

Interim Progress Report for the
AAA-SRJC-NBEAA
State-of-the-Art Electric Vehicle Conversion Project

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Updated May 25, 2011

Summary

It comes with great sadness to report that the electric vehicle conversion project that AAA so generously funded, the SRJC so generously executed, and the NBEAA and other EV enthusiasts so generously volunteered their time and expertise to, burned beyond repair on Friday night, March 18th, 2011. It was scheduled to be test driven for the first time as early as the very next day, after being worked on for 5 semesters. Arson is not suspected, so the vehicle appears to have caught fire by itself while unattended and unplugged. This is ironic, since the premise of the project was to take the best ideas and build and document a safe and reliable electric vehicle.

The only likely failure scenario presented so far is that the design was fundamentally flawed by exposing high voltage, high power sources too close together such that in the event of an accidental fault, the resulting plasma continued to feed itself by absorbing conductive material from the adjacent terminals, much like an arc welder, long enough to start a fire. The accidental fault has not yet been determined, but regardless, this vehicle was supposed to safely fail in the event of such an accidental fault, and the fusing system was not robust enough to stop it.

In the spirit of the original project, a follow-up investigation by a small group of experienced volunteers will carefully inspect and document the vehicle and post their results for all electric vehicle designers to comment on and take in to account as they develop their vehicles. Even if voltage spacing is not proven to be the cause of this fire, it is a risk and will be published to encourage others to assess their designs for this risk. The following interim report is being provided at the request of AAA, who has graciously accepted this report as a fulfillment to the obligation of the grant they provided in lieu of repayment or restarting the project to produce a car they would show. This report is a brief summary of the project progress towards the original goals, initial failure analysis, and next steps. More detailed information can be found at www.nbeaa.org/osev/sota/.

Project Progress

Here are the major steps that had been completed in the conversion process:

1. Designed the conversion, including posting a parts list, 2-dimensional mechanical drawings, and wiring diagrams.
2. Obtained the donor vehicle, a 2005 Ford Focus sedan with a manual transmission, during the summer of 2009.
3. Removed the gasoline related components from the vehicle, including the exhaust system, fuel system, cooling system and engine during fall semester 2009. Took critical measurements such as axle weights, ride heights and flywheel spacing away from the motor to properly design and assemble the vehicle with electric components.
4. Procured all electric vehicle components to install, including 90 60 amp-hour Thunder Sky Lithium Iron Phosphate batteries, eLithion battery management system, Azure Dynamics AC induction motor controller, Brusa charger, MES-DEA DC-DC converter and cabin fluid heater, EV Source electric power brake and power steering systems, and Ferraz-Shawmut high power fuses by February 2010.
5. Had motor to transaxle kit machined and assembled to the motor by Make Mine Electric in February 2010.
6. Had SRJC EV conversion class students experienced with metalworking fabricate the motor, battery and electronics mounts using angled steel, a band saw and MIG welder. Work spanned spring and fall 2010 semesters.
7. Made junction box and radiator assembly and mounted all EV components in the vehicle in fall 2010.
8. Made almost all of the electrical interconnections between EV components in January and February of 2011.
9. Turned on the charging system March 12, 2011 and found that the BMS had a communications error, and was not shutting down the charger as it should in such an error state. Found the mistake on the wiring diagram that was preventing the BMS from shutting down the charger and was planning to fix it on March 19, 2011. Agreed to not charge the car until these issues were resolved for safety reasons.
10. Turned on the drive system March 12, 2011 and verified that the BMS did shut down the drive system in its error state. Temporarily disabled the BMS and turned the wheels with electric power with car up on a lift. Agreed to not drive

the car until the BMS error problem was resolved for reliability and preservation of investment in the batteries. BMS troubleshooting was underway.

11. The traction battery pack was energized for the drive and charge system tests and left connected at ~298 volts starting on March 12th 2011. Prior to that the pack had been fully connected a few times, but not left fully connected when unattended.
12. Car burned around 10 PM Friday night March 18th 2011. Smoke detectors kept getting set off by gas engine exhaust so heat sensors were installed, but not connected to the sprinkler system. Alarm system went off, but was not connected to any communication system, so no one heard it. Finally someone reported smoke passing by and the fire department arrived about 11 PM, but the fire was almost out, it only took 50 gallons to extinguish the fire. Nearly all plastic, rubber and paint was burned, and the lift and garage door was damaged. The rest of the shop was filled with soot, but otherwise no other damage. Here are some pictures of the car:





Initial Failure Analysis

Many ideas have been brainstormed to be the cause. Here is a list, starting with those that are considered at this time to be less likely:

1. The Batteries Were Overcharged

Overcharging is a well known way to ignite any battery, and has been inferred to be the cause of other recent LiFePO₄ battery fires including Neil Young's LincVolt EV conversion. It could be due to either a misconfigured charger, BMS or BMS to charger control interface, but was not the likely cause of this fire because:

- a. The car was unplugged (verified the week of March 28) and had been instructed to remain unplugged until the BMS problems were solved.
- b. The 12V battery was removed, which disables the charger from starting (verified in early March), and it was removed because it was at 8V, probably because it was a worn out battery being temporarily used and was dying because it was not being charged by the DCDC converter yet, and the 12V battery was not noted to be hot when removed, and the 12V ignition jumper was not connected (verified week of March 28), so it couldn't have been charging after the 12V battery was removed.
- c. The charger was programmed correctly, so had it been plugged in it only would have overcharged if one cell was unbalanced and much higher than the others, which is opposite of what is likely when cells sit.

2. A Battery Self-Combusted

A fire started by a self-igniting battery is not likely since the LiFePO₄ chemistry is supposed to be thermally stable. If these cells are shorted internally or externally, they only get up to ~200C, vs. 450C required to ignite. Some lithium ion batteries have been tested to heat up to almost 600C when shorted, which explains why some laptops have burned by themselves.

3. Lightning Started the Fire

Coincidentally there was a lightning storm at the exact time of the start of the fire, and a very rare tornado had touched down earlier that day and destroyed a shed less than 2 miles away, and the car was resting on a grounded conductive lift. But lightning it is not the likely cause of the fire since:

- a. Lightning very rarely strikes the ground in Santa Rosa. It is usually sheet lightning between clouds, and no ground strikes are known of that night.

b. The car was several feet inside the building, not near the edges where lightning is expected to travel.

c. There was no other evidence of lightning travel inside the building.

4. The Drive System, Charger or DCDC Converter Started the Fire

These loads are located only a few inches away from the front batteries with no firewall between them and could have caught fire. But this is not likely since the DCDC converter has a relay that disconnects it from high voltage when off, all three components appeared to still be in tact after the fire, inferring they were not at “ground zero” of the fire. Here is a picture of the motor controller, charger and DCDC converter attached on top of the radiator assembly rack:



The following idea is considered to be the most likely cause amongst those ideas presented to date:

5. Closely Spaced Exposed High Voltage Started a Fire During an Accidental Short

Both the junction box and front battery rack have non-insulated high voltage terminals spaced between 2 and 10 Volts per millimeter (V/mm) vs. 1 V/mm recommended by Bill Dube of KillaCycle, who holds the world electric motorcycle speed record, in a post to the EV Discussion List on March 23, 2011. His post is reprinted here:

"It is really important for a number of safety reasons to maximize the distance between voltages in a battery pack. You want to put the highest positive terminal (and positive cell) as far away as possible from the lowest negative terminal (and positive cell.)

"Over the years we have discovered that you need to maintain a "one mm per volt" distance between terminals and other conducting surfaces inside a battery pack. Basically, you force an arc between conducting surfaces to travel a mm per volt of potential difference. This makes any accidental arc, perhaps initially caused by a metal shaving, loose bolt, wire "whisker", etc. travel one mm for every volt available. When plasma is fed by the metal vapor of the conducting surfaces and huge amps, it will self-extinguish only if there is at least one mm per volt separation. Otherwise, like an arc struck by a welder, the plasma will sustain, and then likely spread to other "too close" spots inside the battery pack, leading to a chain reaction.

"You can place insulating barriers, (like G-10, and FR4) between surfaces that are unavoidably close. The barrier needs to be substantial enough to withstand the initial "fault" arc for a few moments while the accidental conducting bridge vaporizes. The barrier needs to extend beyond the "line of sight" between the conducting surfaces and present a total path length of greater than one mm per volt. These " arc revetments" also greatly reduce the consequences of >a dropped tool, nut, bolt, etc."

Failure to adhere to these spacing requirements can lead to fires caused by accidental shorts, one of which is described by John Wayland of Plasma Boy Racing, whose White Zombie holds the world electric street legal car acceleration record. His fire led to his nickname and racing team name. David Roden pointed to his story that is posted at <http://www.evdl.org/docs/plasmaboy.pdf> to the EV Discussion list in April 2011.

The following two areas of the car are the most likely sources of the fire if exposed voltage spacing is proven to be the cause:

a. The front batteries, with areas up to 10 V/mm, were covered with rubber strips made from cut car inner-tubes to protect passersby from electrocution hazard, so a falling object was less likely to cause a fire, but an exploding component on a BMS cell board, or a wet rodent or dry one carrying a conductive wire to make a nest crawling under the rubber, may have caused a fire. The picture below shows how badly burned the front batteries were, inferring that they may have been near the start of the fire:



b. The junction box, with areas $>2V/mm$, was enclosed with no potentially volatile components near it such as circuit boards, but per the picture below, its lid is peeled back, possibly due to the high heat of a fire inside:



Next Steps

As educational organizations, both the SRJC and NBEAA are committed to learn as much as we can about the cause of the fire and share our knowledge with those developing electric vehicles so they can learn from our mistakes. We have assembled a team of several volunteers including some experienced in engineering, failure analysis and electric vehicle design to get together as a group and carefully inspect the vehicle, taking high resolution pictures, and post our findings for others to comment on and learn from. This meeting is expected to occur within the next few weeks, and our results published on the NBEAA website and in the EAA Current Events Newsletter this summer.

Regardless of what, if anything, is proven to be the cause of the fire, the following recommendations will be published for consideration when designing an electric vehicle:

1. Space all exposed high voltage $<1V/mm$. Insulate all others.
2. Put a firewall between the batteries and its loads.
3. Do not put batteries in a place where they would move during a collision in such a way that could cause accidental shorting.