in both air and in vacuum without having to change any circuitry or software. It is critical to note that the critical operating window – in vacuum/space where it must work – is larger than the worst case window that includes operation in air for ground testability. Additionally, in all tests to date where the nichrome wire has been overheated to failure, it has first cut through the Vectran cable for a successful release prior to the nichrome wire failing such that this has not actually resulted in a failure to deploy but rather ended the reusable life of the nichrome wire filament. This shows that the nichrome burn wire release mechanism has a much larger margin to work successfully in vacuum where it counts. The schematic for the constant current circuit design used on the nichrome burn wire release mechanism is given in Figure 5.

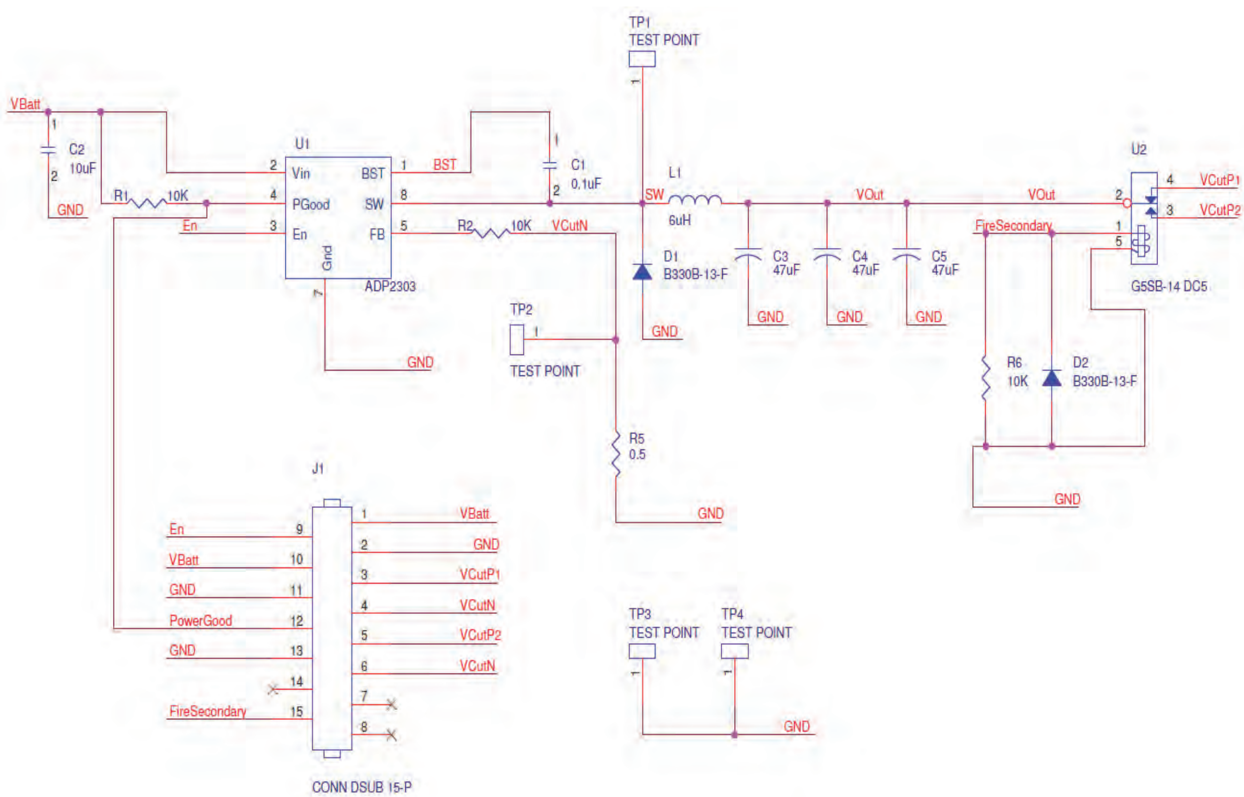

Figure 5. Schematic for the constant current circuit design.

Results

The design and optimization of the burn wire release mechanism revolved primarily around understanding the performance of the nichrome wire. The failure current of the nichrome wire under only the tension of its own weight was first investigated and the results for the 30 AWG nichrome wire is given in Table 1. This data shows that the upper bound of the nichrome wire failure current is established at 1.90 amps.

Table 1. Failure currents of the 30 AWG nichrome wire under only the tension of its own weight.

Nichrome Wire Resistive Length (mm/in)	Resistance (Ω) – as measured from screw to screw	Failure Current (amps)	Failure Time (sec)
13 / 0.50	0.8	2.15	7
19 / 0.75	1.1	2.05	7
25 / 1.0	1.5	1.95	7
32 / 1.25	1.3	1.95	9
38 / 1.50	1.5	1.9	10
45 / 1.75	1.6	1.95	14
51 / 2.0	1.8	1.9	20
57 / 2.25	2	1.9	17
64 / 2.5	2.1	1.975	30
70 / 2.75	2.2	1.975	19
76 / 3	2.2	1.975	13
83 / 3.25	2.4	1.9	15
89 / 3.5	2.6	1.9	19
	Avg. Failure Current	**1.960**	

Using the tight tolerance constant current circuit, 419 successful tests of the release mechanisms have been conducted without a failure. Of the 419 tests, 242 were conducted in air at room temperature and 177 were conducted in vacuum at various temperatures. Tests were also conducted to intentionally overheat the nichrome wire and cause it to fail but even in these cases; the nichrome wire always first cut through the tie down cable ensuring a successful release and then the nichrome wire would fail after the successful cut from overheating. Figure 6 shows test data taken for the air and vacuum operation of the burn wire release mechanisms cutting through 200 and 400 denier Vectran cables.

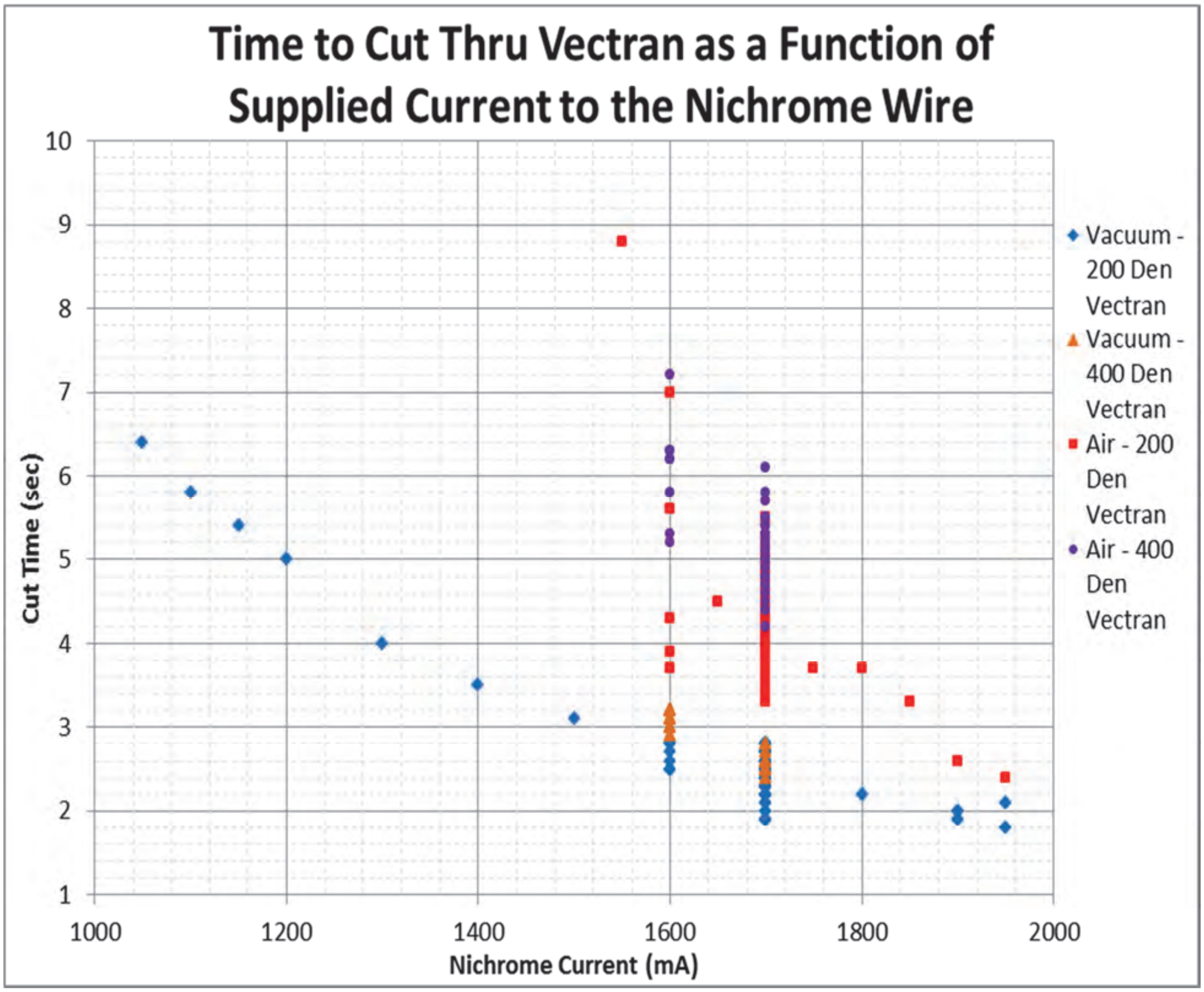

Figure 6. Release mechanism deployment times for varying currents of both Vectran cables in air and vacuum environments.

Using the constant current circuit which supplied the nichrome wire with 1.60 amps with a 30 second powered timer, the cut times for the burn wire release device in air and vacuum and using both Vectran cables ranged from 2.4 to 7.2 seconds. For the critical operating window in vacuum this gives approximately a 10X margin on the cut time versus the 30 second powered timer limit. Table 2 gives a summary of the average cut times for the operating conditions.

Table 2. Average cut times of the burn release mechanisms.

	Average Cut Time (sec)
200 Denier Vectran in Air	5.3
200 Denier Vectran in Vacuum	2.6
400 Denier Vectran in Air	6.2
400 Denier Vectran in Vacuum	3

The burn wire release device was also tested down to -50°C and up to 70°C without any noticeable effect on the performance. This is likely due to the nichrome wire heating up to over 750°C and having negligible thermal mass, such that the difference in initial temperature has a negligible effect. It was also demonstrated that when using the tight tolerance constant current circuit the burn wire release mechanism can be actuated at least 50 times without having to change out the nichrome wire. Many of the burn wire release mechanisms were used past the 50 actuations, up to 80 actuations, and still performed nominally Figure 7 shows the release mechanism immediately following a successful cut through the Vectran cable in vacuum with the nichrome wire still glowing hot.

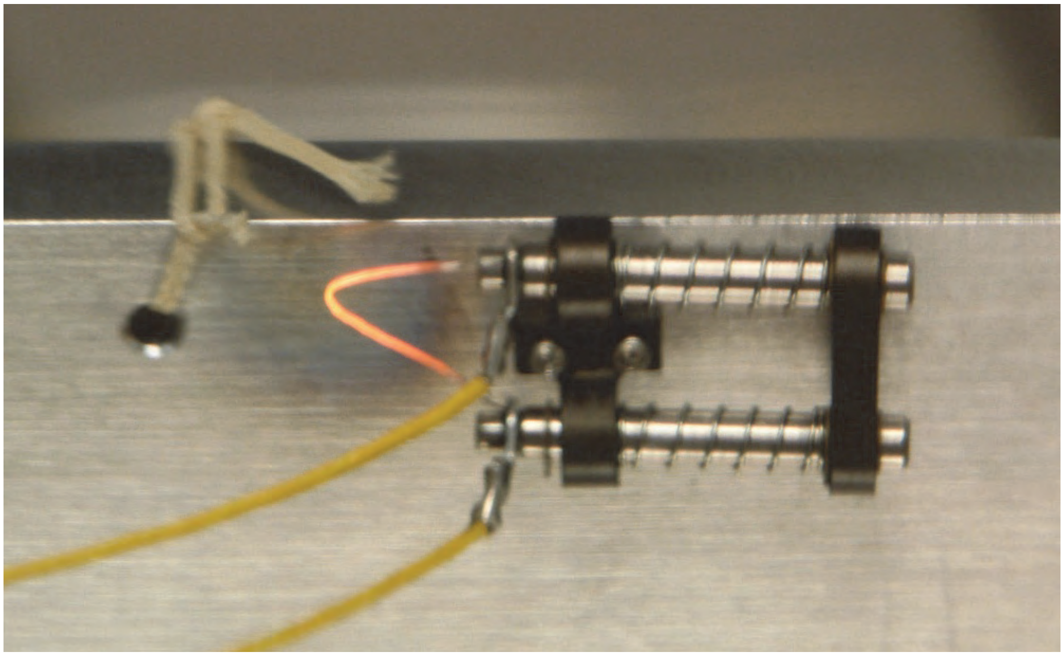

Figure 7. Burn wire release mechanism immediately following a successful cut through Vectran cable.

To be useful to all CubeSat users, including Universities the burn wire release mechanism needed to be simple to manufacture and assemble and to be cost effective. For the NRL TEPCE CubeSat program headed by NRL, the cost for all hardware associated with building 10 of the burn wire release mechanisms was $1600 making the cost per mechanism $160. This cost included having a local machine shop manufacture both the upper and lower saddles and the dowel pins. However, a student with reasonably proficient machining skills could make the mechanism components themselves and eliminate all but the anodizing costs which could drop the price for 10 mechanisms to approximately $200. Table 3 gives a price breakdown of the hardware associated with machining and building up the burn wire release mechanisms for use on a small satellite.

The nichrome wire release device has been through component level testing in different configurations ranging from carpenter tape deployments to a stacer and tether deployment to the deployment of 3U solar array panels on a CubeSat. The release device has also undergone system level testing on the TEPCE CubeSat program.

Table 3. Cost breakdown for burn wire release mechanisms.

Part Description	Material	Secondary Processing	Quantity	Total Cost
Upper Saddle	Aluminum 6061	Hard Anodize	10	$849.00
Lower Saddle	Aluminum 6061	Hard Anodize	10	$200.00
Dowel Pin	18-8 Stainless	None	20	$430.00
Compression Springs (CI013DE03M from Lee Spring)	302 Stainless Steel	None	100	$101.00
1/8" External Snap Rings (McMaster-Carr)	Beryllium Copper	None	100	$12.50
#0 Stud Ring Terminals (McMaster-Carr and Stripping Manufacturer)	Copper	Tin Stripping	100	$45.30
#0 Fasteners (McMaster-Carr)	18-8 Stainless Steel	None	100	$5.68
0.0100" Diameter Nichrome Wire	Nickel Chromium	None	1/8 lb.	$18.65
			Total Cost for 10 Mechanisms	**$1,662.13**
			Cost per Mechanism	**$166.21**

Cautions and Areas for Potential Improvement

A drawback to the burn wire release mechanism is that the successful operation of it relies largely on the workmanship and assembly of the mechanism in its intended application. A loss of spring preload is possible if the Vectran tie down cable is not tensioned properly. Additionally, the available play and stiffness of the electrical wiring for the flying leads or and improperly securing the nichrome wire under the screw head can all lead to potential failures of the burn wire release mechanism to successfully cut through the Vectran tie down cable. Therefore it is critical that throughout the assembly and installation of the burn wire release mechanism that careful attention is given to these areas of concern and risk of failure is mitigated. Properly tensioning the Vectran tie down cable, ensuring an appropriate free length of nichrome wire and proper placement of the burn wire release mechanism will help to avoid the threat of the springs losing preload. Conducting pull tests of the nichrome wire and verifying the connection under a stereo microscope after securing it between the ring terminals and the screw head will verify that the nichrome wire connection is reliable and the possibility of the nichrome wire coming unattached can be avoided. When installing the release mechanism it is vital to verify that ample play is given for the electrical wiring of the flying leads to the mechanism and that snag hazards of the wiring are avoided. If the electrical wiring does become snagged or runs out of available room to move, the small force associated with the burn wire release mechanism will likely not be sufficient to compensate for a snag and the release mechanism would fail to cut through the tie down cable.

Improvements could be made to the burn wire release mechanism to lower the reliance on workmanship and add confidence and reliability to the mechanism. To minimize the risk of the flying leads being a snag hazard, one could investigate adding a jumper wire to the mechanism with a connection pad that would have all of the moving wires on contained to the mechanism itself and then the electrical leads could be mounted to the stationary portion of the mechanism. This would mandate a design change to the saddles and add slight complexity to the release mechanism but would help to alleviate the risk of failed release due to the electrical wiring to the mechanism. Another improvement could be a new way to mechanically connect the nichrome wire to the release mechanism instead of using the preload and clamping force of the screw to hold the nichrome wire. While properly securing the nichrome wire and verification of this connection has proven successful in testing to date, the concern still exists that the nichrome wire could slip out from under the screw head and increase the nichrome wire free length which would in turn allow the compression springs to relax and spring preload could be lost.

Conclusions

The burn wire release mechanism was designed in order to be used by a broad range of small satellite users in a manner that was simple, reliable, and inexpensive. Using a nichrome burn wire design the release device is capable of cutting through various tie down cable materials and providing successful satellite mechanism deployments. The burn wire release mechanism specifications were chosen in order to be user friendly in both air and vacuum environments and to give the user the ability to implement a release mechanism which has been previously tested and will work in a number of applications.

Drawings and assembly procedures have been produced in order to allow any small satellite user to conveniently reproduce the nichrome burn wire release mechanism for their specific application. The nichrome burn wire release mechanism will hopefully allow for a more universal release mechanism which can be reliably used in a wide array of applications for CubeSat and other small satellite users. By giving the engineer a mechanism which has proven reliability, the hope is that the cost and complexity of smaller satellite programs can be kept at a minimum.

References

1. Vectran Technical Data Brochure. Kuraray America, Inc. Vectran Division. 2008
2. General Considerations for the Processing of Vectran Yarns. Kuraray America, Inc. Vectran Division. 2007
3. Fette, R.B., M.F Sovinski. Vectran Fiber Time-Dependent Behavior and Additional Static Loading Properties. NASA/TM-2001-212773. December 2004
4. ASTM B344-01. Standard Specification for Drawn or Rolled Nickel-Chromium and Nickel-Chromium-Iron Alloys for Electrical Heating Elements. American Society for Testing and Materials. August 2010.
5. JMP 9 Statistical Discovery software. SAS. 2010