MLEC Failure Analysis – The Final Chapter

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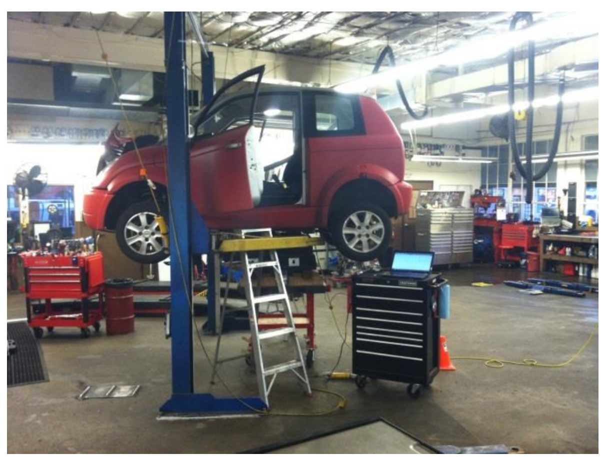
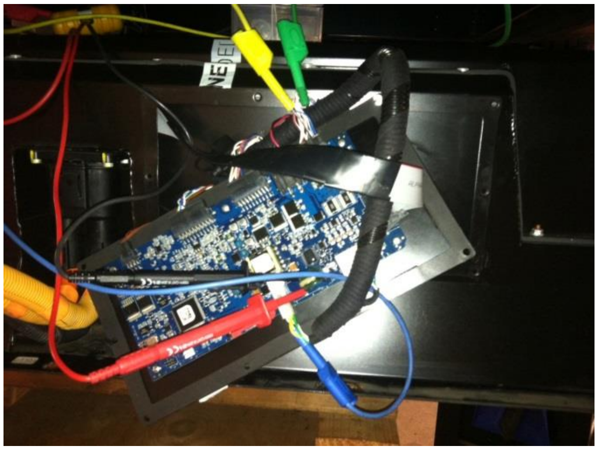
After many, many attempts we have finally discovered one of the conditions that causes precharge resistors to overheat. Until now we have only deduced that the precharge resistors must have been burning up during the contactor closing sequence, but we were never able to recreate the actual event in a controlled setting. The precharge resistor overheats when the cabin heater is on, the contactors open, and then the contactor closing sequence re-starts shortly thereafter. Presumably the climate/demist control module (CDCM) does not have sufficient time to turn off and shut down from the time that the key is turned off and the contactors open, to the time that the key is turned back on. I suspect that the CDCM continues to demand current from the traction battery after key off and all the way through to the contactor closing sequence.

I was first suspicious of the cabin heater being left on (blower in any position other than off, and temperature selector in the hot range) as a potential cause of MLEC failure when I noticed that contactor opening occurred a few seconds after key off. Normally contactors open immediately when the key is turned to the off position. I suspect that the BMS delays contactors from opening because it detects current flowing and prefers to not cause arcing at the contactors. It waits about 2 seconds after the order to open contactors, presumably to give components time to stop drawing current.

The photos below illustrate the test set-up that was reconstructed several times over the course of just over a year in trying to document an MLEC failure.





Based on the notion that the delayed contactor opening was caused by the cabin heater still drawing current, I thought it might be possible that the cabin heater might still attempt to draw current if the car was turned back on shortly after being shut down. The oscilloscope traces below illustrate just such a scenario.

The trace starts just after the contactors have opened, about 2 seconds after the key has been turned off with the cabin heater still on. Key on occurs at about 1.3 seconds.

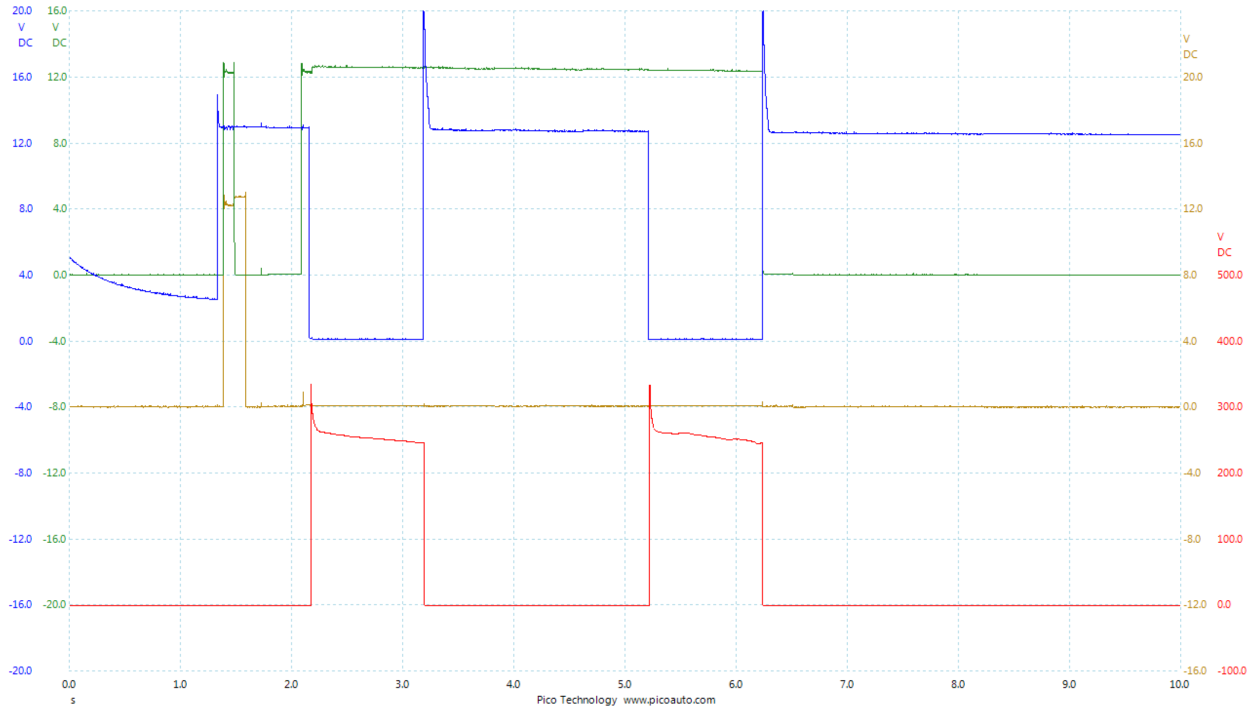
The blue trace is the precharge contactor driver signal. When this trace is 0V, the precharge contactor is energized (closed).

The green trace is the driver for Main Contactor 1. When this trace is 12V, the contactor is energized (closed).

The yellow trace is the driver for Main Contactor 2. When this trace is 12V, the contactor is energized (closed).

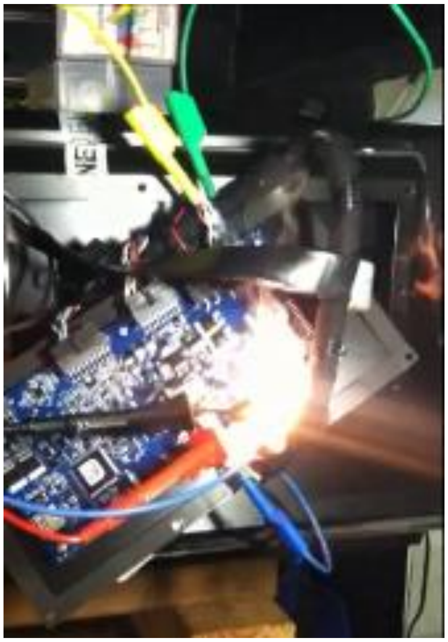
The red trace is the voltage across the precharge resistor, measured directly at the precharge resistor through a 100:1 differential scope probe.

Note that the blue, green and yellow traces are all shown at a scale of 4V per division, but the 0V levels are offset from each other to simply avoid overlapping of signals. The red trace scale is 100V per division.



At approximately 1.3 seconds the key is turned on, and voltage is applied to the precharge contactor through the emergency power off (EPO) circuit (but this does not energize the precharge contactor—it is only energized when the driver signal is pulled to ground). Main Contactors 1 and 2 are briefly energized to test their operation just hundredths of a second after key on. At approximately 2.1 seconds, Main Contactor 1 is energized and shortly thereafter the precharge contactor is energized. Normally we would see the voltage across the precharge resistor spike to battery voltage and then decay to near zero within 0.4 seconds. But in this case voltage across the precharge resistor remains greater than about 250V for an entire 1 second. The precharge contactor de-energizes (opens) for 2 seconds, and then closes again. The voltage across the precharge resistor is about the same as it was in the previous precharge attempt.

Assuming that battery voltage was around 350V for this snapshot and the average voltage across the precharge resistor was about 250V, this circuit behavior is what would be predicted with about a 20 Ohm load across the PCU's internal capacitors. The energy dissipated as heat in the precharge resistor during each of the two precharge attempts was over 1300 Joules, so that by the end of this snapshot 2600 Joules, well over three times its 700 Joule rating, had gone into the resistor. The result is dramatic, but does not cause the resistor to fail immediately. The still photos below, taken from video concurrent with the oscilloscope capture above, show a large flame and smoke pouring from the resistor after the second precharge attempt.

But after the resistor had a chance to cool off it continued to work properly to start up the car, with the exception that it emitted a bright flash of light each time it was energized. There is no telling how long an overheated precharge resistor can go on working properly—or even intermittently—before it finally gives out due to mechanical vibrations or deterioration from repeatedly being energized in a degraded state.

There is no guarantee that the mechanism of failure here is the only way that precharge resistors are being damaged. Whether this particular series of events is caused by a Think owner turning the key off and then back on, or whether the contactors open for some other reason and then attempt to re-close again, there is a looming possibility that a module other than the heater could cause a similar failure. We could attempt to make changes to the CDCM software to address the issue that has now been confirmed, but we can only hope that such an effort would eradicate the only failure mechanism.

The best solution to the problem would still be prevention of the precharge resistor from being damaged regardless of any conditions external to the battery. I recommend that we pursue a solution by modifying the BMS software to prevent precharge resistor overheating. This discovery of the MLEC failure mechanism comes only a few days after I composed and submitted a proposal titled, “Think City Precharge Circuit Behavior Modification,” and I still stand by that recommendation.

Additionally, we should officially communicate this important finding to Think owners as soon as possible and advise them how to avoid damage to their cars. Think owners have already been advised to turn off all 12V loads as a precaution, but I believe that relaying the specific message to turn the blower off before turning off the car and before turning the key on will be heeded much more strictly if the recipients of the message understand how ignoring that specific action can immobilize their car.