REPORT OF INVESTIGATION: HYBRIDS PLUS PLUG IN HYBRID ELECTRIC VEHICLE

Prepared for:

National Rural Electric Cooperative Association, Inc.

And

U.S. Department of Energy, Idaho National Laboratory

By:

An ECOtality Company

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- Hybrids Plus
- A123 Systems
- NRECA

Introduction

ETEC was recently retained by the National Rural Electrical Cooperative Association (NRECA) and the U.S. Department of Energy, Idaho National Laboratory to lead an investigation of a fire in a Toyota Prius that had been converted to a Plug-In Hybrid Electric Vehicle (PHEV) by Hybrids Plus. This document presents the report of that investigation and the determination of the root cause of the fire.

Background

In February, 2008, the Central Electric Power Cooperative, Inc. (CEPCI, Colombia, SC) purchased a Toyota Prius and had it converted to a PHEV by Hybrids Plus (Boulder, CO). This vehicle was designed to be a PHEV-15 meaning that it had a battery pack sized to provide 15 miles of all-electric driving. To effect this conversion, Hybrids Plus replaced the stock Toyota battery pack and replaced it with a higher-capacity pack fabricated using lithium-ion cells purchased from A123 Systems (Watertown, MA).

On Saturday, June 7, 2008 a CEPCI engineer was driving the PHEV Prius. The reported high temperature that day was 98F. After approximately 40 miles of highway driving, The driver noticed a warning light on the Prius's display screen and simultaneously noticed that the combustion engine was operating at high rpm. He pulled the vehicle to the shoulder, turned the car off and inspected the vehicle. At that time, he noticed an acrid smell but attributed that to the high rpm operation of the engine. The driver restarted the vehicle and pulled back onto the highway, accelerating quickly to achieve highway speed. After another four-to-five miles, the driver again experienced a warning light on the vehicle display (although the engine did not operate at high rpm this time) and noticed a strong odor of burning material. He opened the windows and began to pull over. When the windows were opened, a significant amount of smoke was pulled forward to the driver's area. The driver exited the vehicle and noted a fire at the right side in the rear (cargo) compartment of the vehicle which eventually consumed the vehicle. Figure 1 shows the results of the fire (See Appendix A for additional images of the fire-damaged vehicle).

Figure 1--Fire Damaged PHEV Prius

The vehicle was towed to Firmin Ford (Laurens, SC), a close, convenient spot for the tow truck driver. Davide Andrea of Hybrids Plus was dispatched to Columbia where he performed the initial inspection of the vehicle. During this inspection, Mr. Andrea found that there was still voltage present at the battery pack, although not as high as would normally be present on this pack. Mr. Andrea cut several cables on the pack to reduce the available voltage in an effort to make it safer to handle. After completing his initial inspection, Mike Hoff and Ricardo Bazzarella of A123 Systems arrived in South Carolina to inspect the vehicle. Following that, a determination was made by Hybrids Plus, CEPCI and A123 to remove the battery pack and transport it to A123 Systems' facility in Hopkinton, MA for further investigation. Ricardo Bazzarella of A123 Systems transported the battery pack in his rented vehicle back to Hopkinton.

Design

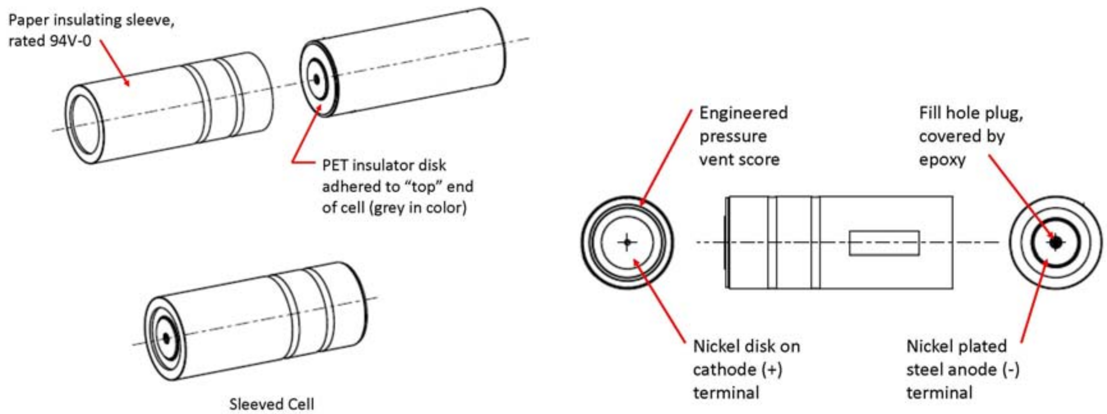
ETEC's VP of Engineering, Garrett Beauregard, traveled to Hopkinton on June 13 to participate in the battery investigation. A team was assembled consisting of several engineers from A123 Systems, Carl Lawrence, CEO of Hybrids Plus along with ETEC's Mr. Beauregard. The chain of events leading to the fire was first reviewed. Following that, the Hybrids Plus battery design was reviewed.

The Hybrids-Plus battery pack is based on the A123 Systems Lithium-Ion cell which uses a Nanophosphate[1] technology to limit the reactivity of these cells. The cell uses an aluminum can which contains a roll of copper and aluminum foil onto which the active materials are coated. A flammable, solvent-based electrolyte is used. The cell is sealed with a laser-welded cap which is machined with a relief groove that turns this cap into a rupture disk should internal pressure build beyond a design point (the pressure vent). A fill hole is present on the anode end of the cell through which the electrolyte is loaded into the cell. This hole is sealed with epoxy. As the sides of the cell can are at anode potential, the cell is placed inside a heavy, cardboard sleeve (rated UL 94 V-0, self

[1] A trademark of A123 Systems

extinguishing). With the sleeve in place, only the ends of the can are available to conduct energy. Figure 2 shows the features of the A123 cell.

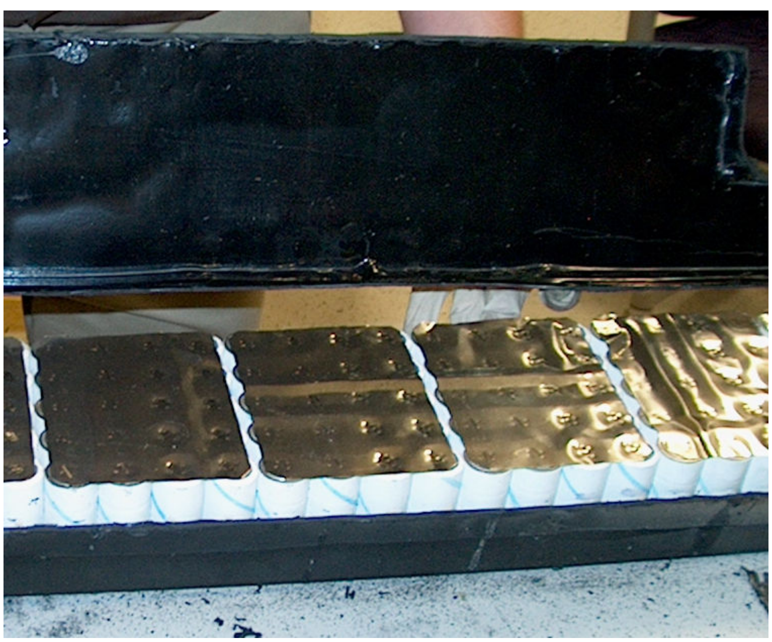
Figure 2--A123 Lithium Ion Cell



The battery pack consists of 600 cells arranged in a 10P 60S configuration; groups of 10 cells connected in parallel joined into a series string of 60 of these groups.

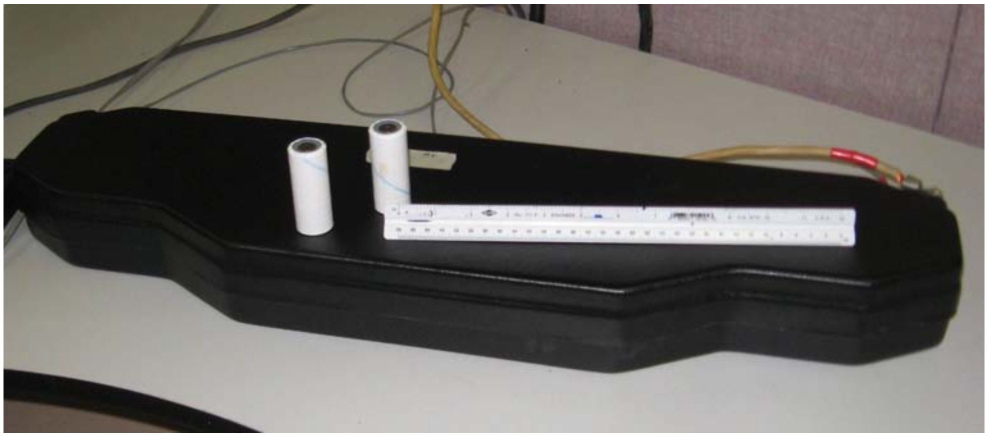
The parallel groups are created by spot welding the poles (all positive or negative) of the cells to a Nickel sheet which acts as the bus bar. Each A123 cell has a Nickel disk (or rivet depending on which pole) attached at the end of the can to facilitate welding to the Nickel bus bar. See Figure 3 for details.

Figure 3--Bus Bar Arrangement



The 600 cells are arranged in four large "batteries" which consist of 160 cells (front batteries, 16 series strings of parallel groupings) or 140 cells (rear batteries, 14 series strings of parallel groupings). These four batteries are created by welding the cells to Nickel sheets (used as bus bars) and then enclosing this construction into a plastic clamshell housing which is vacuum formed from Boltaron 1165 (Acryllic/PVC alloy plastic). The two halves of the clamshell are adhesively bonded together. Figure 4 is a typical battery assembly, although not identical to the one used in the PHEV 15 Prius.

Figure 4--Assembled battery



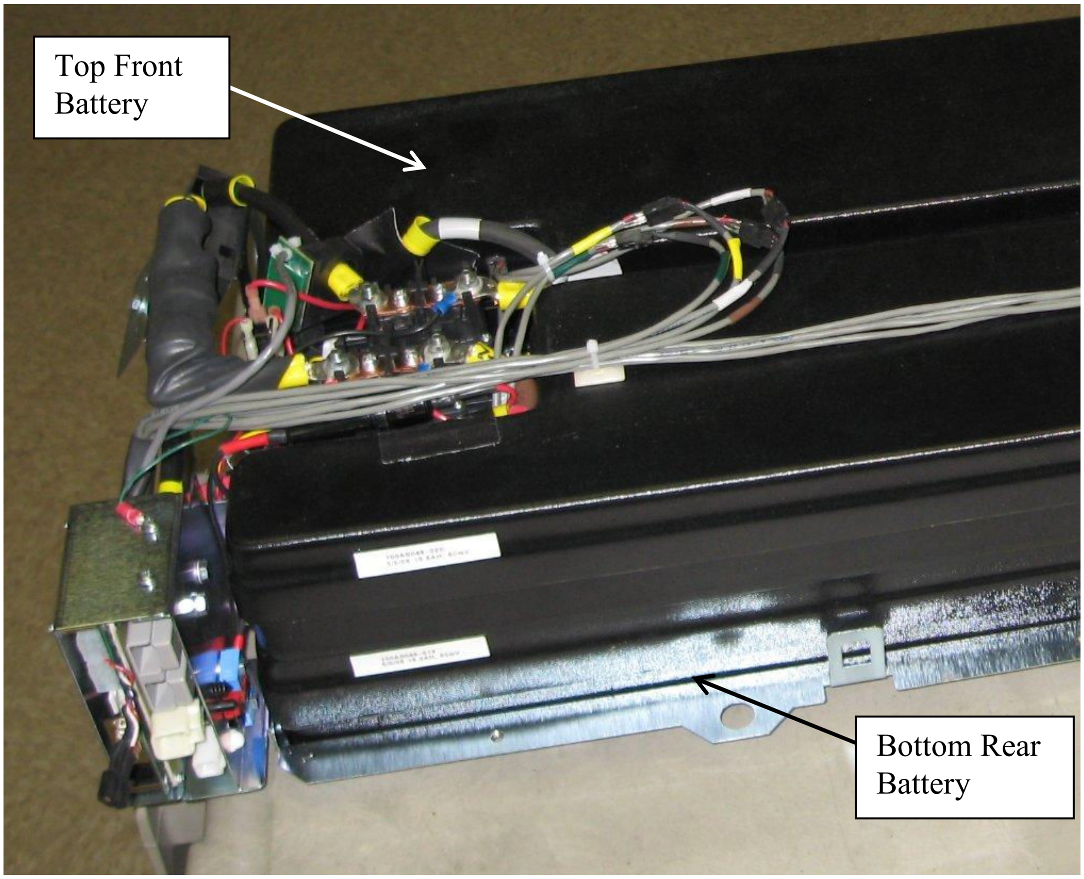
The four batteries are stacked two high and two deep so that the following descriptions are used:

- Bottom Front[2]
- Top Front
- Bottom Rear
- Top Rear

Figure 5 shows a close up of the left-hand end of the four-battery assembly.

[2] Throughout this document, typical automotive convention is used—front is vehicle front and right is driver's right when seated in the driver's seat and facing the steering wheel

Figure 5--Four-Battery Assembly

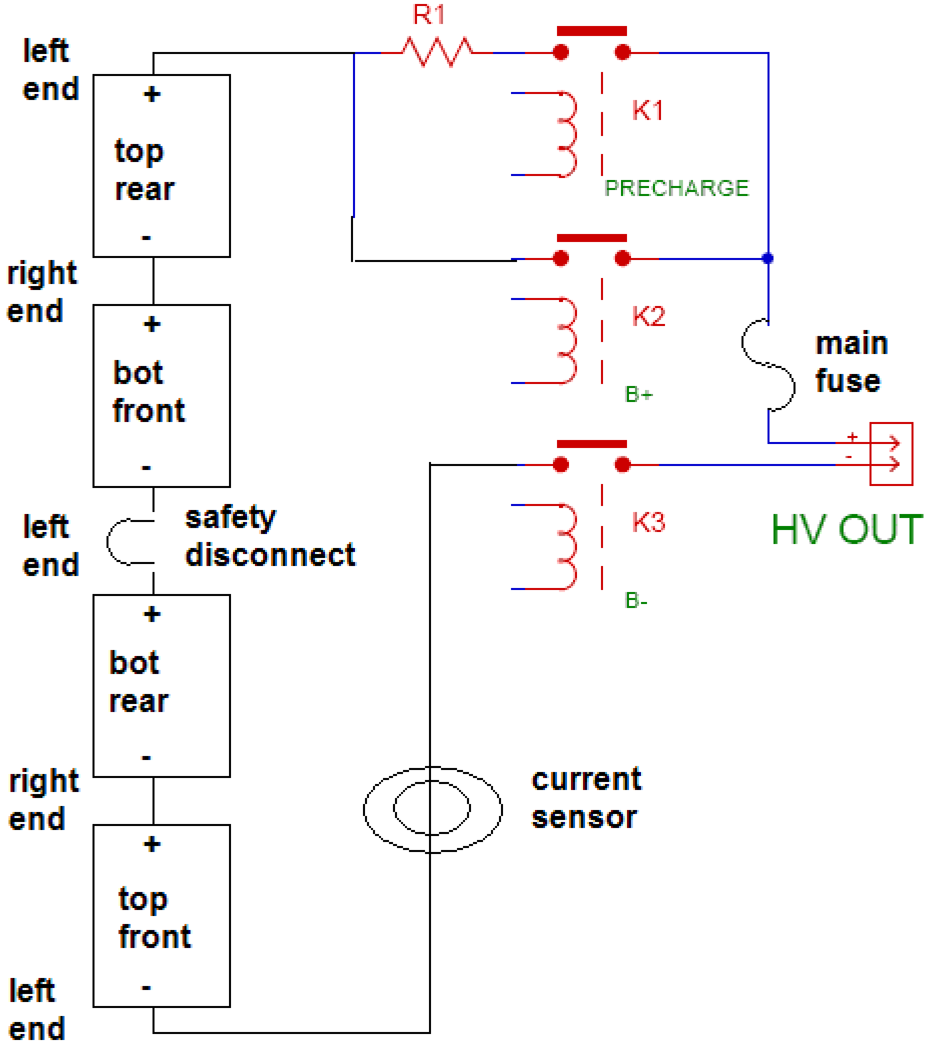


The four batteries are restrained by the top cover which is bolted to the vehicle's chassis in the original battery mounting locations; there is no mechanism for restraining the individual battery assemblies. Figure 6 shows the battery pack with the cover in place.

Figure 6--Battery Pack Assembly with Cover

Figure 7 presents a general schematic for electrical connection of the batteries as they are configured in this pack.

Figure 7--Hybrids Plus PHEV 15 Battery Schematic



Although not shown on this diagram, each battery is equipped with a 250A fuse that is connected directly to the Nickel sheet grouping one parallel set of 10 cells via a tab that is formed in the Nickel sheet. A brass nut is soldered to the back of the tab and a brass bolt is run through the blade at one end of the fuse and into the brass nut on the back of the tab (therefore, the fuse blade and Nickel tab are clamped together. The other fuse blade has a brass nut soldered to its back side. The fuse is encased in the plastic clamshell. A small square of open-cell foam is located between the fuse and the cells which is used to push the fuse blade out toward the plastic cover so that the bolt will more easily engage in the threads of the nut on the back of the blade. This foam is known to be flammable from tests conducted at Hybrids Plus and at A123 Systems. A hole is cut in the clamshell so that a lug can be attached to the fuse via another brass bolt. The opposite end of each battery (physically and electrically) uses a brass nut soldered onto the back of the formed tab with a hole cut into the clamshell to allow for the attachment of a lug. See Figures 8 and 9.

Figure 8--Formed Tab

Figure 9--Battery Terminal

Each parallel group is monitored for voltage and temperature by small printed circuit boards soldered to tabs on the Nickel sheets at the top and bottom of each group. The temperature sensor is a component on the circuit board and is not in contact with any of the cells; it is instead located in the interstitial space between two adjacent cells.

Battery Inspection

The battery was wrapped in plastic sheet and located on a table in A123 Systems' assembly area. The plan of action was to slowly and methodically inspect, document and remove components from the battery pack to look for the initiating point. Upon initial viewing, it was apparent that the right end of the battery pack was most severely damaged in the cavity that is formed between the front and rear batteries (the batteries are designed so that a U-shaped pocket is formed on the right end to provide clearance for cables that attach from front to rear batteries). Much of the clamshell was missing or severely melted in this area. Several cells from both the Front and Rear top batteries were found open with their contents missing or protruding from the can. See Figure 10.

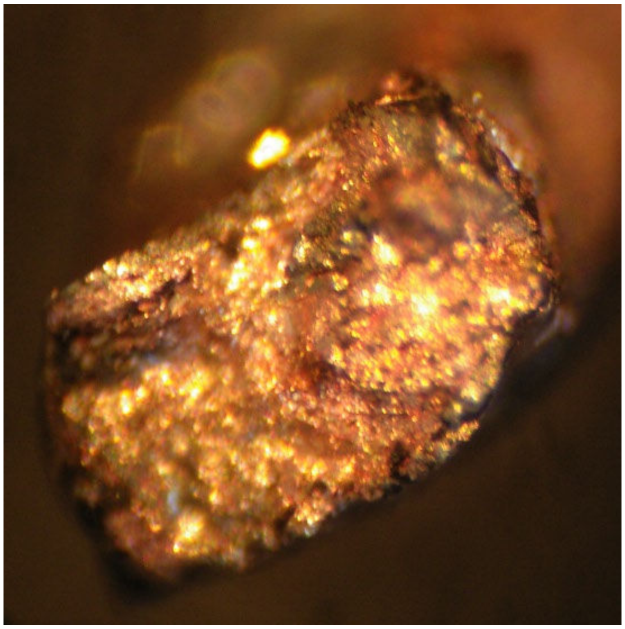
Figure 10--Empty Battery Cells

In the middle of Figure 10, a heavy cable can be seen with the remnants of a fuse connected to it. This is the Cross Connect Cable that connects the Front Bottom battery to the Rear Top battery. The plastic housing of the fuse is missing (melted or baked away) but the fuse is still intact. In fact, all of the three intact battery fuses were still electrically conductive. The main pack fuse (125A) was also electrically conductive. The cable connecting the Rear Bottom battery to the Front Top battery was not attached to the assembly but was present (loose) with the battery. This assembly had the fuse from the Rear Bottom battery still attached and a portion of the Front Top fuse attached (Figure 11).

Figure 11--Interconnect Cable

Again, the intact fuse had a severely melted housing but the fuse was still electrically conductive. A microscope examination of the partial fuse shows that the fuse suffered a mechanical break and likely did not melt in an overcurrent condition (Figure 12). Examination of photos taken of the vehicle shortly after the fire show that this fuse was intact after the vehicle was towed to Firmin Ford. The fuse was likely broken during the vehicle investigation in South Carolina.

Figure 12--Broken Fuse



On checking the left-hand end of the battery pack, it was noted that the burning and melting of components wasn't as significant as that found on the right-hand end.

After thoroughly inspecting the assembly, the pack was disassembled so that all four batteries were removed from the steel tray. These were marked to note their location.

In order to examine the individual cells and any damage that was present inside the batteries, the Top Front battery was cut apart and removed (Figure 13—the remaining three batteries were shipped to Hybrids Plus for their inspection).

Figure 13--Opening the Clamshell

With the batteries removed from the tray, the terminals on the left-hand end (non-fused) could be more closely examined. On all four batteries, these connections were found to be loose (Figure 14).

Figure 14--Non-fused Terminal

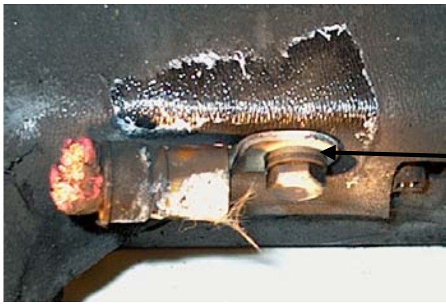
With the clamshell removed, all cells inside that battery could be visualized. It was noted that significant burning was present at the right-hand end, some heat deformation of the plastic and soot on the cells at the left-hand end and little damage in the middle except at the front face where a significant amount of melting occurred (Figure 15).

Figure 15--Burn Pattern in a Battery

The cells were removed from the clamshell housings to allow for inspection of the cells and Nickel sheets on the bottom side. Nothing unusual (beyond the same burning seen from the top) was noted.

Following the cell inspection, the lugs/fuse/bus bar interfaces were examined. During the design review, it was noted that the clamshell design creates a situation where the plastic clamshell is placed between the fuse blade and the interconnecting cable terminal. Mr. Lawrence of Hybrids Plus indicated that the design required that a bushing or spacer be placed between the fuse blade and the terminal so that the plastic would not be placed in compression. Upon inspection of the various connections no spacers were found between the terminal and the fuse (or the bus bar tab in the case of the non-fused locations. See Figure 16 for some examples and Appendix C for an assembly diagram.

Figure 16--Terminations

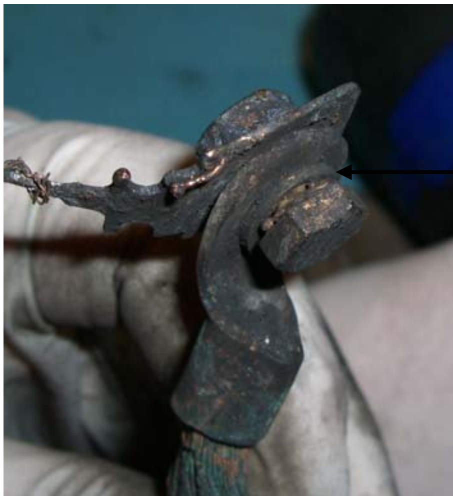


Spacer (washers) placed between bolt head and lug—lug contacting plastic housing

No spacer under lug. Note witness marks where lug rubbed on plastic

Washer located under bolt head. No spacer between lug and fuse blade

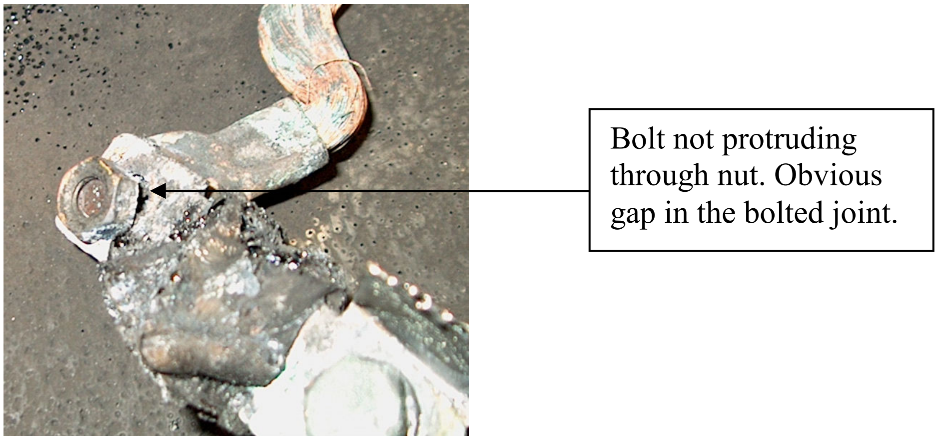
Note witness marks left by lug compressing plastic housing

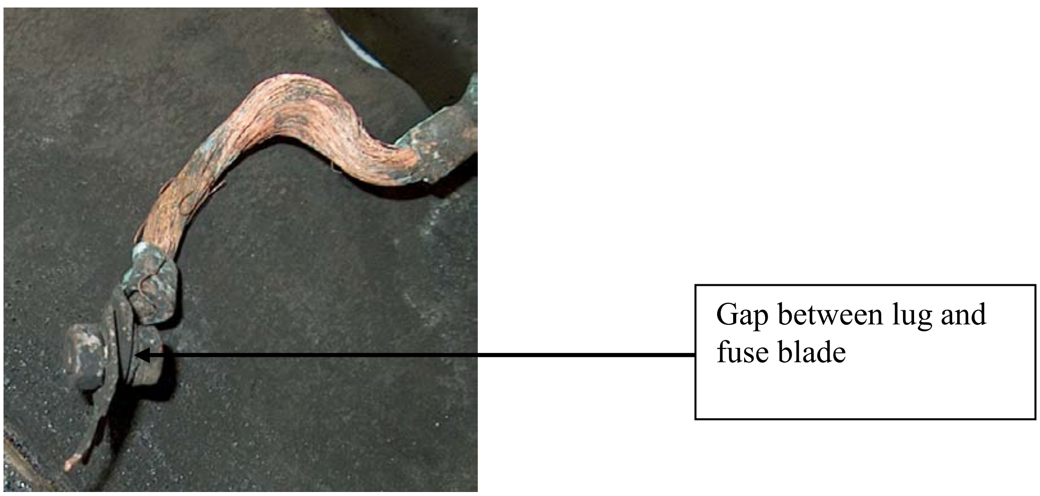


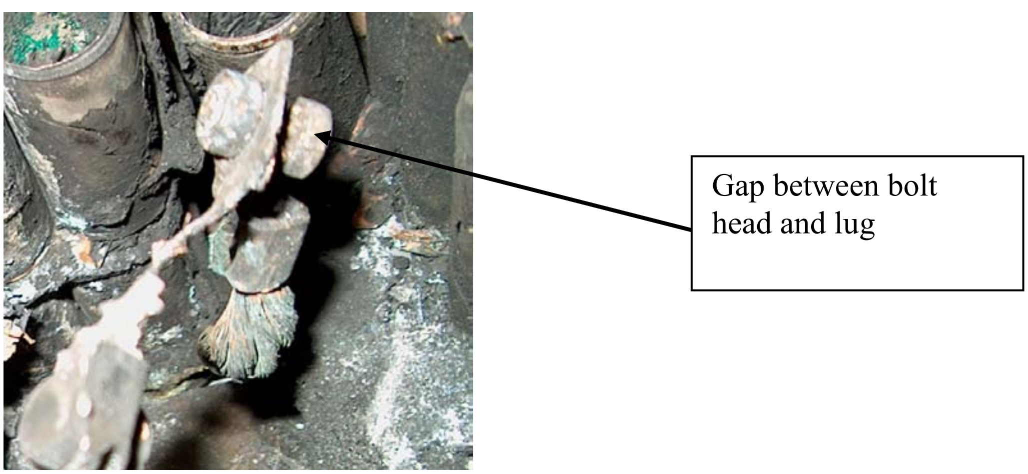
Washer placed under bolt head. No spacer between lug and fuse blade.

While examining the various terminations, several of the fused connections were found to be loose (Figure 17).

Figure 17--Loose Terminations





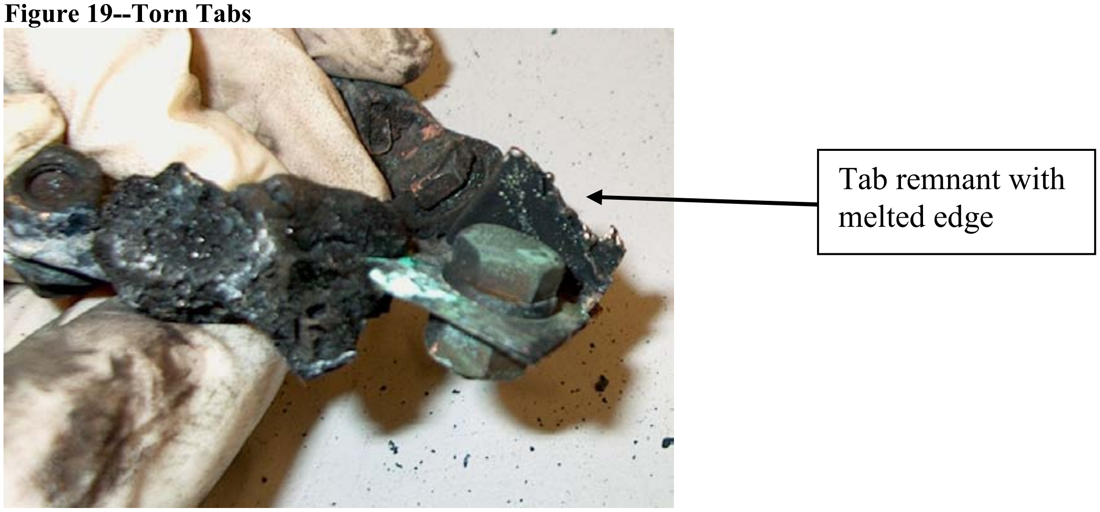


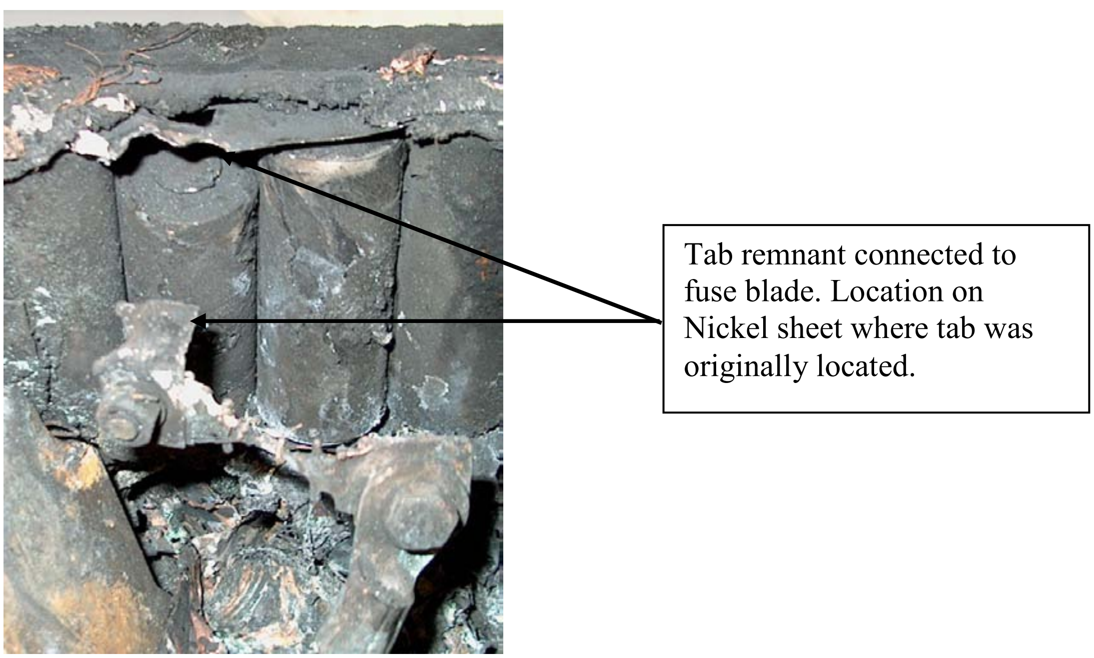
During this inspection, it was also noted that there was significant transfer of material between the brass bolts and nuts, the cable terminals and the fuse blades (Figure 18). This material transfer is indicative of significant electric arcing and very high temperatures.

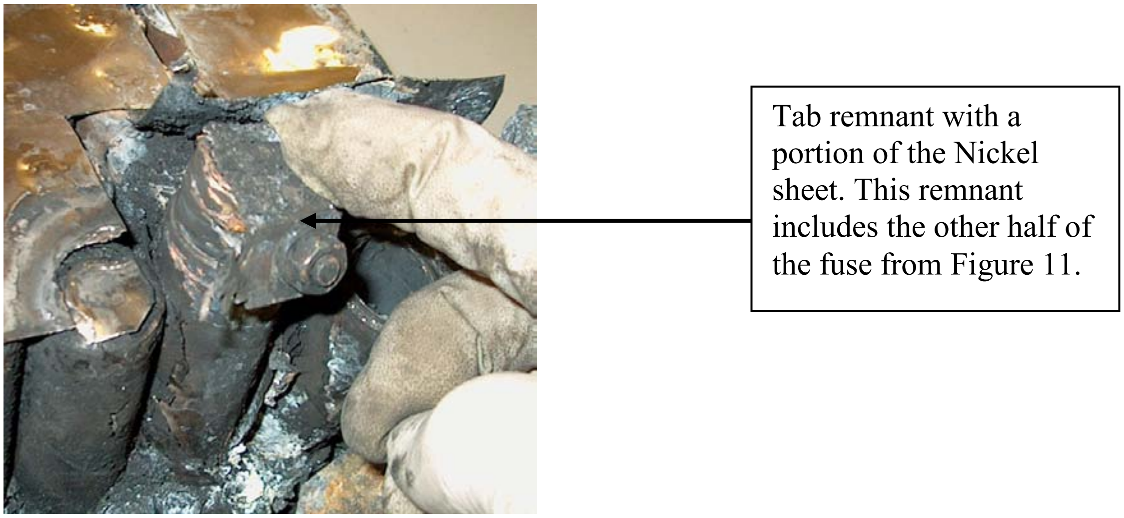
Figure 18--Material Transfer at Terminations

The Nickel sheet bus bars were also closely examined. The great majority of spot welds appeared to be intact. Where cells ejected their contents, some spot welds were torn where the Nickel sheet was lifted up and away from those cells. In some cases, the spot welds were intact and the Nickel disks used at the ends of the cells were still attached to the sheet Nickel. It was also noted that the tabs on the Nickel sheets formed to be the attachment location for the fuses were all missing. They were found still attached to the fuse blades. All of these remnants exhibited signs of melting at their edges as opposed to stretch or fracture marks. See Figure 19.

Figure 19--Torn Tabs







During this inspection, two curiosities were noticed with regard to the Nickel bus bar sheets. The first was at the Top Rear battery on the right-hand side. The Nickel sheet was no longer attached to a cell. Instead, the Nickel sheet had a circular hole in it and the missing portion of the sheet was still attached to the top of that cell (Figure 20). The area around the circular hole show signs characteristic of excessive heating.

Figure 20--Circular Feature[3]

The second feature was located at the Top Front battery on the right-hand side. A cell at the corner of the second series group and located at the corner of a Nickel sheet had become disconnected from the rest of its group, taking the corner of the Nickel sheet with it (Figure 21). The crescent-shaped area on the remaining Nickel sheet shows characteristic signs of excessive heating.

[3] Some debris and charring was removed from the Nickel sheet using a plastic-bristle brush to more clearly see the features on the sheet.

Figure 21--Torn Corner Cell

See Appendix B for a collection of images recorded during the inspection.

Determination

The inspection of the battery led to the conclusion that the fire was most likely the result of a loose connection, probably at the right-hand side of the Bottom Rear battery. This connection was found to have a nearly 0.1” gap between the bolt head and the lug (Figure 22).

Figure 22--Loose Connection

As can be seen in the photo, this assembled joint was found with the bolt screwed only partially into the nut. It is unlikely that this occurred during either of the vehicle or battery inspections as it required wrenches to remove the nut from the bolt. More likely, this was a result of a) the lack of a locking device to prevent the bolt from backing out, b) the lack of a spacer between the fuse blade and the lug which placed the plastic of the clamshell housing in compression between the two and c) vibration from normal vehicle operation causing the bolt to back off from its original installed position. This joint was found to have approximately 0.16” clearance in the assembly. Assuming that the clamshell plastic was nominally 0.06” thick, the clearance at the time of the fire would be approximately 0.1”.

As a current-carrying joint becomes loose, the resistance of the connection increases. The power dissipated in heat by a resistor is given by $P=I^2R$. Therefore, a doubling of the resistance increases the power dissipated by heat by a factor of two. The battery pack will experience a maximum discharge current somewhere near 100A during normal driving. Given that the power dissipated by heat is proportional to the square of this current, an increase in resistance to even a few Ohms will result in extreme heat generation. Experience shows that loose connections can lead to temperatures over 250°F.

Once the lug began to heat, that heat was transferred up the copper Cross Connect Cable as copper is an excellent conductor of heat. This heat passed through the connection to the Top Front battery fuse, through the fuse and into the cells through the Nickel bus bar sheet. This heat would also cause the plastic clamshell housing to soften in that area. The soft plastic would be unable to withstand the clamping load and would displace where the lug mounted to the fuse (sandwiching the plastic). This displacement likely resulted in the connection at the Top Front battery (fuse end) to become loose, adding to the resistance in the circuit.

The initial theory was that this heating caused the insulation to fail on the large-gauge Cross Connect Cables that connect the four batteries at the right-hand end of the pack. At this location, two cables were installed—one that connected from the Bottom Rear battery to the Top Front and one that connected the Bottom Front battery to the Top Rear. The assumption was that the insulation failed and caused the bare copper to touch and short. However, assuming that both cables had loose connections and the insulation burned, melted or otherwise failed, the short-circuit current would have been significantly higher than the 250A fuse attached to each battery, causing at least one fuse to open. All four fuses were found intact (the fuse at the Top Front battery was broken at some point after the initial vehicle inspection but before it reached A123 System’s facility).

Instead, it is more likely that heat continued to build up in the system through the loose connection and that this heat was conducted into the cells of the Top Front battery. Once this battery built up sufficient internal heat, it began to develop gas pressure internally and eventually ruptured the cell at the designed pressure vent point.

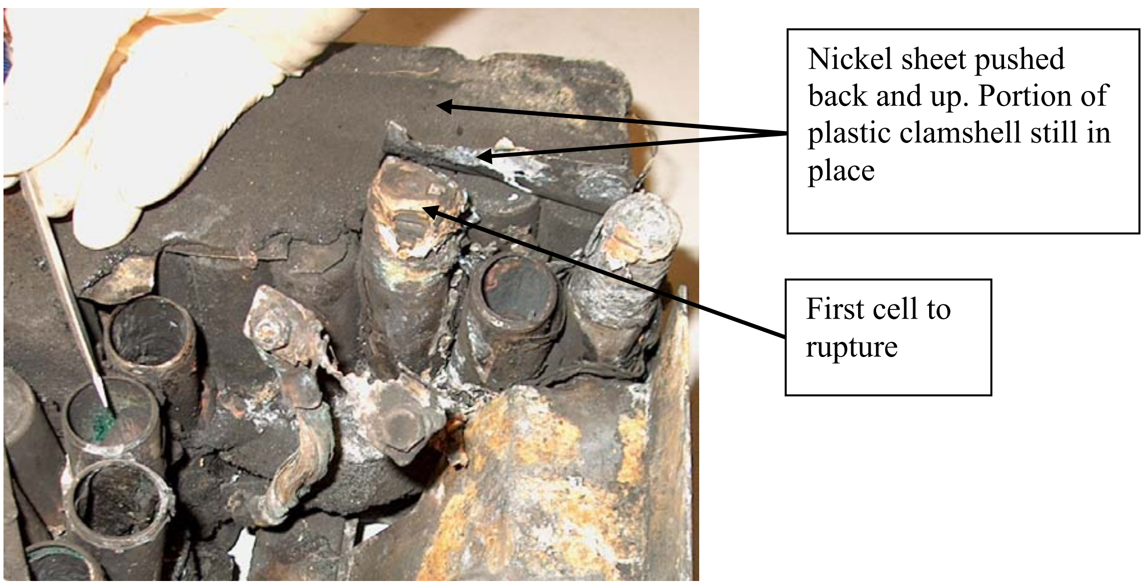
It should be noted that there was likely an additional source of heat generation. Due to the placement of the connecting tab at the edge of the Nickel sheet and the layout of the 10 cells in each parallel group, the cell closest to the tab would experience a higher current throughput than the rest of its parallel group mates. This additional current would tend to make this cell run warmer than the rest. Therefore, the cell in the Top Front battery where the tab was located would have been running warm to start with, and would be the first to receive heat conducted via the Cross Connect Cable, through the fuse and into the tab.

The temperature sensors used to monitor the temperature across the parallel groups in a battery were likely very slow to respond to this internal cell heat. The fact that they were not in contact with any cell and that each cell is somewhat thermally insulated via the cardboard sleeve means that heat conduction into the temperature sensor would be a slow process, lagging greatly behind the actual temperature of the cells.

The design for the Nickel bus bar sheeting served to restrain the cells so that it is likely that the actual pressure required to rupture the vent would be much higher than its design rating. That is, if we assume that the pressure vent is designed to rupture at 100 psi (an arbitrary number for the purposes of this example) and the pressure vent is 1" in diameter, the resulting force required to rupture the can is $100*.5^2*PI = 79$ lb. However, the Nickel sheet would begin to stretch as the pressure vent began to deform in the rupture process. This stress would apply a force in the opposite direction of the force being applied from the inside of the cell. Thus, a higher pressure is required inside the cell to generate enough force (or delta-force) to overcome the opposing forces imparted by the stress in the Nickel sheet in order to rupture the pressure vent.

Once the cell built up enough pressure, the pressure vent ruptured and the contents of the cell were ejected with great force; enough to rip the tab off the end of the sheet (the fuse was captured inside the clamshell next to the cells), to pull the Nickel sheet off several adjacent cells and to punch through the plastic clamshell cover (likely softened due to the heat). See Figure 23.

Figure 23--First Rupture Site



It is likely that the tab on the Nickel sheet was ripped off first as there is evidence of melting, a sign that current was passing through this area which resulted in arcing as the tab became separated from the sheet.

With the first cell ruptured, an amount of electrolyte would have spilled out of the cell can. Any arcs or sparks in the area would have caused the electrolyte to burn which in turn would cause the foam behind the fuse to burn.

When the first cell ruptured, pieces of the foil roll may have become separated from the roll and come in contact with the next adjacent cell. This cell is part of the next series group of 10 in parallel. As such, contact between these two cells would have caused a short circuit between these two series groups and all the current would have flowed through these two cells. This is the likely cause of the cell at the corner where the Nickel sheet is separated. Such high current would have caused the Nickel sheet to melt (1560°C), acting as a fuse for the rest of the parallel group.

The short circuit current would cause additional heating in the cells of the two groups that participated in the short. The two cells closest to the first ruptured cell would have already experienced high heat from the initial loose connection. With the short circuit current, these cells likely overheated and ruptured. The cell adjacent to the first ruptured cell was found with no contents, indicating that the contents likely were expelled into the cavity between the front and rear sets of batteries. It should be noted that while many of the cells were found empty during the inspection at A123 System' facility, the report from those who conducted the initial vehicle inspection shows that they removed the partially-expelled contents from many cells at the time of their inspection. They also reported that the cavity between the Front and Rear batteries was packed full of the expelled contents from various cells.

At this point, there was enough conductive material to start short circuits across batteries and cells (Figure 24).

Figure 24--Ejected Cell Material[4]

Arcing would have occurred at any area where a short circuit occurred. The ejected material contains electrolyte so it would catch fire in the presence of this arcing. These short circuits along with any burning material caused additional cells to rupture. The inspection showed that all of the ruptured cells were immediately adjacent to this cavity area, indicating that they were exposed to enough heat to cause the rupture.

With the conductive ejected material in the cavity, there was certainly a loss of isolation to the vehicle chassis (the battery normally is electrically isolated from the vehicle chassis, unlike a typical 12V accessory system that uses the chassis as the ground return). The Hybrids Plus employee who inspected the vehicle after the fire confirmed that there was voltage present from the battery tray to one end of the battery. This means that short

[4] Some material remains but the majority was pulled out of the cavity during the initial vehicle inspection and can be seen to the left of the battery in this image

circuits could then occur between battery and chassis so long as there was a return path from the chassis to the battery (provided by the material collecting in the cavity).

It was noted that there was a hole in the top of the steel battery pack cover. It is likely that this hole was burned into the cover through electrical arcing—a short from the battery to the cover now that chassis isolation was lost. The report from the vehicle inspection states that there was cell material welded to the bottom side of the cover. These contents came from one cell in the Top Front battery and one from the Top Rear battery. There would normally be a potential of 100V across these two batteries which would cause a significant arc discharge when shorted through the battery cover. There was an upholstered mat over the battery at the time of the fire. It is likely that the electrical discharge from the cells underneath burned a hole (as with a plasma torch) in the steel cover and caused the mat to catch fire. Alternatively—or perhaps in addition—the battery pack cover had an elevated center section that allowed for convected airflow over the batteries. With the cover in place and the battery installed, there is an opening at the end of the cover that is adjacent to the back of the rear seats and to the sides of the cargo area. As the seats are carpeted, this presents another likely location for an upholstery or trim panel fire to initiate.

Once the fire spread outside the confines of the steel battery case, there was enough flammable material to consume the vehicle. It should be noted that reports of explosions during the fire are false. Both rear tires ruptured during the fire which is typical of a vehicle fire. However, the gasoline tank was intact following the fire and there is no evidence of a gasoline explosion or any explosion occurring in the battery.

The driver's report indicated that while he was driving at highway speeds, the "triangle" fault warning light illuminated on the instrument panel and that the engine began to turn at high rpm. This most likely occurred when the Prius' hybrid control system detected either a momentary open at the battery pack (loose connection) or a low voltage condition (voltage drop due to high resistance connection). When this occurred, the hybrid controller would have opened the battery pack contactors. With the high-voltage circuit open, the Motor Generator 1 in the Synergy Drive system is unable to develop the torque (by generating electricity sent to the battery pack) which is used to regulate engine speed. Without that torque available, the engine would rev to high rpm. When the vehicle was restarted and the driver accelerated to highway speed, it is likely that there was a high current demand from the battery, exacerbating and accelerating the problem by causing significant heat to be generated in the high resistance connections (via I^2R heating). When the driver noticed the "triangle" fault light again, the engine did not rev to a high rpm. By this time, the first cell was ruptured and the battery pack was no longer isolated from chassis ground. The hybrid controls monitor this isolation and illuminated the fault light when this isolation was lost.

There is no indication that this incident was the result of a shorted or spontaneously ruptured cell. The manufacturer's tests show that an internally shorted cell will not generate enough heat—in and of itself—to rupture the cell.

Recommendations

All vehicles of similar construction should be inspected to see if these bolted connections were a) assembled properly and b) retain their clamp load at all electrical connections on the four batteries. Any improperly assembled joints should be disassembled and reassembled as per the design documents.

It is important to note that this may not be sufficient to eliminate all risks of future failures. The design of this battery pack deviates from the design guidelines of A123 Systems in several areas (ref Appendix D).

The full-sheet bus bar system does not provide for cell-by-cell fusing as is recommended for parallel cell assemblies. In parallel assemblies, a short from one cell to another cell in the next series string causes the energy of all the paralleled cells to flow through the one cell and into the short. Cell-by-cell fusing prevents that from happening by separating the shorted cell from the rest in the group. The corner cell in the Top Front battery (Figure 21) shows signs that indicate that sufficient current passed through this area to melt the Nickel sheet so that it acted as a fuse. However, the current required to do so was likely much higher than the cell could safely withstand.

The full-sheet bus bar system also prevents the pressure venting mechanism from operating properly. As the sheet is continuous in all directions, the pressure vent is unable to expand and open at design pressure due to the additional forces required to displace, deform or tear the Nickel sheet in order to open the vent. Similarly, packaging the cells in a close-fitting plastic case with additional axial clamping load provided by the steel cover restricts the ability of the cell vents to open at design pressure.

The design of the battery assemblies do not provide a mechanism to positively clamp or restrain (radially) the individual cells (the vacuum-formed clamshell cases cannot provide sufficient clamping). As such there is a possibility that adjacent cells may vibrate against each other to a point where the metal cans would touch and short a cell. While there were witness marks where cells rubbed against each other, there was no strong indication of significant wear. Testing with a vibration table is the only way to accelerate this phenomenon and determine if there is a strong risk.

ETEC has no data to determine if such deviations from the recommended design guidelines are sufficient or likely to lead to cell failure or to other loss of electrical or mechanical integrity of the battery pack or otherwise compromise the safety of other vehicles already in the field. However, good automotive engineering practice would suggest that a rigorous failure mode and effects analysis be conducted on the current design. Furthermore, rigorous testing to Society of Automotive Engineers (SAE) standards should be conducted to uncover any design weaknesses.

Summary

A Toyota Prius converted to a Plug-In Hybrid Vehicle configuration was destroyed by fire. The likely cause of the fire is improper assembly of bolted joints with electrical lugs. These joints became loose causing excessive heating which led to the rupture of individual battery cells which resulted in significant short circuiting of the battery ultimately resulting in the vehicle fire.

The batteries were designed so that a spacer should have been placed between the fuse blade and the electrical lug so that the plastic battery cover would not be in compression. Compressed plastic has a tendency to creep which would result in loss of clamp load on the fastener. Inspection shows that the brass washers that were intended to be the spacers were instead installed underneath the bolt head (between the bolt and the lug which served no purpose). Additionally, there was no locking mechanism (lock washer, safety wire, adhesive, etc.) that prevented the bolt from backing out of the nut. It is likely that the bolted joint became loose over time and during regular vehicle operation which resulted in a high-resistance connection causing those components to increase in temperature.

A123 Systems' design guidelines appear to be violated in several areas which may have contributed to the severity of this incident.

APPENDIX A

(See accompanying CD for a folder labeled "Vehicle Photos")

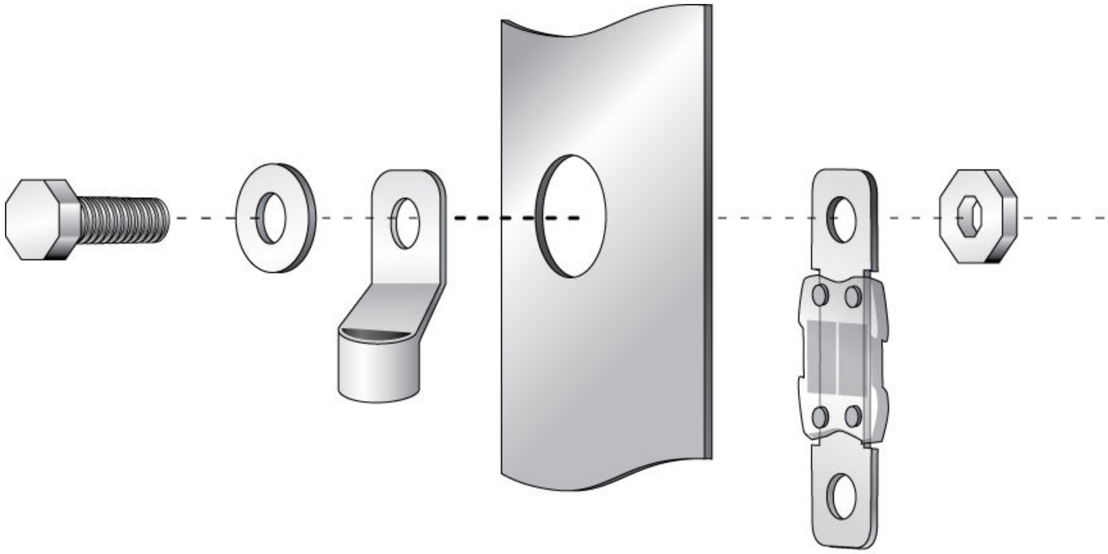
APPENDIX B

(See accompanying CD for a folder labeled “Battery Inspection”)

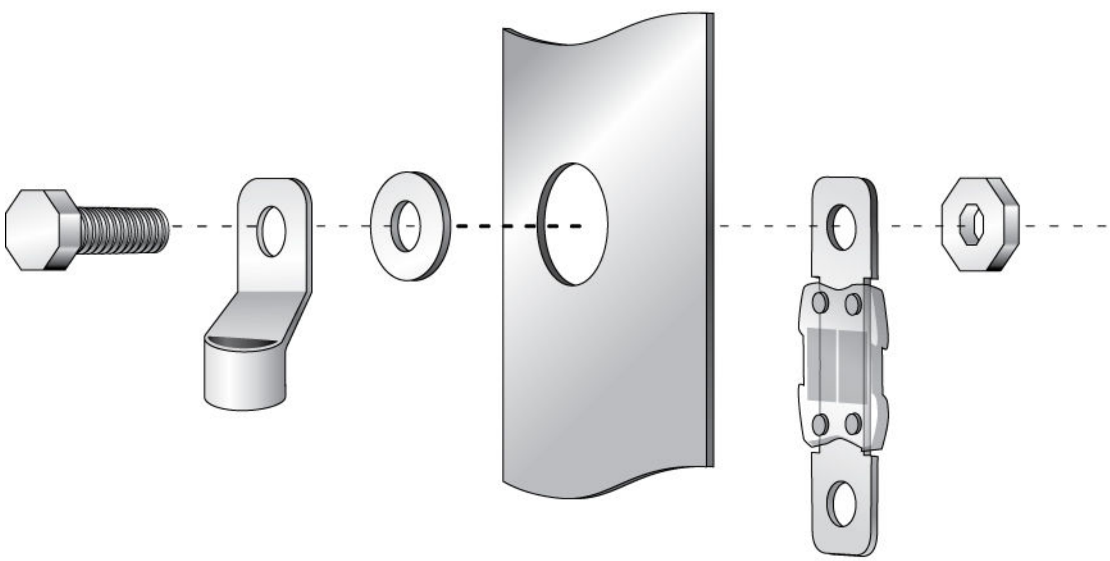
APPENDIX C

Bolted Joint Assembly Comparison

Appendix C--Bolted Joint Assembly Comparison



Incorrect Assembly Order



Correct Assembly Order

APPENDIX D

A123 Systems Design Guidelines

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Battery Pack Design Safety Guidelines (DRAFT)

While we believe the A123Systems' Nanophosphate™ cells are the safest lithium ion cells on the market, there remain ways, including improper use or abuse, to make our cells fail, which can lead to potential safety hazards to the end user. Packs must therefore be designed in accordance with the customary parameters of battery pack design to avoid a safety incident:

Guidelines for safe cell protection and battery design:

- Pack must have dual, redundant over-voltage protection, with at least protection by hardware and one via software.
- The voltage of every single series element must be measured and monitored.
- In multi-cell batteries, use cell balancing and/or individual cell voltage controls to equalize the state of charge (voltage at full charge) of cells in series. Doing this will also maximize the life of the system.
- Cells discharged below 0.50V will be damaged and must be removed and properly disposed.
- Recommended and Absolute ANR 26650 Cell Limitations:

	Recommended	**Absolute**
Maximum cell voltage	3.85 volts	4.20 volts
Minimum cell voltage	1.60 volts	0.50 volts
Maximum continuous recharge current		10 amps
Maximum continuous discharge current		70 amps
Maximum 10 second pulse recharge (at Room Temperature)		10 C rate
Maximum 10 second pulse discharge		120 amps
Maximum temperature difference between cells in a pack	< 5°C	8°C

- Maximum charge and discharge current ratings are at STP (standard temperature and pressure); at different temperatures, especially lower temperatures, maximum current rates will be lower.

- Cells must not be subject to reverse polarity or short circuited. Fuses or some other protection must be incorporated in pack designs with batteries in parallel to avoid all the energy in one string being dumped to the neighboring batteries in the event of a hard short cell failure.
- Cells must not be charged or discharged outside the operating temperature range in the datasheet, and reduced charging limits must be followed for lower operating temperatures.
- Cells must not be exposed to heat in excess of 60°C during operation, 70°C in storage; or incinerated, stored or used near open flames.
- Cells must not be punctured, ruptured, dented or crushed; and the pack design must ensure this under normal operations or in a crash.
- Cell packaging must not be altered in any way, and cells must not be immersed or exposed to water or liquids
- Tabs should be resistance or laser welded to cells to avoid excessive heat. When leads are soldered to the cells, the cell casing must not exceed 150°C for more than 10 seconds.
- Never use a clamping force at the top and bottom of the cell or hold cells together, end to end, in a way that restricts the cell rupture vents at the ends of the cells. If the vents are blocked, the gas can't exit the cell in case of cell failure.
- **Overall: Cell specifications in the datasheets must be followed. Cells must be balanced during recharge for long life and safety, and individually monitored and protected from exceeding specified operating parameters. Battery packs must be designed and confirmed via testing to provide sufficient mechanical, thermal and electrical protection to keep each individual cell within proper operating limits. Do not ship product before thoroughly testing a pack design.**

In automotive or EV solutions we recommend that your pack abides by these general guidelines and makes use of the following components:

- All high voltage components, including wires, cables, connectors, and batteries with a potential greater than 54 volts must be colored orange.
- Crash sensor signal to disconnect the battery pack from the vehicle.
- Reliable and validated mechanical design that meets SAE J2464 & J2380 standards.
- National Highway Traffic Safety Administration, DOT, Part 571 – Federal Motor Vehicle Safety Standards, Standard No. 305; Electric-powered vehicles:

electrolyte spillage and electrical shock protection, and other FMVSS standard(s) that govern PHEV or crash testing

- Appropriate mechanical vibration tests to ensure the pack will meet the applicable environmental requirements.
- Mechanical mounting should prevent mechanical stressing of seals and joints on the cell. Mechanical design should also prevent deformation of the cell under all conditions.
- System components should be compatible with cell electrolyte solvent, in case a cell is vented and the electrolyte leaks.
- Battery cases and mounting hardware should be protected or made of appropriately rated dielectric material to prevent accidental shorting to chassis.
- All high voltage connections should be robustly isolated and protected from contacting adjacent components to prevent shorting during severe mechanical abuse (crash, crush, impacts, etc).
- Battery systems should be designed that it should be impossible to drop a tool into the pack and cause a short circuit. No high voltage should be accessible with an average finger.
- Batteries and battery packs should be fused. One fuse should be located in the center of the battery system to break the load at the center of the pack.
- Battery packs should use contactors capable of breaking full current loads on both the positive and negative poles of the battery pack. These contactors should be normally open contactors such that if supply power is stopped, they will open.
- Battery packs should include a HVIL (High Voltage Inter Lock) that supplies power to the main contactors. This loop should also run through switches that ensure that the housing is closed, the crash sensor (if included) is closed, and the high voltage power connector, low voltage communications connector, and other key interfaces are in place. In the event that any one of these opens, the contactors will open.
- Current conductors and connections should be of sufficiently low impedance to prevent localized heating of surfaces and components.
- A battery pack should be equipped with a battery management system to operate the pack properly and to shut down the pack in case of internal or external abusive conditions. The battery management system should provide the following:
    - Minimum and maximum voltage limits should be included in the algorithms to prevent abuse from overcharge and overdischarge.

  - Temperature sensors should monitor system and cell temperatures throughout the system for both safety and algorithm purposes.
  - The battery management system must be able to monitor each series element voltage.
- Temperature can act as a redundant check against overcharge, short circuit, and over discharge conditions that are not reported due to an error in voltage measurement. Both Tmax and dT/dt limits should be considered to prevent abuse of the cells.
- Monitoring the SOC of the cells is necessary to ensure a long life battery, but also should act as a secondary detection of overcharge and overdischarge conditions. Max SOC and min SOC limits should be set in the algorithm to prevent abuse.
- State of Health software algorithms should be implemented to detect weakening cells during operation. Examples of this are a cell being the highest voltage cell on charge and the lowest voltage cell on subsequent discharge. This is an indication that the cell is becoming resistive and should trigger a service condition.
- The customer further acknowledges that the following potential consequences may occur if the cells are subjected to misuse or abuse:
  - Cell may vent and will become inoperable
  - Cell life will be degraded
  - Cell performance to datasheet specifications will be degraded
  - Cell may cause burns due to excessive heating

A123 is providing this information based on its current knowledge of best practices in battery pack design in order to raise your awareness on appropriate cell use so that immediate corrective action can be taken if your firm is employing a pack design that can potentially cause safety problems.

A123 shall have no liability with respect to its products or any failure of its products to perform in accordance with their specifications or in accordance with any applicable warranty if such performance or failure results, either in whole or in part, from any use that is inconsistent with the above recommended Guidelines or any changes or modifications to the products that are not made by A123 or authorized in writing by A123. In such event, you will be solely responsible for the consequences of any noncompliance. In addition, A123 makes no warranties, either express or implied, regarding the contents of this letter or the completeness or accuracy of the guidelines and best practices described herein, which is provided for informational purposes only.