Development of the Next Generation Battery Cell Isolation Switch

Ruben Betancourt* and Michel Knight*

Abstract

EBAD's NEA Battery Cell Isolation Switches (BCIS) have been used to isolate the electrical circuit of a lithium-ion cell within the battery due to safety or performance concerns. Previous testing has shown that there are limitations to the capability of the heritage design under extreme thermal environments and low actuation input current. For example, if a BCIS was functioned at low temperatures and low actuation current there was a possibility of the device not meeting the actuation requirements. This limitation led to the design of the next generation BCIS as described in this paper.

The next generation NEA BCIS was designed to be able to operate under the most extreme environments and lowest current that our customers have requested. This was validated with a combination of analysis and testing.

Introduction

<u>BCIS Design Description</u>

The BCIS is an electromechanical switch that serves two basic functions. The first is that it is used to interconnect lithium ion battery cells, which requires the BCIS to conduct a continuous current up to 400 amps. EBAD has three BCIS product lines: the NEA8020 series with a 135-amp current carrying capability, the NEA8030 series with a 250-amp current carrying capability, and the NEA8040 series with a 400-amp current carrying capability. The different models operate in a similar manner but are scaled depending on the current carrying capability. A cross section of a typical 8030 BCIS is shown in Figure 1. The components on the right side are the high current carrying components which conduct the power output by the batteries. Prior to activation of the BCIS, the electrical terminals T1 and T2 form a closed circuit and conduct the high current, while T3 remains electrically isolated.

The second function of the BCIS is to isolate a battery cell from other battery cells. When a battery shows signs of degradation, the BCIS may be utilized to divert the flow of electrical power between sets of terminals to isolate the degrading battery cell. On the left side of Figure 1 is the release mechanism portion of the BCIS, which provides the switching mechanism. The BCIS utilizes a set of internal spools which are restrained by wire, which is then attached to a fuse wire (T4 to T5). The switching function is initiated by the application of a minimum activation current of 1.5 A for a duration of up to 230 ms, across the fuse wire circuit. The current causes the fuse wire to break and release the restraining wire that holds two spool halves together. This allows a preloaded spring assembly to push a plunger forward, which creates a closed circuit between T1 and T3, and electrically isolates T2. Related to this switching function, the BCIS must meet a set of requirements which include:

- Commutation time less than ~10 msec (varies by customer)
    - o Defined as the time required to switch the circuit from T1-T2 to T1-T3
- Make-Before-Break time of <1 ms
    - o Defined as the time all electrical terminals (T1, T2, T3) are in electrical contact

* Ensign-Bickford – NEA Electronics Inc., Moorpark, CA

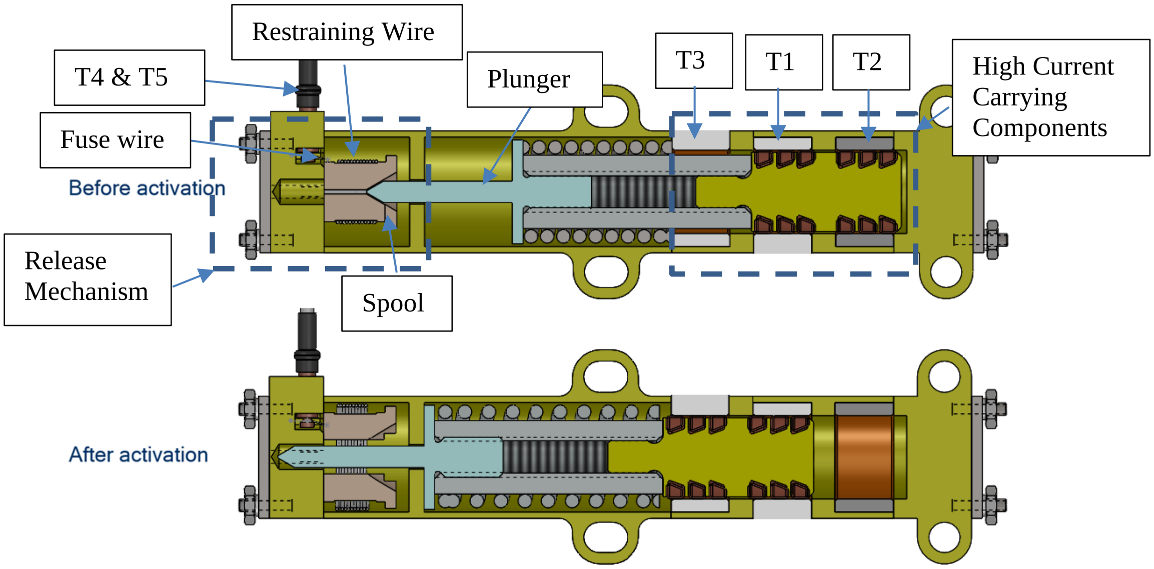

Figure 1: NEA BCIS 8030 Family

<u>Design Development Background</u>

At the 2019 European Space Mechanisms And Tribology Symposium (ESMATS), a summary of lessons learned during Qualification testing of the heritage design was presented. The presentation discussed how the BCIS had failed to actuate properly, and the details can be found in the ESMATS archive (Titled "Bypass Switches – A Case Study in Test Like You Fly Merits"). To summarize the results, the failure investigation found that there were multiple causes for this anomaly.

1. A low actuation current (less than 3 amps) leads to an undesirable condition that could affect the performance of the BCIS.
2. At temperatures less than ambient, the likelihood of an anomaly increases.

The reason that these two causes led to a failure was because they led to a potential negative force margin on the split spool actuation device within the BCIS. Force margin is defined as the ratio between the separating force and the resistive force. In this case, it is specifically the ratio between the restraining wire separating force and the fuse wire resistive force, including all frictional forces. If the restraining wire separating force is greater than the resistive forces caused by the interaction between the restraining wire loop and fuse wire, then the restraining wire can unwind resulting in successful actuation.

The heritage design used a restraining wire with a 0.014-in (0.36-mm) diameter, which corresponded to a separation force of approximately 0.44 lbf (2 N). In most cases, this force was sufficient to separate the restraining wire from the fuse wire, leading to a successful actuation, but the causes 1 and 2 listed above, combined with production lot variation, led to a possible condition where the restraining wire would not separate from the fuse wire or the separation would be delayed. This paper discusses the design iterations and lessons learned during the design and qualification of the improved BCIS design, specifically within the release mechanism portion of the BCIS.

Design Development

The development of the improved BCIS started with a set of basic requirements:

1. The design improvements should not affect the envelope of the existing design
2. The improved design should be able to withstand the most extreme environments and conditions that have been requested by our customers
3. The electrical performance of the BCIS should remain unchanged

Knowing the limitations of the existing design, the approach was to improve the force margin to such an extent that low current, environmental impacts and assembly variation would not affect the performance of the BCIS. There were two initial designs that were considered.

The first was to reduce resistive forces by removing some of the insulating material around the fuse wire and restraining wire. This would eliminate frictional forces and would guarantee a positive force margin. However, a Design Failure Mode and Effects Analysis (DFMEA) was held and multiple potential risks were identified. Removing material had the potential of creating pinch points, snagging possibilities and other potential risks that eventually led to the elimination of this option. A rigorous vetting process was able to detect these issues before significant resources were expended on this design.

The second option was to increase the separation force. The easiest approach was to increase the restraining wire diameter, thereby increasing the spring back force of the wire and yield positive margin. Initially, two different sizes were considered, a 0.016-in (0.41-mm) diameter wire and an 0.018-in (0.46-mm) diameter wire. Analysis and prototype testing were performed to determine the best choice.

<u>Prototype Testing</u>
The spring back force of each size restraining wire was calculated through a mathematical model, and both sizes were expected to provide significant margin over the heritage design. Since the envelope of the design was critical, an assessment of the clearance was one of the first tests performed. Multiple units were functioned, and the unwinding diameter of the restraining wire was measured. This was important, as a large unwinding diameter could indicate that the restraining wire may not have sufficient clearance to unwind properly. In addition to post-test inspection, functional testing was performed with the use of a high-speed camera. It was clear that the 0.016-in (0.41-mm) restraining wire unwound smoothly and fit well inside the BCIS, while the 0.018-in (0.46-mm) restraining wire unwound to a considerably larger diameter and resulted in a condition where the restraining wire could potentially become jammed against the wall of the housing. Therefore, the 0.016-in (0.41-mm) restraining wire was chosen for the final design. The analytical model was validated by test and shown to be in good agreement with the test results, with the restraining wire loads found to be normally distributed about the mean. It was also shown to be a significant improvement to the heritage design. Figure 2 is a plot of the restraining wire force of both the 0.014-in (0.36-mm) and 0.016-in (0.41-mm) restraining wire. The data shows that with the 0.014-in (0.36-mm) restraining wire there exists a very low probability of not providing enough force to separate from the fuse wire. For the 0.016-in (0.41-mm) restraining wire, the force margin was always positive when using a +4 sigma for the frictional force and a -4 sigma for the separation force.

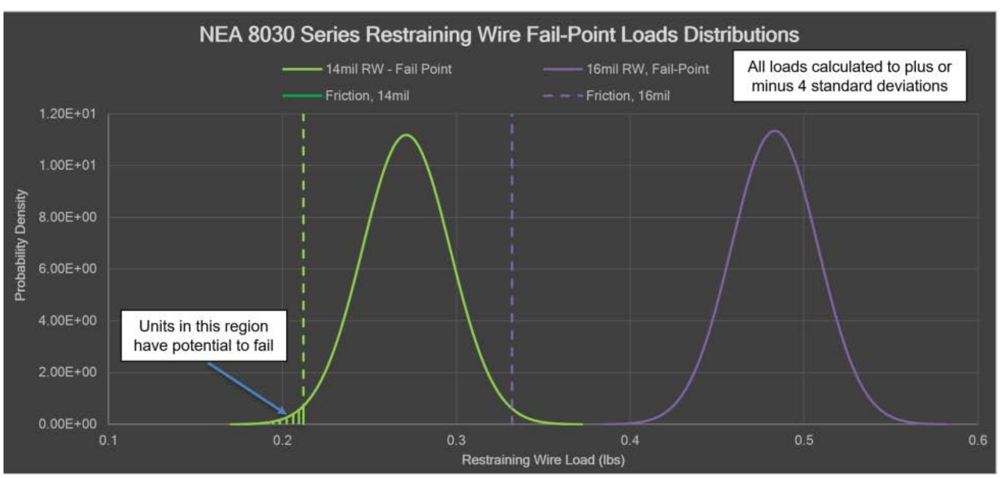

Figure 2: NEA Ultimate Load Test

While performing the prototype testing with the 0.016-in (0.41-mm) restraining wire, the BCIS was tested to very extreme conditions to draw out any other potential issues. This included using various actuation currents, test temperatures, and vibration levels. Based on this testing, the next limiting component in the design was the spools. The heritage design used a spool that was made of a glass-filled Torlon and reacting against it was a metallic plunger with an edge that only had a small radius. Due to the low loads on the plunger, this was not seen as an issue as there were never any signs of indentations or any other observable issues. However, when testing at extreme environments, the additional wear from higher level environment and temperatures, revealed a new failure mode. High-speed video revealed that the restraining wire could fully unwind, and yet the spool would temporarily not move (Figure 3). While this was only temporary, it would fail to meet the customer commutation time requirement.

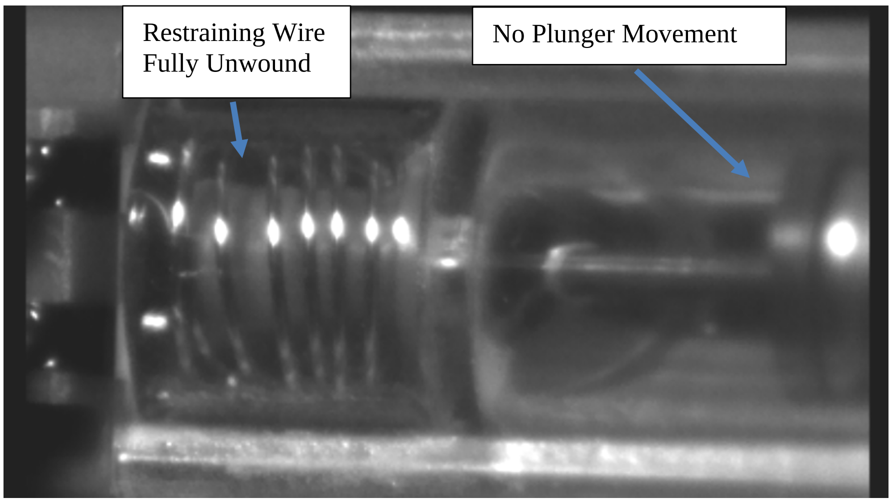

Figure 3: Unwound Restraining Wire with No Movement

From the high-speed video it was evident that the slow commutation time was related to either the spool-to-insulator interface, or the spool-to-plunger interface. It was determined that the lowest risk approach would be to replace the plastic spools with metallic spools. This would create a better coefficient of friction between the three components and would eliminate the concern of any spool indentations. Since the load on the components was low, Aluminum 7075 was chosen. A DFMEA was held to determine potential risks with a material change. The biggest concern was that the metallic spools would be conductive, which could lead to a short between the terminal T3 and the actuation circuit, as seen in Figure 4.

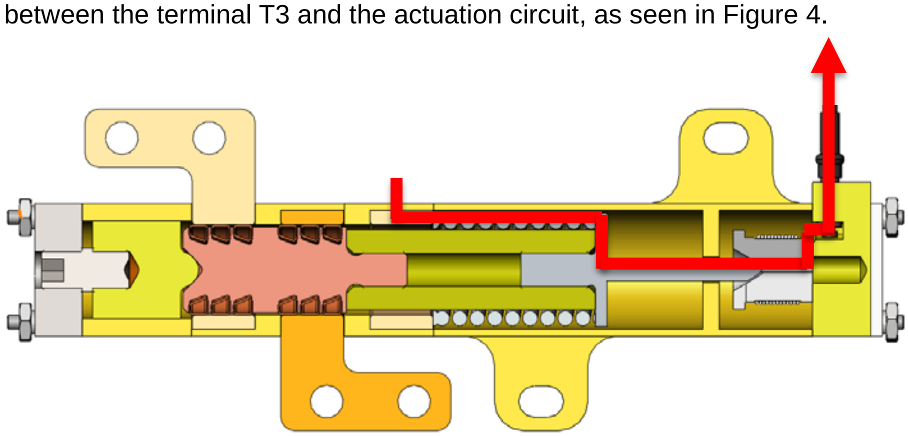

Figure 4: BCIS Potential Electrical Path

In order to eliminate this concern, a thin wall of insulating material was added to the insulating driver. This added a physical barrier between the metallic plunger and the metallic spring that contacts T3. In addition, a proprietary coating called Magnaplate® HCR was applied to the spools. This provided three benefits. The first is that Magnaplate® HCR has high dielectic strength, meaning that it will isolate the metallic spools from any other metallic components. The second benefit is that Magnaplate HCR increases the hardness of the aluminum spools to above 50 Rockwell C, which is harder than the plunger. It is ideal for the spools to be harder than the plunger, as this prevents the plunger from digging into the spools and preventing or slowing release. A stress analysis was performed and showed that the stress remained well below the material capability for the spools and plunger (Figure 5). Testing was also performed to validate the results. The testing showed that the spool and plunger combination could sustain loads over 900 lbf (4000 N), while the load during use was expected to be on the order of 44 lbf (2 N).

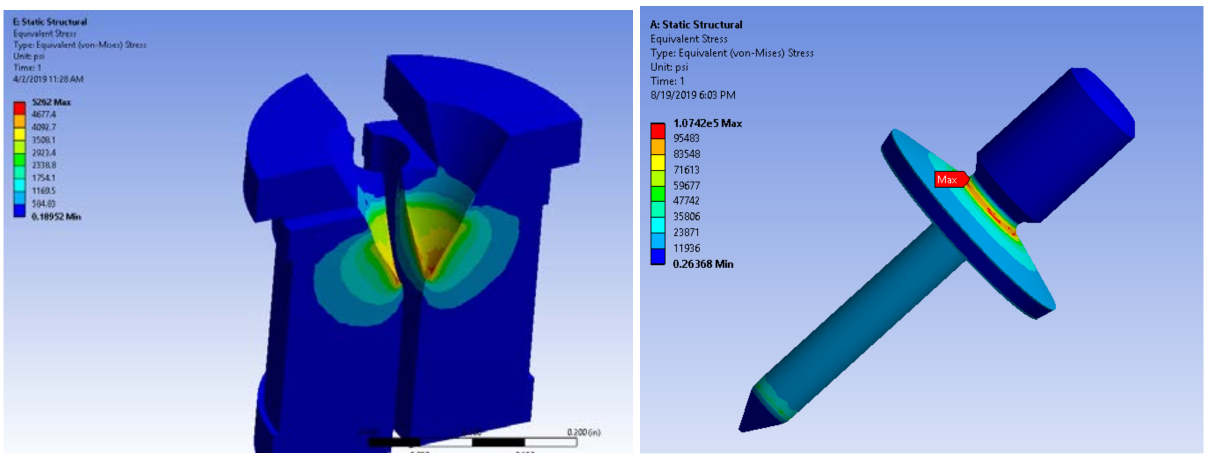

Figure 5: FEA of the Spool and Plunger

The final benefit is that Magnaplate® HCR is self-lubricating, with a published coefficient of friction of 0.35 when used in combination with aluminum. Since the plunger is stainless steel, it is likely that the actual coefficient of friction between the plunger and Magnaplate coating is less. A cross-section of the final design is shown in Figure 6. The design meets the primary design requirement of fitting within the initial envelope and it has passed all initial development tests.

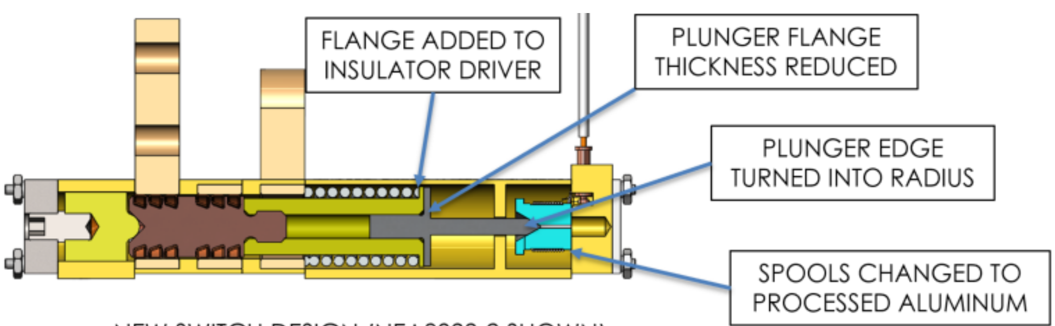

Figure 6: Final BCIS Design

Test Results

As of the end of 2019, the unit has successfully completed prototype and development testing. The development testing included the following:

- 40+ actuations
    - Actuation Current = 1.5 amps and greater

- Temperature = -70°C to +130°C
- Vibration Testing:
    - Sine Vibration: Up to 110G
    - Random Vibration: Up to 56 Grms
- Shock Input
    - 2300G from 1300 Hz to 10000 Hz
- Thermal Shock:
    - -62°C to +137°C
    - 10 cycles

Qualification testing will be conducted in April 2020 and is expected to be completed by May 2020. The expected qualification sequence is in Table 1.

Table 1: Qualification Test sequence

TEST #	TEST DESCRIPTION	Section
1.0	Mass Measurement	5.0
2.0	Dimensional Inspection	6.0
3.0	Fuse Wire Resistance	7.0
4.0	Insulation Resistance	8.0
5.0	Contact Resistance/Voltage Drop	9.0
6.0	No-Fire Current	10.0
7.0	Sine and Random Vibration	11.0
8.0	Engineering Examination	12.0
9.0	Fuse Wire Resistance	13.0
10.0	Shock, Mechanical, Non-Operational	14.0
11.0	Engineering Examination	15.0
12.0	Fuse Wire Resistance	16.0
13.0	Thermal Cycle	17.0
14.0	Contact Resistance/Voltage Drop	18.0
15.1	Thermal Vacuum (TVAC)	19.0
15.2	Vacuum No-Fire Current	19.0
15.3	Actuate Hot	19.0
15.4	Actuate Cold	19.0
16.0	Engineering Examination	20.0
17.0	Fuse Wire Resistance	21.0
18.0	Insulation Resistance	22.0
19.0	Contact Resistance/Voltage Drop	23.0

Conclusions and Lessons Learned

1. EBAD has developed an updated NEA BCIS design that is insensitive to extreme environments and actuation conditions (within reason)
2. During the initial phase of a program, parallel paths should be chosen to reduce the impact of unforeseen risks
3. Perform mini design reviews, DFMEAs, etc. early and often to prevent spending resources on risky design concepts
4. The force margin on even the smallest components should be determined