U.S. Department of Transportation
National Highway Traffic Safety Administration

NHTSA
www.nhtsa.gov

DOT HS 811 573 January 2012

Chevrolet Volt Battery Incident Overview Report

Technical Report Documentation Page

1. Report No. DOT HS 811 573	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Chevrolet Volt Battery Incident Summary Report		5. Report Date January 20, 2012 6. Performing Organization Code NHTSA NVS-224
7. Author(s) Smith, B.		8. Performing Organization Report No.
9. Performing Organization Name and Address NHTSA Office of Vehicle Safety Compliance NVS-224 1200 New Jersey Avenue, SE Washington, DC 20590		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address NHTSA Office of Vehicle Safety Compliance NVS-224 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract		
17. Key Words		18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.gov

19 Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21 No. of Pages 19	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page a

CONTENTS

1.0 Overview

Each year the National Highway Traffic Safety Administration (NHTSA) performs vehicle crash tests for the New Car Assessment Program (NCAP) and for the enforcement program that verifies compliance with Federal Motor Vehicle Safety Standards (FMVSS). It is our normal policy to test vehicles with new technology to assure acceptable crash performance and occupant protection. One type of emerging technology, electric vehicles (EV), are expected to become more prevalent because they show great promise as an innovative and fuel-efficient option for American drivers by saving them money at the pump, ensuring a cleaner environment, and reducing the Nation's dependence on foreign oil. With this in mind, in 2011 the agency decided to test vehicles equipped with lithium-ion battery chemistries that were being introduced for sale.

The program subjected EVs to frontal (FMVSS No. 208), side (FMVSS No. 214), electrical isolation (FMVSS No. 305), and post-crash rollover tests (FMVSS No. 301 and 305). The side crash tests included pole tests and moving deformable barrier tests. FMVSS 305 specifies performance requirements for limitation of electrolyte spillage, retention of propulsion batteries, and electrical isolation of the chassis from the high-voltage. Each crash test, whether frontal or side, included a post-crash rollover. The rollover is performed to test for electrolyte spillage from EV batteries and fuel leakage from liquid fueled vehicles.

As part of NHTSA's policy involving new technology, the agency conducted a NCAP side-pole crash test of the Chevrolet Volt in May 2011 at a test facility in Wisconsin. Based on its performance, the Volt received a NHTSA five star rating for both frontal and side impact vehicle crashworthiness and occupant protection.

On Monday June 6, 2011, NHTSA was notified by personnel at MGA Research, Inc. (MGA) that a fire event had occurred over the previous weekend and had been discovered by laboratory personnel on that Monday morning. The laboratory provided details of the vehicles involved in the event which included the Chevrolet Volt subjected to an NCAP pole test three weeks earlier on May 12th.

NHTSA's test contractor, MGA, after informing NHTSA personnel about the fire, notified the local fire authorities who performed an initial scene investigation which primarily focused on identifying any possible arson issues. NHTSA contracted with a battery and fire expert, Hughes Associates, to investigate the origin and cause of the fire. The initial forensic inspection was conducted on June 13-14, 2011 at the MGA facility. In July 2011, Hughes Associates preliminary findings indicated that the fire incident at MGA most likely originated in the Chevrolet Volt. For the remainder of this report the term "battery" will refer to the lithium-ion propulsion battery in the Chevrolet Volt.

This preliminary finding triggered further investigation. The vehicle, along with the fire damaged battery, was shipped to NHTSA's Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. Hughes Associates, NHTSA, and General Motors (GM) representatives conducted a forensic inspection and battery teardown. The inspection of the crash damage to the Volt revealed that the transverse stiffener located under the driver's seat had penetrated the tunnel section of the battery compartment, damaged the lithium-ion battery, and ruptured the battery's liquid cooling system. Review of the crash test photographs and video confirmed that battery coolant leaked from the battery compartment. Hughes Associates concluded ultimately that the damage to some of the Volt's battery pack cells and electric shorting precipitated the fire.

In September 2011, NHTSA performed another side-pole NCAP crash test on a Chevrolet Volt at the MGA. The test objective was to observe any battery cell damage, shorting, battery coolant system rupture, and post-crash battery fire. The test vehicle was fitted with additional cameras and equipment to monitor post-crash events. This side-pole test resulted in no intrusion into the battery compartment to cause cell damage or shorting, no leakage of coolant, and no post impact fire. The vehicle was monitored for three weeks after crash.

Thus, in 2011, NHTSA conducted five side-pole crash tests to evaluate the crashworthiness and occupant protection of the Chevrolet Volt. All of the tested vehicles met compliance test requirements and were favorably rated for the NCAP program. The following is a summary of the Chevrolet Volt crash testing performed and observations made by NHTSA:

Vehicle Testing Performed

	Date	Test Program	Test Type	Battery Intrusion	Battery Coolant Leakage	Fire	*Test No.
1	4/20/11	Compliance	Side-pole 50^{th} Male	Yes – minor plastic damage	No	No	7385
2	5/6/11	New Car Assessment	Side - Moving Deformable Barrier	No	No	No	7392
3	5/11/11	New Car Assessment	Frontal	No	No	No	7393
4	5/12/11	New Car Assessment	Side-pole 5^{th} Female	Yes	Yes	Yes	7394
5	9/21/11	Compliance	Side-pole 5^{th} Female	No	No	No	7454

*These test reports can be found on the NHTSA web site: http://www-nrd.nhtsa.dot.gov/database/veh/veh.htm . Search on the listed Test No. to access the records for a particular test.

NHTSA is not aware of any real world post-crash fires involving EVs. NHTSA reviewed all crash reports of events in the field that involved Chevrolet Volt vehicles that were considered severe (involved an air bag deployment, a speed change during the crash of over 12 mph, or injury to the occupant), all relevant Early Warning Reporting (EWR) data, and Vehicle Owner Questionnaire (VOQ) data. No post-crash fires were reported.

Separately, NHTSA worked with the U.S. Department of Energy (DOE) and the U.S Department of Defense (DOD) to devise a program to test Chevrolet Volt lithium-ion battery packs in an attempt to replicate the damage that was sustained by the battery in the Chevrolet Volt that caught fire at MGA. An impact test was designed and equipment constructed to replicate the damage and post impact rollover.

Using the newly developed NHTSA/DOE/DOD testing procedures, in mid-November, three undamaged batteries recovered from NHTSA crash test vehicles tested earlier in 2011 were impact tested at General Testing Laboratories (GTL) in Colonial Beach, Virginia (battery test numbers. 1-3). After impact, each battery was rotated 360 degrees in 90 degree increments, as performed following a vehicle crash test. The battery coolant system was intentionally ruptured in these tests either by impact or manual introduction of coolant so the coolant was free to wet parts of the battery and battery electronics. Testing of the coolant showed that it was conductive at high voltages when the battery was sufficiently charged. We found that the battery coolant is capable of causing electrical short circuits under certain conditions. Test monitoring methods allowed for technicians to note whether or not battery coolant flowed onto components of the battery, and whether the battery coolant caused electrical shorts.

NHTSA designed another series of battery pack tests to attempt to isolate the individual effects of cell damage, shorting of the battery bus bar to chassis, and battery coolant leakage, another series of battery pack tests were designed. Those three tests were: (Test 4) no impact or cell damage, rollover, no shorting of the battery bus bar to chassis, battery coolant released into the battery compartment, (Test 5) no impact or cell damage, rollover, shorting of the battery bus bar to chassis, battery coolant released into the battery compartment, and (Test 6) impact with cell damage, no rollover, no intentional shorting of the battery bus bar to chassis (shorting was still possible as a result of impact), battery coolant released into the battery compartment. In early December, NHTSA performed these tests using three new batteries.

The following is a summary of Volt battery pack testing performed and NHTSA observations made on all six battery packs:

Battery Pack Testing Performed

Test No.	Test Description			Observations
	Impact	**Rotation**	**Bus Bar Grounding**	
1	Yes	Yes	unknown	Battery pack destroyed during 11/24 fire initiated by test 2 battery
2	Yes	Yes	unknown	Battery pack caught fire on 11/24. (one week after impact) Fire originated in Module 3
3	Yes	Yes	Yes	Sparks/ flames jetted from battery pack at 180 rotation position. Battery disassembled on 11/21
4	No	Yes	No	Discolored wires indicated battery heating, but no fire occurred.
5	No	Yes	Yes	Rapid electrolysis observed at180 and 270 rotations. Battery pack caught fire on 12-12 (6 days after impact)
6	Yes	No	unknown	Slow voltage discharge of one cell group

In summary, six tests were performed on Volt battery packs to isolate potential factors involved in the MGA vehicle fire. Of the six tests, two batteries caught fire (Tests 2 and 5), one battery experienced a short arcing event with sparks and flames (Test 3), one battery showed signs of heating at the connector (Test 4), one battery had no test activity other than a slow discharge of one cell group (Test 6), and one battery was inadvertently consumed in the fire (Test 1).

In addition to the testing activities described above, following the fire event in June, NHTSA's Special Crash Investigation Division and GM began monitoring all crashes involving Chevrolet Volts and conducted some on-scene examinations of crashes involving severely damaged vehicles. However, no fires were reported in any of these events. Also, NHTSA investigated two non-crash fire incidents involving Chevrolet Volts. In both cases the vehicles were parked in home garages, and in both cases it was determined that the initial fire did not originate in the Chevrolet Volt.

Prior to the Chevrolet Volt fire, NHTSA developed a research plan to understand failure risks, develop safety methods, and develop performance-based metrics for lithium-ion based Rechargeable Energy Storage Systems (RESS)(i.e batteries). NHTSA has awarded three contracts to date as part of the multi-tier research plan.

In November 2011, NHTSA also began working with the National Fire Protection Association to assist first and second responders in identifying vehicles powered by a lithium-ion and other lithium-type batteries in taking appropriate steps in handling lithium-type batteries following a crash. NHTSA also has been working with vehicle manufacturers to develop appropriate post-crash protocols for dealing with lithium-ion battery powered vehicles.

In November 2011, because of the vehicle fire and subsequent testing, NHTSA opened a defect investigation (PE 11-037) on the Chevrolet Volt. The agency rarely opens a defect investigation without any data from real-world incidents. By taking this uncommon step, NHTSA sought to ensure the safety of the driving public with emerging EV technology. As a result, GM proposed a potential change (field fix) to mitigate intrusion of the transverse stiffener into the battery. NHTSA observed the installation of the proposed reinforcement into a 2012 production Chevrolet Volt and the vehicle was then shipped to MGA in Wisconsin where an NCAP type side-pole test was performed on December 22, 2011. The vehicle was monitored for three weeks. There was no intrusion into the battery compartment, no leakage of coolant, and no post impact fire observed.

This report summarizes the findings and conclusions of the forensics inspection, determinations of fire origin, and cause(s) of the MGA event. The report also documents the follow up vehicle and battery pack testing conducted by NHTSA in conjunction with the DOE, the DOD, and related NHTSA contractors to support the Chevrolet Volt incident assessment and defects investigation.

The forensic inspections along with battery pack level impact testing performed at GTL identified four possible effects on the Volt battery from the impact intrusion and rollover observed in the MGA side-pole test. The intrusion alone can produce cell damage, shorting of the battery negative bus bar, and battery coolant leakage. The rollover of the vehicle after the intrusion event can result in electrical short circuits caused by dispersion of conductive battery coolant into the battery monitoring system.

The Hughes Associates report (attached) found that a pre-fire pressure event occurred in the Volt which caused the dislocation of the windshield and rearview mirror from the vehicle. The report deduces from the forensic evidence that the pre-fire pressure event was most likely a direct result of cell venting (release of electrolyte gases due to a thermal event). The report also concludes that the cell venting and subsequent fire were most likely caused by some combination of the four effects listed above. GM and its contractor propounded a theory that the latency of the fire event may be explained by dendritic growth arising from the exposure of the electronics to the coolant. The attached report of the GTL testing discusses this issue and explains that various electrolysis reactions may produce results that could result in a delayed thermal event.

It should be noted that NHTSA was not able to replicate the MGA fire event either in full scale vehicle testing or battery component testing, and is not aware of any real world post-crash fires involving an EV battery cell venting event.

2.0 2011 Chevrolet Crash Test Program

As discussed in the overview, NHTSA conducted four Chevrolet Volt crash tests as part of the Compliance and NCAP model year 2011 test programs. Each of these tests also included testing for FMVSS No.'s 301 and 305. The tests conducted were:

	Date	Organization	Test Type	Battery Intrusion	Battery Coolant Leakage	Fire	*Test No.
1	4/20/11	OVSC	Side-pole 50th Male	Yes – minor plastic damage	No	No	7385
2	5/6/11	NCAP	Side - Moving Deformable Barrier	No	No	No	7392
3	5/11/11	NCAP	Frontal - 35 mph belted	No	No	No	7393
4	5/12/11	NCAP	Side-pole 5th Female	Yes	Yes	Yes	7394

*These test reports can be found on the NHTSA web site: http://www-nrd.nhtsa.dot.gov/database/veh/veh.htm. Search on the Test No. shown in the table.

In the test conducted with the 50th percentile male dummy on April 20, 2011, there was minor intrusion into the battery case but little if any damage to the battery and battery cooling system. A photograph of the damage is shown in Figure 2.01. There was no damage to the batteries in either of the next two tests; the side-moving deformable barrier test conducted on May 6, 2011 or the frontal crash test conducted on May 11, 2011. None of the vehicles tested in these first three tests experienced a thermal event at any time during or after the test.

Figure 2.01 Battery Damage from Test 7385

During the NCAP pole test conducted with the 5th percentile female dummy on May 12, 2011 at the MGA test facility (Figure 2.02), the battery was physically damaged by part of the vehicle structure that intruded into the side of the battery. This intrusion, not easily detected by visual inspection, went unnoticed at the time of the test. This intrusion is believed to have produced damage within the battery that eventually led to a vehicle fire three weeks after the test was conducted. See Figure 2.03.

Chevrolet Volt NCAP Pole Test - Pretest	Chevrolet Volt NCAP Pole Test – Post-test
	
Figure 2.02	

Figure 2.03 MGA Fire Scene


As part of the May 12, 2011 test, FMVSS 301 and 305 test protocols specify a rollover of the vehicle about the longitudinal axis with a 5 minute hold period and each of the 90 degree positions. (0, 90, 180, 270, 360) The purpose of this test is to check for leakage of either liquid fuels or battery electrolyte. Figure 2.04 shows the NCAP pole test vehicle in the rollover positions for this test.

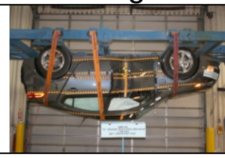
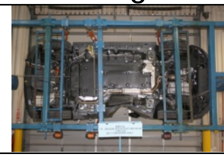
0 degrees	90 degrees	180 degrees	270 degrees	360 degrees
				

Figure 2.04 Post-crash rollover test

3.0 <u>MGA Fire Incident</u>

On Monday June 6, 2011, NHTSA was notified by personnel at MGA that a fire event had occurred over the previous weekend and had been discovered by laboratory personnel on that Monday morning. The laboratory provided details of the vehicles involved in the event, which included the Chevrolet Volt subjected to an NCAP pole test three weeks earlier on May 12th.

MGA, after informing NHTSA personnel about the fire, notified the local fire authorities who performed an initial scene investigation which primarily focused on identifying any possible arson issues. NHTSA contracted with a battery and fire expert, Hughes Associates, to investigate the origin and cause of the fire. The initial forensic inspection was conducted on June 13-14, 2011 at the MGA facility. In July 2011, Hughes Associates preliminary findings indicated that the fire incident at MGA most likely originated in the Chevrolet Volt and the local fire authorities concurred with that assessment. Figure 3.01 shows pictures of the Chevrolet Volt before and after the fire event. The MGA fire incident report is provided as an attachment.

Before	**After**
	

Figure 3.01

The vehicle, along with the fire damaged battery, was shipped to NHTSA's Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. Hughes Associates, NHTSA, and General Motors (GM) representatives conducted a forensic inspection and battery teardown. The inspection of the crash damage to the Volt revealed that the transverse stiffener located under the driver's seat penetrated the tunnel section of the battery compartment (see Figure 3.02), damaged the lithium-ion battery, and ruptured the battery's liquid cooling system. Review of the crash test photographs and video confirmed that battery coolant leaked from the battery compartment. See Figure 3.03. The results of the forensic inspections at VRTC are included in the MGA Incident report.

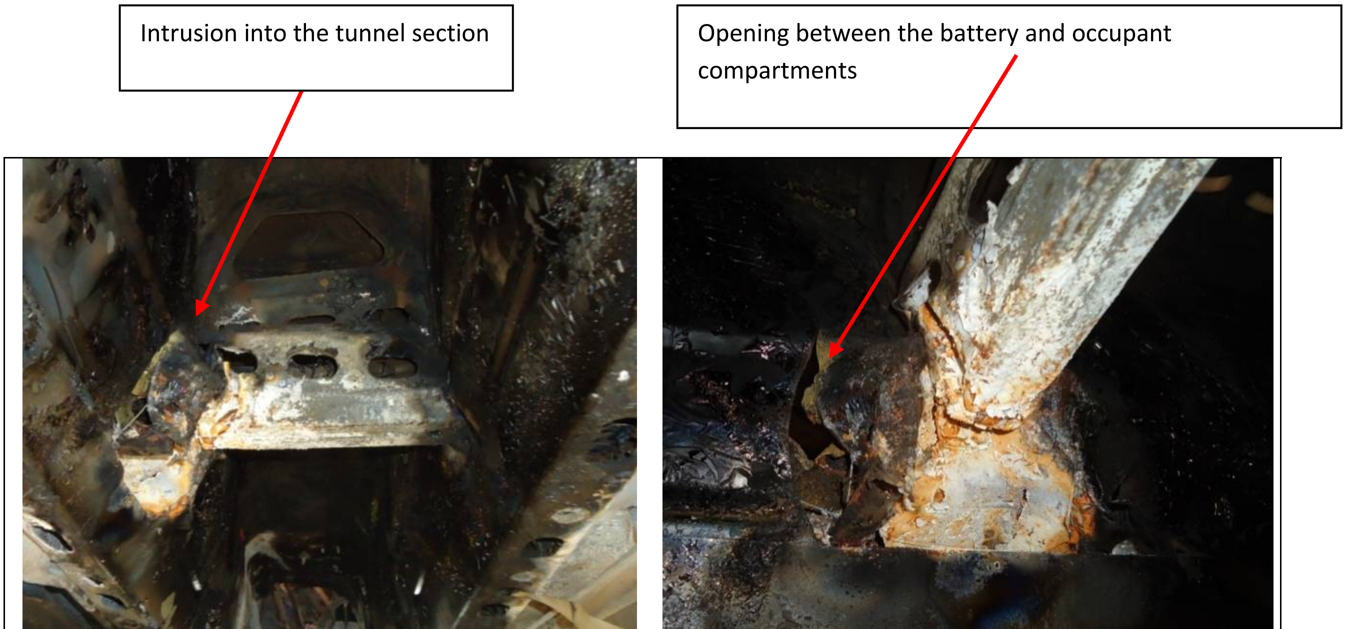


Figure 3.02

Leaked DexCool Coolant from Chevrolet Volt Battery (orange droplets)

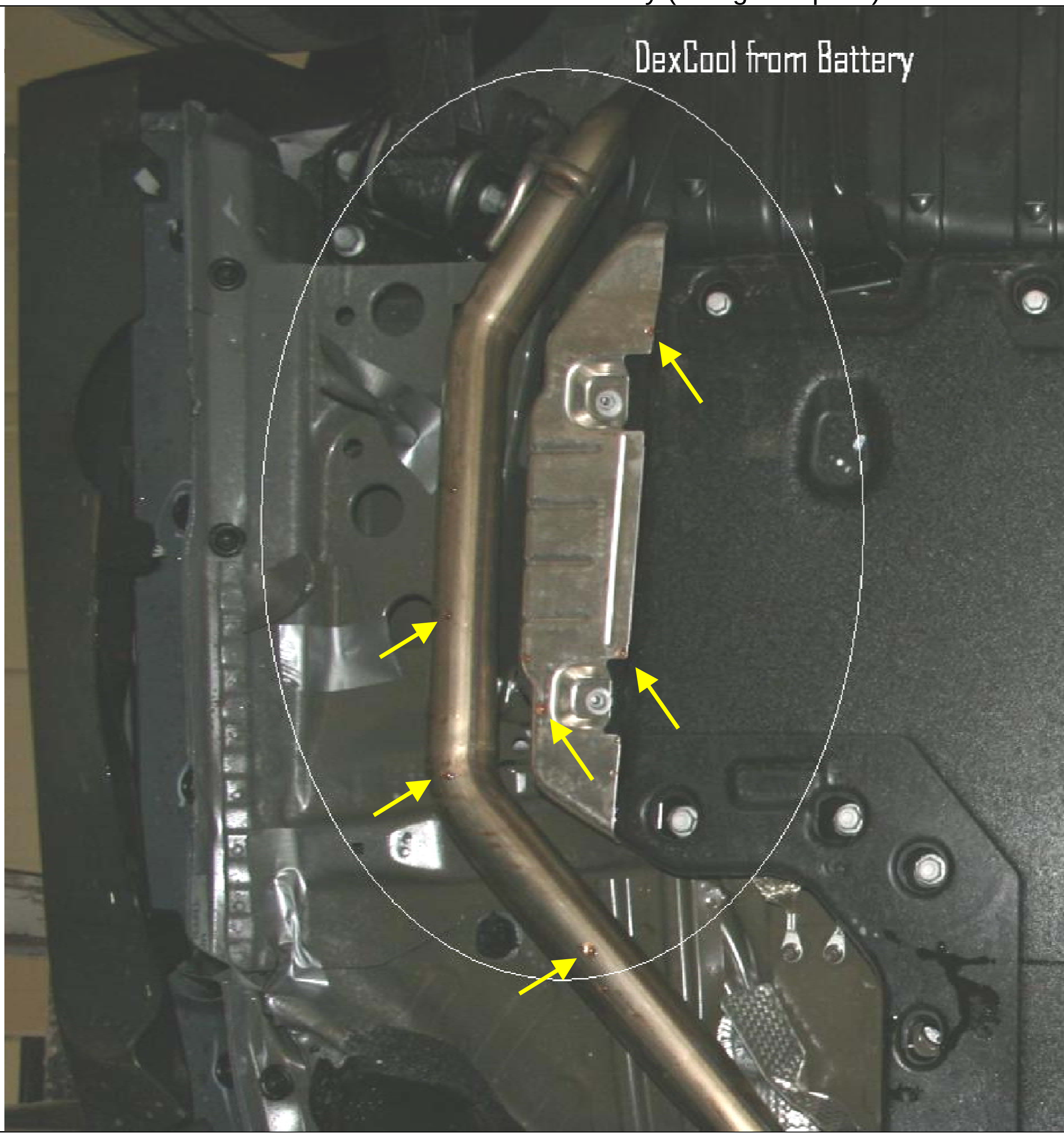



Figure 3.03

The MGA and VRTC forensic inspections, along with subsequent battery pack level impact testing performed at GTL (discussed below), identified four possible effects on the Volt battery from the impact intrusion and rollover observed in the MGA side-pole test. The intrusion alone can produce cell damage, shorting of the battery's negative bus bar, and battery coolant leakage. The rollover of the vehicle after the intrusion event can result in electrical short circuits caused by dispersion of conductive battery coolant into the battery monitoring system. The Hughes Associates report deduces from the forensic evidence that the pre-fire pressure event was most likely a direct result of cell venting, even though cell venting was not replicated in NHTSA tests. The report also concludes that the cell venting and subsequent fire were most likely caused by some combination of these effects resulting from the impact intrusion and rollover during the MGA side-pole impact test.

4.0 Follow-up Repeat Test

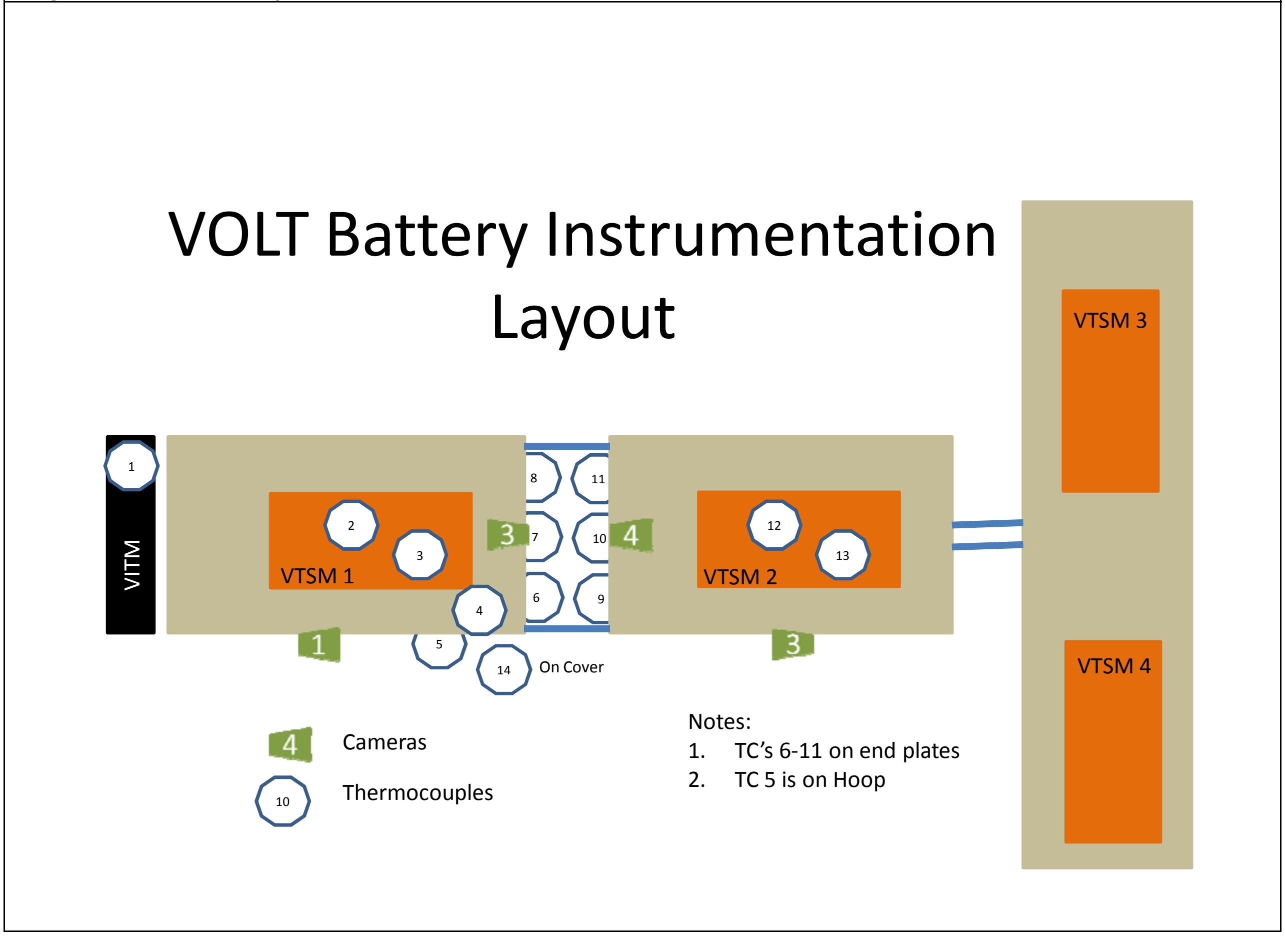
After completing the initial scene and battery inspections and review of the initial design and test data requested from GM, NHTSA performed a repeat test to attempt to replicate the results of the May 12th test. Emphasis was placed on monitoring the level of intrusion and damage to the battery coolant system.

A suite of add-on instrumentation, not normally used for a standard Compliance or NCAP tests, was developed to better monitor internal damage to the battery as well as to pinpoint the location of any events that could propagate a vehicle fire as a result of the crash test. This instrumentation recorded and monitored battery activity for an extended period after the test.

The instrumentation included: (See Figure 4.01)

14 – Type K thermocouples for battery temperature measurements.
4 – Miniature video cameras and light sources
1 – 16 Channel Data acquisition unit to record temperature data (AGILENT 34972)
1 – 4 Channel DVR to record internal video cameras (Defender SN502)
1 – Storage area camera and DVR to provide 24 hour surveillance of the vehicle.

Figure 4.01 Battery Instrumentation



In addition, x-ray imaging of the impact area was performed to evaluate the amount of intrusion damage to the battery. X-ray images from the fire damaged vehicle were available for comparison. (See Figure 4.04)

The vehicle was prepared by the test lab and NHTSA engineers outfitted the vehicle battery with the additional instrumentation on September 19th and 20th of 2011. The vehicle was crash tested and the post-crash rollover was performed on September 21, 2011. Figures 4.02 and 4.03. The x-ray of the impact area indicated that the battery did not sustain the level of intrusion observed in the May 12, 2011 test. See Figure 4.04. The vehicle was monitored for three weeks after the impact test and the battery did not experience any thermal or electrical events during the observation period.

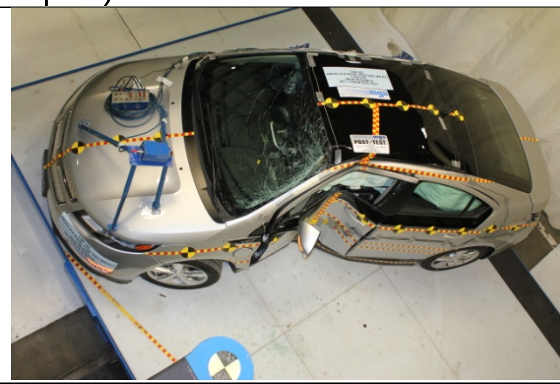
Chevrolet Volt 9/21/11 Test (Pre-Impact)	Chevrolet Volt 9/21/11 Test (Post-Impact)
	

Figure 4.02

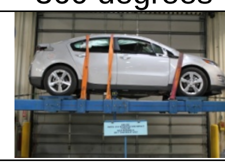
0 degrees	90 degrees	180 degrees	270 degrees	360 degrees
				

Figure 4.03

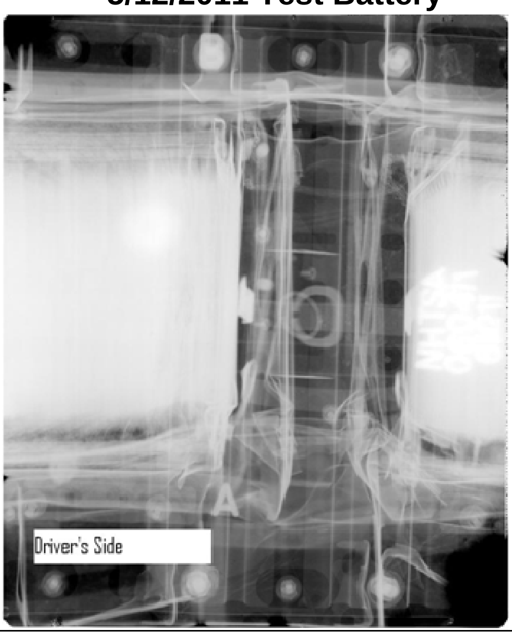
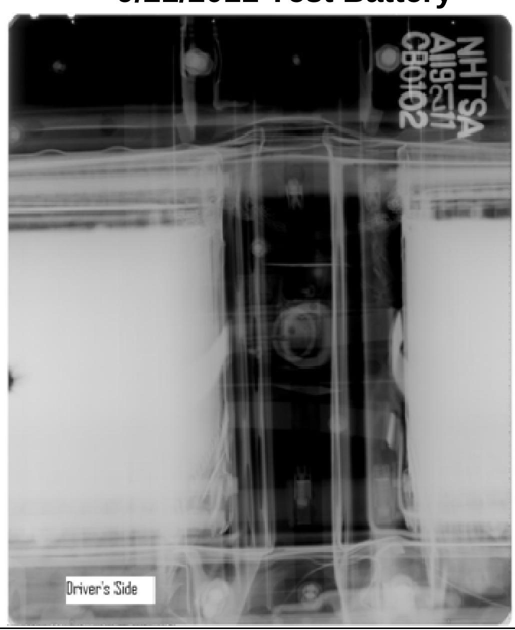
5/12/2011 Test Battery	**9/21/2011 Test Battery**
	

Figure 4.04 Intrusion X-Rays

No significant battery deformation or intrusion was observed for the September 21, 2011 crash test. There were no signs of coolant leakage during the crash test or the subsequent rollover test as evidenced by the coolant reservoir level post-test. See Figure 4.05. No thermal or electrical activity was observed in the vehicle or the battery immediately after impact or during the three week monitoring period following the test.

Battery Coolant Level (Pre-Impact)	Battery Coolant Level (Post-Impact)
	

Figure 4.05

5.0 <u>Chevrolet Volt Battery Pack Testing</u>

NHTSA worked with DOE and DOD to devise a program to test Chevrolet Volt lithium-ion battery packs in an attempt to replicate the damage that was sustained by the battery in the Chevrolet Volt that caught fire at MGA. As described below, six battery pack tests were conducted.

An impact test was designed and equipment constructed to replicate the damage and post impact rollover in the test vehicle that caught fire. The charged battery (87% state of charge) and cradle assemblies were placed on the fixed barrier support fixture. Next the impact block and guide system were positioned on the battery. The cooling system was connected and coolant was circulated through the battery until there was no evidence of entrapped air in the coolant. The circulation pump was then turned off.

Voltage monitoring, thermocouples and gas detection instrumentation were connected to the battery and verified for operation. See Figure 5.01.

Figure 5.01 Battery Ready for Impact

The distance from the moving barrier stops to the impact block was measured and the moving barrier (referred to as the “stinger” in the GTL report) was adjusted to produce the desired penetration of the impact block into the battery. The moving barrier was accelerated to test speed using GTL’s crash test monorail and tow system. Speed was measured approximately one foot prior to impact of the Stinger into the impact block. The impact block traveled forward into the battery until the moving barrier bottomed out on the battery supports/stops.

X-rays provided a non-invasive method of assessing the post impact internal structural deformation to the battery. The x-rays were compared to the previous x-rays of the MGA side impact damaged battery that resulted in a fire. This information, along with physical measurements, was used as an aid in making displacement adjustments to the impactor and moving barrier speed for each test.

The battery remained on the support fixture for approximately one hour while it was being x-rayed. After completion of x-rays the battery/cradle was removed from the support fixture and an FMVSS 305 type rollover was initiated. The battery was manually rolled over, taking approximately one minute to rotate each 90° increment, and held for five minutes at the 90°, 180° and 270° positions. See Figure 5.02

After completion of the rollover, the battery/cradle assemblies with instrumentation attached were moved to storage sheds for long term monitoring. The sheds were heated to control temperature between 70°F and 90°F.

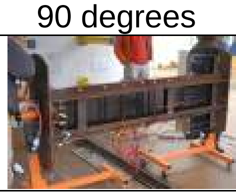
0 degrees	90 degrees	180 degrees	270 degrees	360 degrees
				

Figure 5.02 Battery Rollover Photographs

After the test procedures were completed, the batteries were placed inside of sheds for long term monitoring. The batteries were stored and monitored for a period of up to four weeks. The instruments installed on each battery were scanned at a constant rate during this time. Each shed was equipped with at least one video camera to visually monitor the battery and the conditions in the shed. Each shed was also equipped with a photo/ion smoke detector connected to an auto-dialer. In the event of an alarm, the auto-dialer would notify lab personnel of the incident. The first three batteries were also equipped with 4 internal cameras located in the same manner as the September 21, 2011 vehicle side impact test.

During the last three tests (Tests 4, 5 and 6), the data acquisition system was also programmed to provide an audible alarm if the battery temperatures exceeded 40^{o}C. In addition a hose fitting and shut off valve were added to the battery case so that the battery case could be flooded with water in case of a fire event.

Six tests were conducted during this program. All six tests were conducted on Chevrolet Volt battery packs, not complete vehicles. A brief description of the rationale for each test is provided in the table below. Additional details are provided in the following paragraphs.

Battery Pack Test Description and Rationale

Test No.	**Rationale**
1	Reproduce the battery damage and conditions that occurred during the side impact test and rollover at MGA
2	Reproduce the battery damage and conditions that occurred during the side impact test and rollover at MGA
3	Reproduce the battery damage and conditions that occurred during the side impact test and rollover at MGA
4	Reproduce the conditions that occurred during the rollover at MGA (i.e. the exposure of the electronics to the coolant) without the battery cells being damaged
5	Reproduce the conditions that occurred during the rollover at MGA (i.e. the exposure of the electronics to the coolant) without the battery cells being damaged but the negative bus bar was shorted to ground
6	Reproduce battery cell damage that occurred during the side impact test at MGA without exposing the components to the coolant

The first three tests consisted of damaging the battery and conducting a post test rollover in a similar manner to the side impact test conducted on the Chevrolet Volt at the MGA facility in May, 2011. Once the batteries were damaged during the first two tests and the test procedures were completed, the batteries were placed in a shed under surveillance for a period of four weeks. Less than a week into the four week surveillance period, the battery damaged during Test 2 caught fire and destroyed the contents of the shed including the battery from Test 1. See Figure 5.03.

Figure 5.03 Battery Fire 11/24/2011

During Test 3, while the battery was inverted, an event occurred resulting in smoke, and finally an arcing event that jetted sparks and flames from the battery housing for about a second. See Figure 5.04.

Figure 5.04 Battery 3 Arcing Event

A forensic assessment of the batteries from the first three tests indicated that the exposure to the coolant solution during the post damage roll-over was creating external shorts in the battery wiring and circuitry.

For the remaining three tests, the parameters believed to have contributed to the MGA event were isolated. Specifically, during the fourth test, the battery cells were not physically damaged, but the electronics were exposed to the coolant solution. The fifth test was a repeat of the fourth with the battery negative bus externally grounded to the chassis to create the current path possibly produced by physical damage to the battery in the MGA side impact test. The sixth test consisted of physically damaging the battery cells without exposing the wiring and circuitry to the coolant solution.

After the test procedures were completed for Tests 4, 5 and 6, the batteries were placed in separate sheds for surveillance. Less than a week into the surveillance period, the battery from Test 5 caught fire due to shorting of a connector on the passenger side end of battery Module 3. The fire was quickly suppressed by discharging water into the battery case. The battery remained flooded until the full test team had returned to the facility (approximately 18 hours later). The batteries from Test 4 and Test 6 produced minor heating during the surveillance period but never caught fire. In addition, a slow discharge of one cell group in Battery 6 was observed. The details of each test are provided in the following table.

Battery Pack Testing Performed

Test No.	Test Description			Observations
	Impact	**Rotation**	**Bus Bar Grounding**	
1	Yes	Yes	unknown	Battery pack destroyed during 11/24 fire initiated by test 2 battery
2	Yes	Yes	unknown	Battery pack caught fire on 11/24. (one week after impact) Fire originated in Module 3
3	Yes	Yes	Yes	Sparks/ flames jetted from battery pack at 180 rotation position. Battery disassembled on 11/21
4	No	Yes	No	Discolored wires indicated battery heating, but no fire occurred.
5	No	Yes	Yes	Rapid electrolysis observed at180 and 270 rotations. Battery pack caught fire on 12-12 (6 days after impact)
6	Yes	No	unknown	Slow voltage discharge of one cell group

In summary, six tests were performed on the Volt battery packs to isolate potential factors involved in the MGA vehicle fire. Of the six tests, two batteries caught fire (tests 2 and 5), one battery experienced a short arcing event with sparks and flames (test 3), one battery showed signs of heating at the connector (test 4), one battery had no test activity other than a slow discharge of one cell group (test 6), and one battery was inadvertently consumed in the fire (test 1).

6.0 Summary

The 2011 NHTSA crash test program focused on lithium-ion battery technology currently in production for use in electric and hybrid vehicles. The Chevrolet Volt was selected for testing to the 5th percentile female side-pole impact test under NHTSA's NCAP program. Three weeks after the May 12, 2011 crash test, a fire started in the vehicle which originated from the vehicle battery. NHTSA conducted a repeat test on September 21, 2011 to try to replicate the May 12th test results. There was no intrusion observed into the vehicle battery and there was no leakage of coolant in the battery. The vehicle did not exhibit any thermal or electrical anomalies immediately after the test or during the 3 week post-test monitoring period.

The forensic inspections, along with battery pack level impact testing performed at GTL, identified four possible effects to the Volt battery from the impact intrusion and rollover observed in the MGA side-pole test. The intrusion alone can produce cell damage, shorting of the battery negative bus bar, and battery coolant leakage. The rollover of the vehicle after the intrusion event can result in electrical short circuits caused by dispersion of conductive battery coolant into the battery monitoring system.

In summary, NHTSA crash tested 5 Chevrolet Volts in 2011. NHTSA also conducted battery pack level impact testing on 6 Chevrolet Volt battery packs. Three separate tests resulted in a sustained fire event either at the vehicle level or the battery pack level. The May 12th vehicle fire occurred 3 weeks after the crash event. The battery pack fires occurred 6 – 7 days after the impact test. The Battery test 3 resulted in an electrical arcing event that occurred hours after the impact test. The arcing event did not result in a sustained fire.

No real-world crash data has been reported which indicates that a Chevrolet Volt has suffered a battery induced fire event either immediately after a crash or for an extended time period after a crash.

7.0 Attachments

1. Morrill, J., "NHTSA 060411 Fire Inspection," MorrFire Rpt. #02215, July, 2011.
2. Back, G., "MGA/NHTSA Car Fire Inspection," January 2012.
3. Aylor, A., et. al., "Chevrolet Volt Battery Pack Tests" GTL Rpt. #GTL-DOT-11-VOLTBAT, January 2012

MORRFIRE INVESTIGATIONS, LLC

PO Box 4058 • Cartersville, Georgia 30120 • 678.920.0819 • jeff@morrfire.com

July 2, 2011

Gerard G Back
Senior Fire Protection Engineer
Hughes Associates, Inc.
3610 Commerce Drive, Suite 817
Baltimore, Maryland 21227

RE: NHTSA 060411
2011 Chevrolet Volt (MBO125 test)
Date of Incident: June 3-6, 2011
MorrFire File #02215

Dear Mr. Back,

On June 9, 2011, MorrFire Investigations, LLC, was requested to determine the origin and cause of a fire that has damaged several vehicles used in NHTSA safety testing at the MGA Research facility located at 5000 Warren Road in Burlington, Wisconsin. It is my understanding that the vehicles involved were crash-tested prior to the fire incident. The following vehicles were damaged in the fire incident:

2006 Ford F150
2011 Lexus RX350
2011 Chevrolet Volt
2011 Dodge Charger
1995 Chevrolet Z71 (this vehicle is owned by an employee, not involved in crash testing)

The vehicles were located at the northern portion of the testing facility. The Ford F150, Lexus, and Chevrolet Volt were parked front to back (all three vehicles were parked facing west). The Chevrolet Volt and Dodge Charger were parked front to front (the Charger was parked facing east). The Dodge Charger and the Chevrolet Z71 were parked back to back (the Z71 was parked facing west), all on the south side of the roadway.

On June 6, 2011, during a routine drive-around, an MGA maintenance man observed that several vehicles had burned. He notified management who in turn contacted the fire department. Robert Sharp of the Walworth County Sheriff's Office headed the public sector inspection. Several pieces of different vehicles were identified, marked, tagged, and collected by the Sheriff's department.

On June 13-16, 2011, the author, along with representatives of MGA Research (MGA), Walworth County Sheriff's Department, Hughes Associates, the National Highway Transportation Safety Administration (NHTSA), the National Transportation Safety Board (NTSB), and General Motors (GM), inspected the fire scene, inspected the collected articles from the Sheriff's Department, disassembled the Chevrolet Volt, identified and collected additional evidence.

All of the crash-damaged vehicles were to be parked with a minimum of ignitable liquids remaining. Stoddard solvent is used in all fuel tanks. Coolant, brake fluid, power steering fluid, etc., is removed from the fluid reservoirs. Some 12vdc batteries are disconnected. The Chevrolet Volt's high-energy battery disconnect (Manual Service Disconnect (MSD)) was removed prior to the incident. The entire fire scene was evaluated and then each individual vehicle involved was evaluated.

Although any number of intentional acts could have been responsible for the fire(s), the focus was on inspecting the vehicles for accidental fire causes. If a person (or persons) deliberately caused the fire(s), certain evidence observed at the scene would not likely have occurred. The displaced components from the Chevrolet Volt would not likely have been removed, placed a distance from the vehicle, then the vehicle set on fire. For an act such as a carelessly discarded cigarette, one would have to make the assumption that said cigarette was disposed of 'inside' the Chevrolet Volt. Other 'known' causes, such as a Molotov cocktail or lightning were considered during the inspection. No evidence of either fire causing event was observed. In accordance with NFPA 921, all fires are assumed to be accidental until proven otherwise. During the course of the inspection, no evidence was found to indicate that the fire(s) were anything other than accidental. A product failure is regarded as an accidental fire cause.

Based on the condition of the vehicles, the only plausible accidental cause for a fire within any one particular vehicle would be electrical energy from the vehicles' battery. All vehicles (in running and/or serviceable condition) have certain conductors and circuits that remain energized when the vehicle is not running; the key is in the 'off' position or not in the vehicle ignition. By understanding the circuitry and effects of a fire upon energized conductors and components, an investigator may determine the direction of a fire and whether the fire originated within a vehicle or from another source. During a fire, if there are energized electrical conductors that become damaged due to the heat from the fire, the expected result is that the now exposed energized conductor will, at some point along the length of the conductor, contact a surface of opposite or differing electrical potential. This will result in the displacement of the copper wiring resulting in a visual observation of 'copper beads' or 'notches'. These are the 'tell-tale' signs of an electrical discharge. Due to the melting temperature of copper (~2000 degrees F), most vehicles fires will not melt the primary conductors. Typically, any evidence of an electrical event will be readily identifiable after a vehicle fire. Although these were 'crash-damaged vehicles, they all may have had the same relative propensity for an electrical event.

Fire pattern analysis is one of the 'tools' that an investigator uses to determine direction of fire travel, area of fire origin, or length , duration, or intensity of the fire. Knowing how a fire will affect certain components of a vehicle will assist the investigator in the interpretation of those fire patterns. Fire pattern analysis is the interpretation of the effects of a fire upon components and surfaces.

Based on the inspection of the site and all of the vehicles including but not limited to, fire pattern analysis, and fire damaged and non-fire damaged components of vehicles, it can be stated with certainty that the incident originated within the passenger compartment of the 2011 Chevrolet Volt. Certain non-fire damaged components were identified at a distance from the Chevrolet Volt are consistent with an internal over-pressurization within the Chevrolet Volt prior to any significant build-up of heat. The windshield was displaced to the passenger's side of the vehicle. The interior rear-view mirror assembly was displaced forward and to the passenger's side of the vehicle. The driver's side exterior rear-view mirror cover and (roof) drip trim were displaced to the driver's side of the vehicle. A fire-damaged pneumatic lift cylinder from the driver's side rear hatch was displaced forward and to the passenger's side. This shows that certain non-fire damaged components were observed at a distance from the Chevrolet Volt as well as certain fire damaged components. This gives the author a time frame when certain activities occurred relative to one another.

The 2006 Ford F150 was crash-tested at the front and driver's side. Fire pattern analysis shows that the fire moved from the front of the truck towards the rear. No vehicles were fire damaged to the rear (east) of the F150. The 12vdc battery was located at the passenger's side of the engine compartment above the passenger's side front wheel-well. The most exposed primary electrical conductors were at the passenger's side engine-mounted alternator and B+ conductor across the upper area of the bulkhead. These conductors would be exposed early in a fire within the Ford engine compartment and as such, would be expected to indicate electrical energy available in the vehicle battery by arcing to a grounded surface during the fire. No evidence of electrical activity was observed on any of the primary battery conductors or normally energized conductors. The lack of any observable artifacts of electrical arcing shows that when these conductors were damaged by the fire, the battery no longer had a sufficient electrical charge to cause any arcing. The 2006 Ford F150 was eliminated as a vehicle of fire origin.

The 2011 Lexus RX350 was crash-tested in the driver's door. Due to vehicles burning both in front of and behind the Lexus, fire pattern analysis was not a useful analytical process. The battery was located at the driver's side front corner of the engine compartment. The most exposed primary electrical conductor was at the passenger's side engine-mounted alternator. This conductor would be exposed early in a fire within the Lexus engine compartment and as such, would be expected to indicate electrical energy available in the vehicle battery by arcing to a grounded surface during the fire. No evidence of electrical activity was observed on any of the primary battery conductors or normally energized conductors. The lack of any observable artifacts of electrical arcing shows that when this conductor was damaged by the fire, the battery no longer had a sufficient electrical charge to cause any arcing. No evidence of electrical activity was observed within the Lexus interior. The 2011 Lexus RX350 was eliminated as a vehicle of fire origin.

The 2011 Dodge Charger was crash-tested at the driver's side. Fire pattern analysis shows that the front (facing the Chevrolet Volt) was more fire damaged than the rear of the vehicle. The battery was located in the trunk with the major electrical conductors routed through the passenger's side of the interior, through the passenger's side of the bulkhead into the engine compartment. The most exposed primary electrical conductors were at the passenger's side engine-mounted alternator and power distribution block. These conductors would be exposed early in a fire within the Charger engine compartment and as such, would be expected to indicate electrical energy available in the vehicle battery by arcing to a grounded surface during the fire. No evidence of electrical activity was observed on any of the primary battery conductors or normally energized conductors. The lack of any observable artifacts of electrical arcing shows that when these conductors were damaged by the fire, the battery no longer had a sufficient electrical charge to cause any arcing. The 2011 Dodge Charger was eliminated as a vehicle of fire origin.

The 1995 Chevrolet Z71 truck only exhibited minor thermal damage at the taillights and lightweight materials at the very rear of the truck. It was reported that the truck had been parked in this location for at least a year. A check of the battery with an electrical test meter indicated that it had no observable voltage. The 1995 Chevrolet Z71 was eliminated as a vehicle of fire origin.

The 2011 Chevrolet Volt was the only vehicle to exhibit non-fire damaged components displaced a distance from the vehicle. It was also the only vehicle with two battery systems. If the Volt was attacked by a fire from one of the other vehicles, the displaced components would have been expected to be fire damaged in place, not displaced from the vehicle. The12vdc battery was located in the trunk. The most exposed 12vdc primary electrical conductors were at the battery location in the trunk and at the forward portion of the engine compartment. These conductors would be exposed early in a fire within the Volt engine compartment or rear vehicle interior and as such, would be expected to indicate electrical energy available in the 12vdc battery by arcing to a grounded surface during the fire. All of the battery mounted +12vdc fuses were intact post-fire. No evidence of electrical activity was observed on any of the 12vdc primary battery conductors or normally energized conductors. The lack of any observable artifacts of electrical arcing shows that when these conductors were damaged by the fire, the vehicle's 12 volt battery no longer had a sufficient electrical charge to cause any arcing. Based on the fire analysis it can be stated with certainty that the incident originated within the passenger compartment of the 2011 Chevrolet Volt.

The Chevrolet Volt was the only vehicle exhibiting potential electrical activity at the interior center tunnel area. This observation of 'melting' of portions of the center tunnel sheet metal is consistent with the effects of electrical activity. This is the location of the high energy battery. Evidence of mechanical intrusion into the battery compartment was observed during the vehicle inspection. This intrusion appeared to exceed the outer dimensions of the 'battery pack'. The battery pack was removed with the assistance of GM. This battery pack was further examined at the NHTSA facility in East Liberty, Ohio. The battery examination results will be addressed by others.

Based on the fire scene evaluation, the individual vehicle inspections, the evaluation of fire-damaged and non-fire damaged vehicle components; the following scenario is consistent with all the observations made:

1. An incipient pressure event occurred within the interior of the Chevrolet Volt. This over-pressure event displaced the vehicle windshield, interior rear-view mirror components, exterior rear-view mirror components, and vehicle trim.
2. After the pressure event, a thermal event occurred within the interior of the Chevrolet Volt.
3. The ensuing fire caused the Chevrolet Volt passenger's side upper frontal air bag module to be released from the dash mounting bracket, drop to the passenger's side floor, and remain there until it over-pressurized and mechanically damaged the passenger's side front floor and roof directly over the passenger's side front seat.
4. The ensuing fire damaged the Chevrolet Volt driver's side rear hatch pneumatic cylinder causing it to 'launch' from the rear of the vehicle forward, under the roof sheet metal, to its resting place forward and to the passenger's side of the Chevrolet Volt.
5. The Chevrolet Volt passenger's side rear hatch pneumatic lift cylinder failed in place causing localized mechanical damage.
6. The fire spread through radiation and convection forward to the 2011 Dodge Charger and further to the 1995 Chevrolet Z71 and rearward to the 2011 Lexus RX350 and further rearward to the 2006 Ford F150.
7. The fire consumed most of the combustible material from the 2006 Ford F150, the 2011 Lexus RX350, the 2011 Chevrolet Volt, and the 2011 Dodge Charger. The 1995 Chevrolet Z71 was superficially damaged.

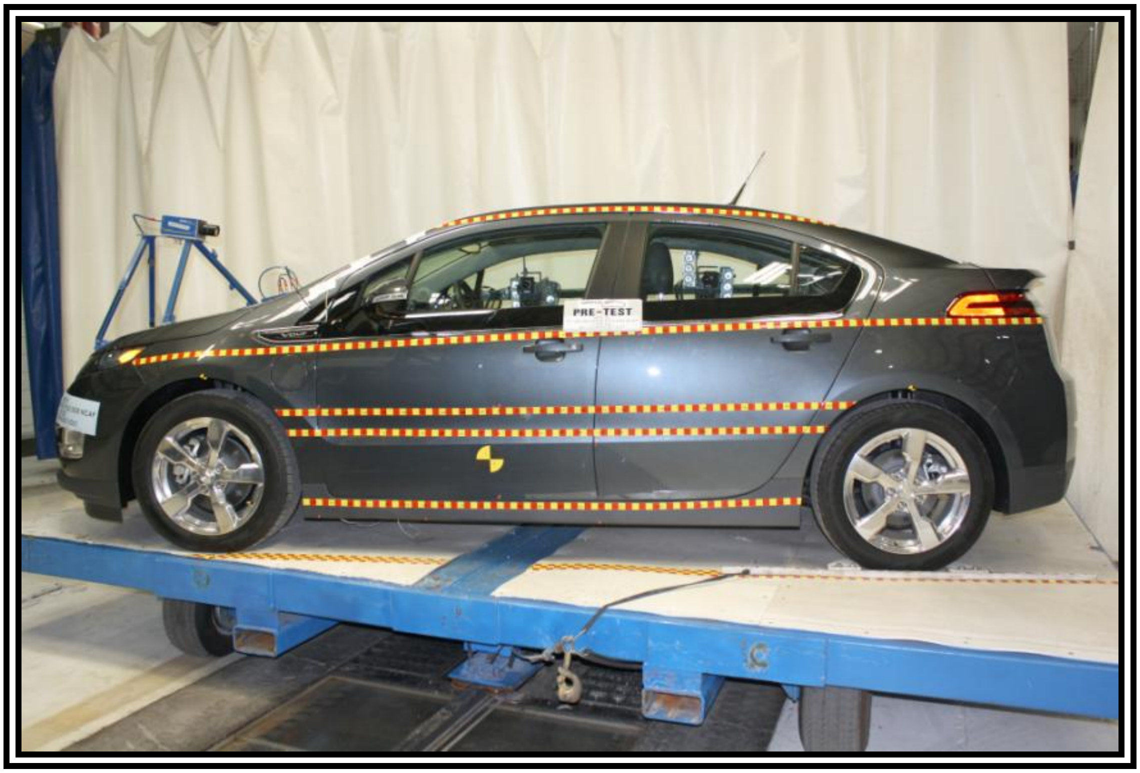
Attached to this correspondence are views of the fire scene, views of each vehicle, views of the Chevrolet Volt during the laboratory inspection, views of the removed battery pack, and views of the mechanical damage to the Chevrolet Volt interior tunnel. Should you have any question, or need any further information, please do not hesitate to contact me.

Sincerely,

MorrFire Investigations

Jeffery T Morrill, IAAI-CFI, NAFI-CVFI

The opinions expressed herein are based on the available information. Should additional information become available, the author reserves the right to evaluate said information and determine if the new information has any bearing on the opinions expressed.

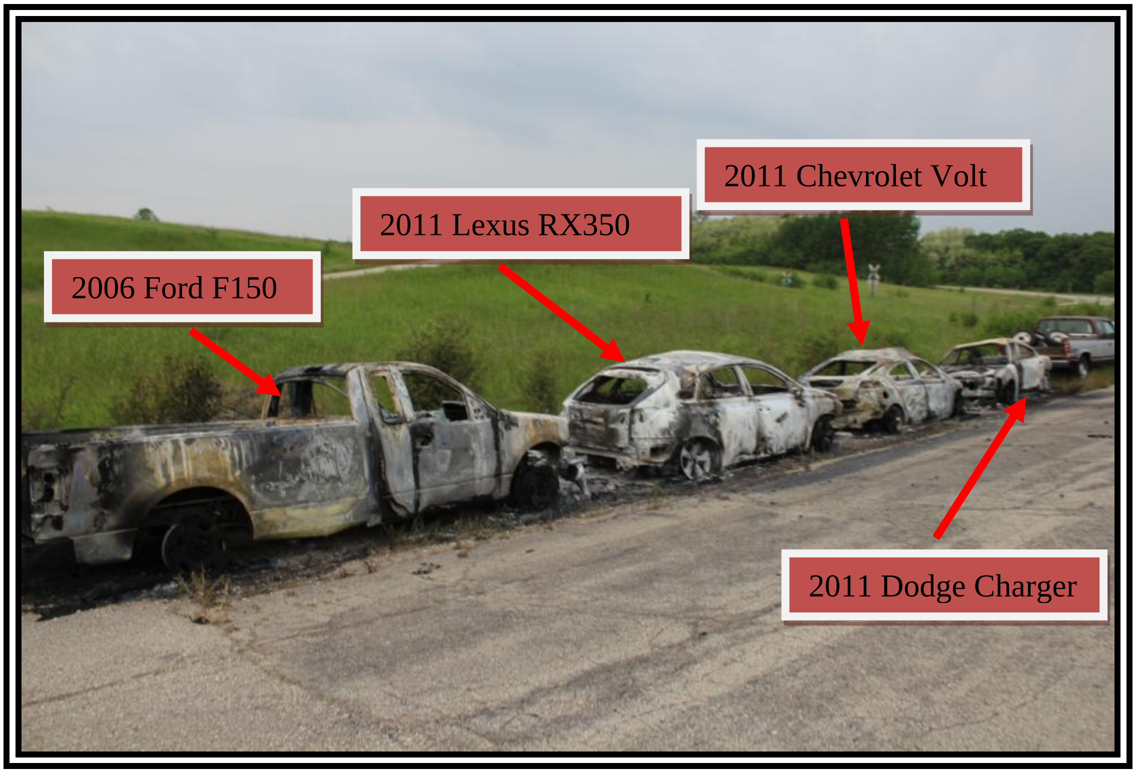


2011 Chevrolet Volt, pre-impact, view from the driver's side

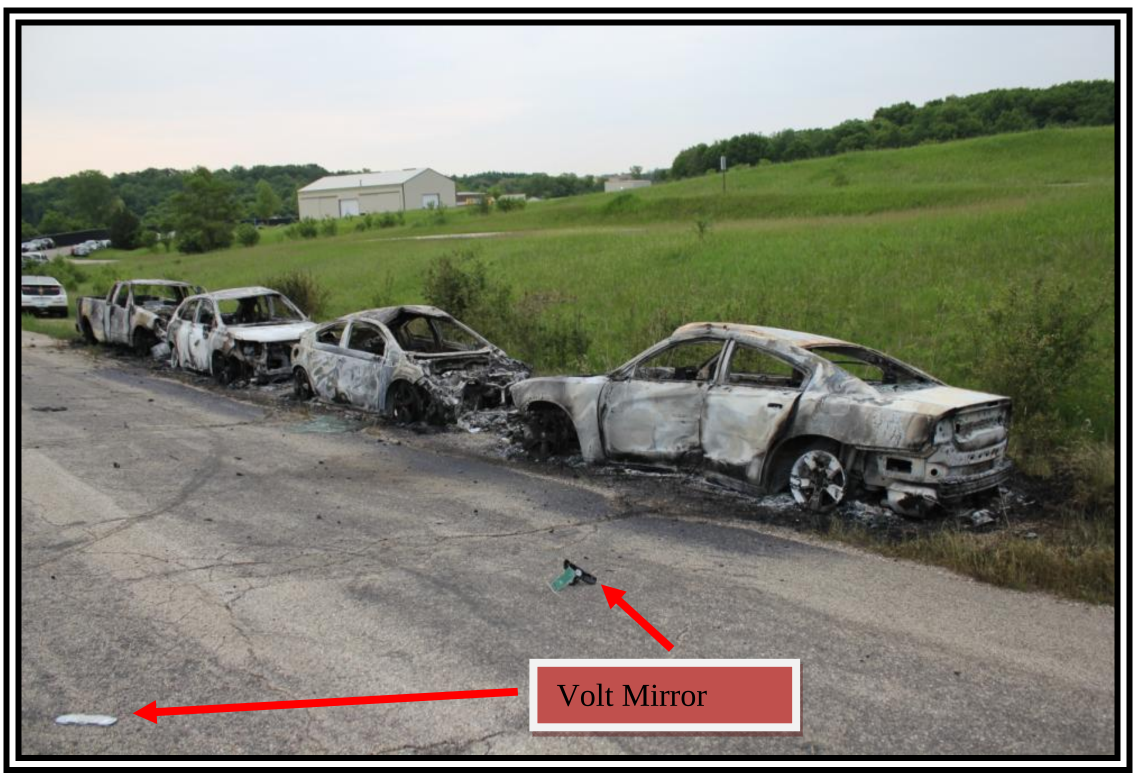
2011 Chevrolet Volt, post-impact, view from the driver's side

2011 Chevrolet Volt, pre-impact, view from the driver's side front

2011 Chevrolet Volt, post-impact, view from the driver's side front



Overall fire scene, view from northeast to southwest.



Overall fire scene, view from northwest to southeast

Chevrolet Volt, driver’s side, rear lift hatch, pneumatic cylinder

2006 Ford F150

2006 Ford F150, driver's side and rear

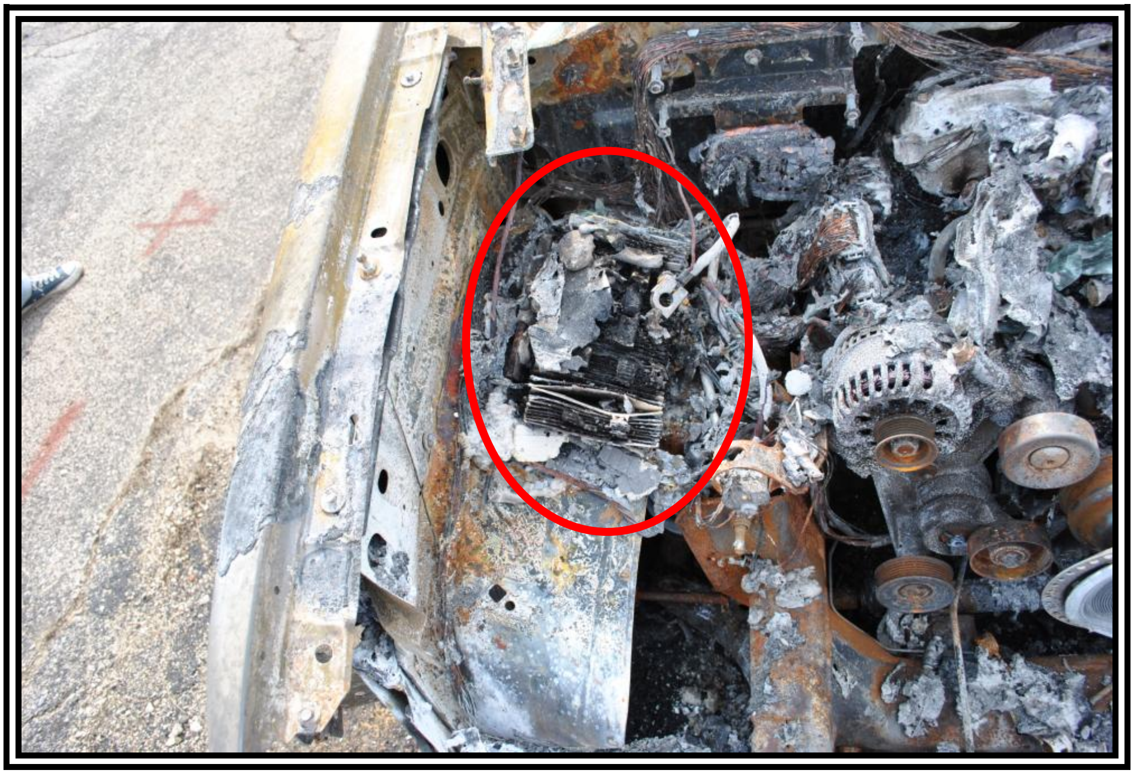
2006 Ford F150, rear and passenger's side

2006 Ford F150, passenger's side and front

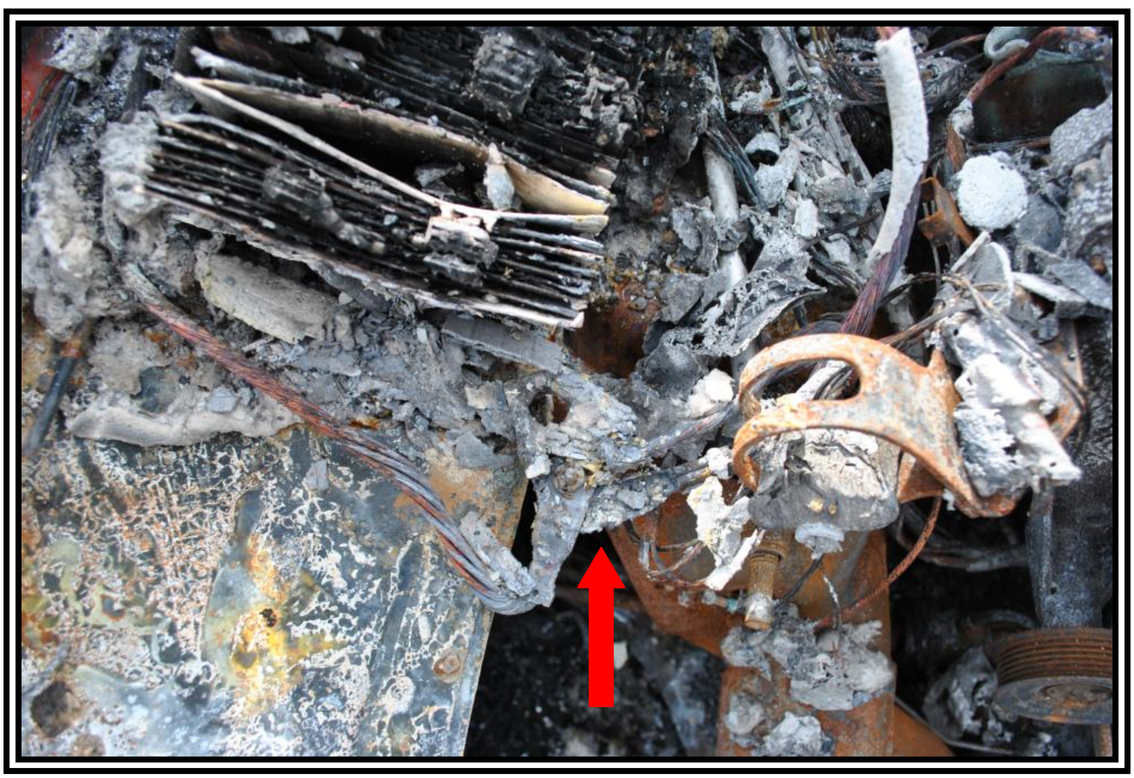
2006 Ford F150, front interior

2006 Ford F150, driver's side engine compartment

2006 Ford F150, passenger's side engine compartment



2006 Ford F150, passenger's side battery



2006 Ford F150, +12vdc battery connection

2006 Ford F150, +12vdc conductors

2006 Ford F150, intact fusible links to the alternator

2011 Lexus RX350

2011 Lexus RX350, front and driver's side

2011 Lexus RX350, driver's side and rear

2011 Lexus RX350, rear

2011 Lexus RX350, rear and passenger's side

2011 Lexus RX350, passenger's side and front

2011 Lexus RX350, front interior

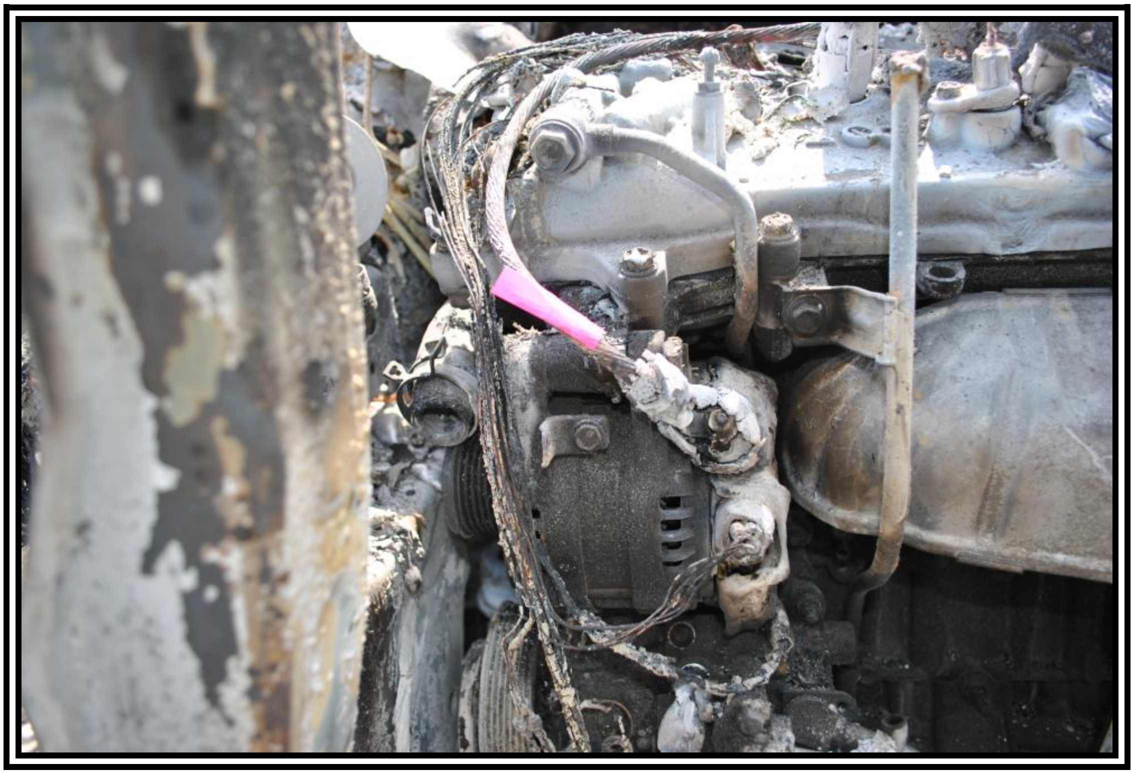
2011 Lexus RX350, underside of the hood

2011 Lexus RX350, driver's side engine compartment

2011 Lexus RX350, passenger's side engine compartment

2011 Lexus RX350, driver's side mounted battery

2011 Lexus RX350, +12vdc battery conductors



2011 Lexus RX350, +12vdc conductor at the alternator

2011 Lexus RX350, +12vdc battery conductors

2011 Dodge Charger

2011 Dodge Charger, front and driver's side

2011 Dodge Charger, driver's side and rear

2011 Dodge Charger, rear and passenger's side

2011 Dodge Charger, passenger's side and front

2011 Dodge Charger, driver's side engine compartment

2011 Dodge Charger, front interior

Passenger’s side engine compartment

2011 Dodge Charger, passenger's side engine compartment power distribution panel

2011 Dodge Charger, battery conductor through bulkhead passage

2011 Dodge Charger, trunk mounted battery

2011 Chevrolet Volt

2011 Chevrolet Volt, driver's side and rear

2011 Chevrolet Volt, rear and passenger's side

2011 Chevrolet Volt, passenger's side and front

2011 Chevrolet Volt, driver's side engine compartment

2011 Chevrolet Volt, passenger's side engine compartment

2011 Chevrolet Volt, driver's side interior

2011 Chevrolet Volt, interior from the rear

2011 Chevrolet Volt, passenger's side interior

2011 Chevrolet Volt, view from rear after debris removal

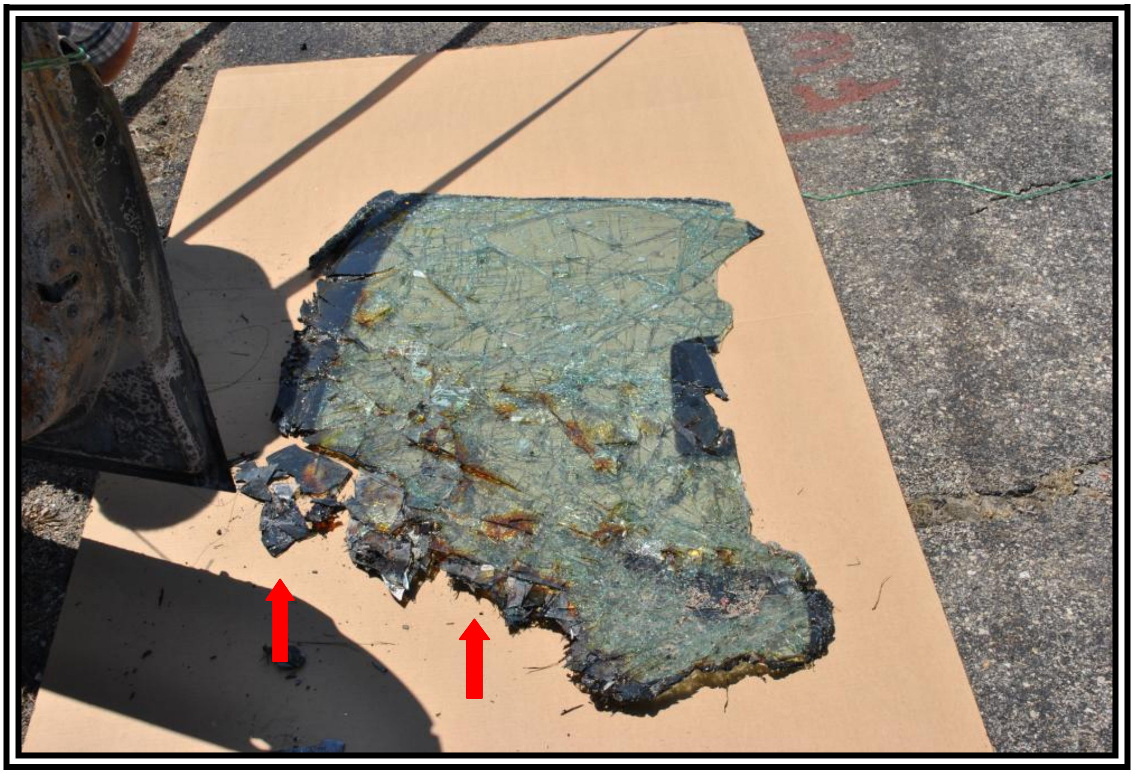
2011 Chevrolet Volt, observable 'radius' of the center tunnel

2011 Chevrolet Volt, view of the side impact and intrusion

2011 Chevrolet Volt, passenger's side upper airbag module and exemplar module on passenger's side floor

2011 Chevrolet Volt, comparison of the recovered airbag module to an exemplar

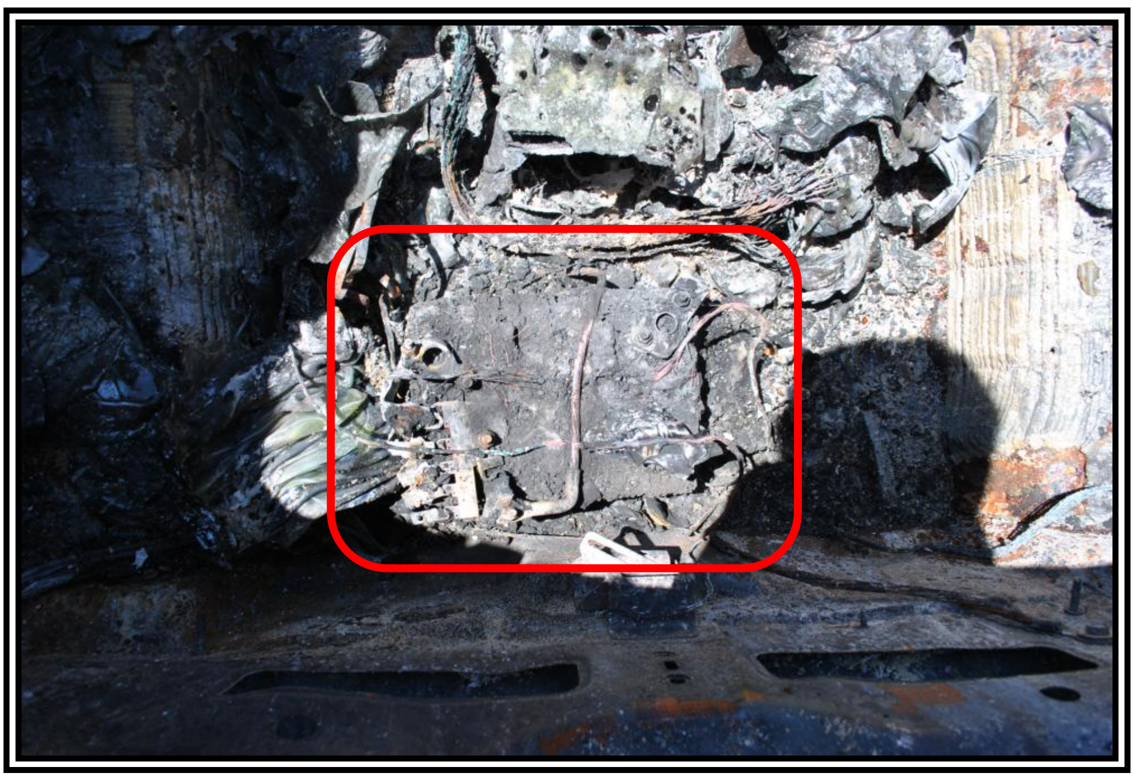
2011 Chevrolet Volt, displaced windshield glass laying face up



2011 Chevrolet Volt, recovered windshield glass exhibiting thermal damage at contact with burned vehicle

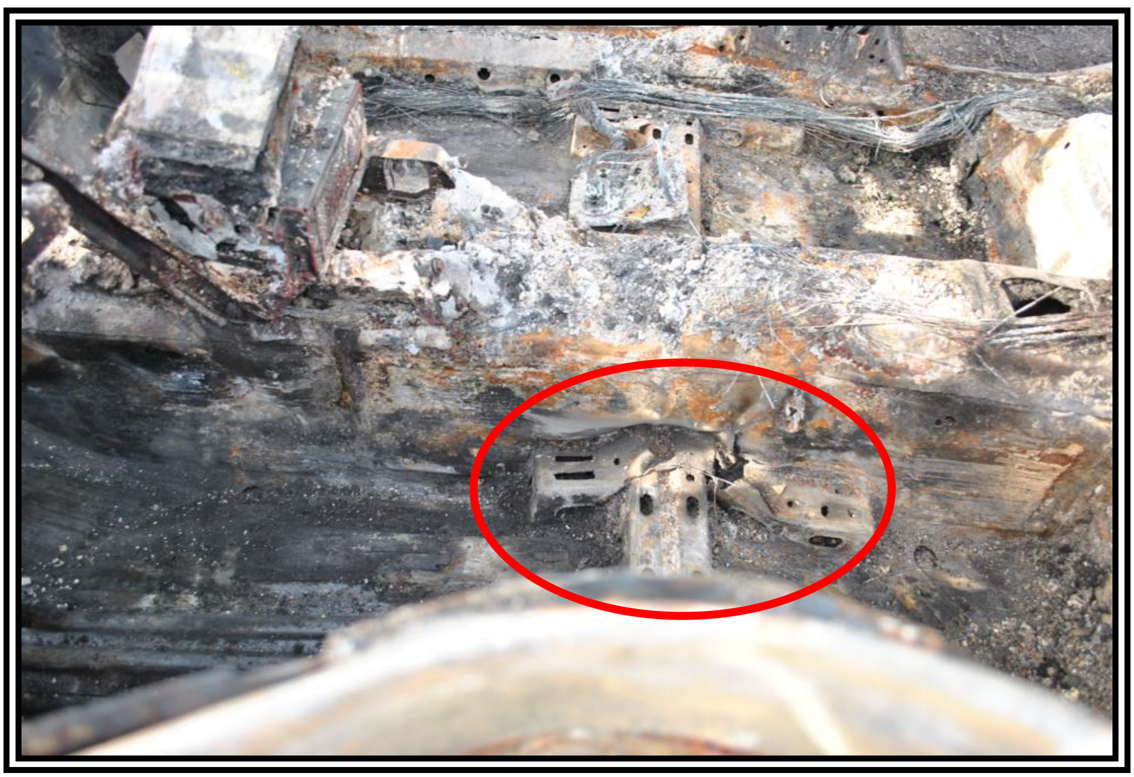
2011 Chevrolet Volt, trajectory illustration of interior rear view mirror components

2011 Chevrolet Volt, dislodged roof sheet metal showing rear lift cylinder trajectory



2011 Chevrolet Volt, trunk mounted 12vdc battery

2011 Chevrolet Volt, intact +12vdc fuses at the battery



2011 Chevrolet Volt, driver's side interior showing impact intrusion into the center tunnel

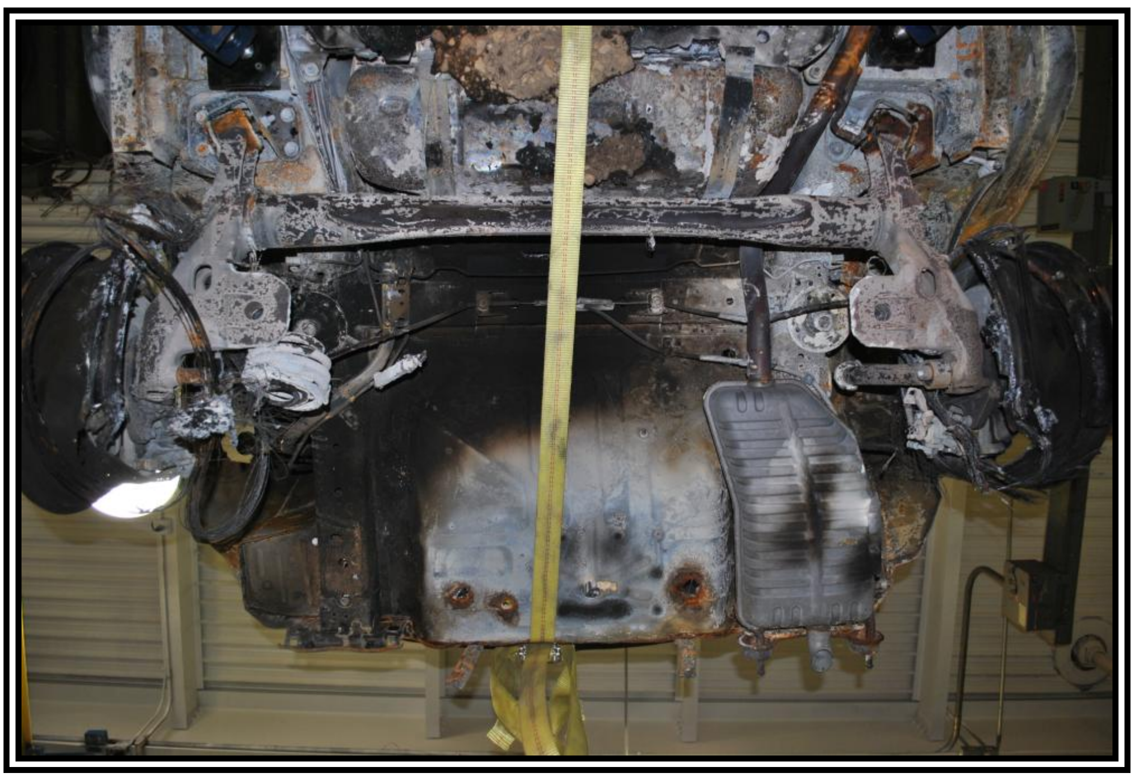
2011 Chevrolet Volt, GM paint marking of tunnel and battery

2011 Chevrolet Volt, front underside

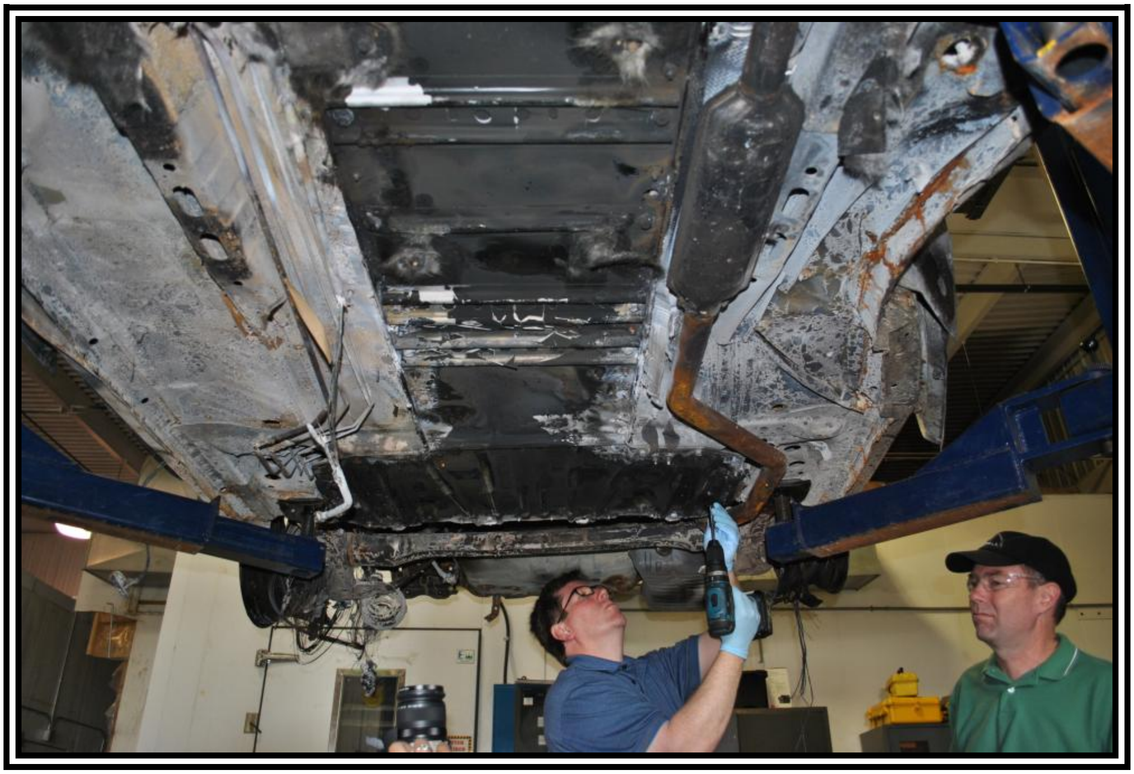
2011 Chevrolet Volt, front center underside

2011 Chevrolet Volt, center underside

2011 Chevrolet Volt, rear center underside



2011 Chevrolet Volt, rear underside



2011 Chevrolet Volt, initial high-energy battery removal

2011 Chevrolet Volt, high-energy battery pack removed from vehicle

2011 Chevrolet Volt, rear of high-energy battery pack

2011 Chevrolet Volt, driver’s side of the high-energy battery pack

2011 Chevrolet Volt, measurement of intrusion into the battery pack tunnel

2011 Chevrolet Volt, view of the intrusion and opening from the tunnel to the vehicle interior

MGA/NHTSA Car Fire Inspection

Prepared for

National Highway Traffic Safety Administration (NHTSA)
1200 New Jersey Avenue, SE, NVS-220
Washington, DC 20590

Prepared by

Gerard Back (Jerry)
Hughes Associates, Inc.
Baltimore, MD 21227
Ph. 410.737.8677 FAX 410.737.8688

January 20, 2012

Title: MGA/NHTSA Fire Inspection	Report Date: January 20, 2012
Author: Gerard Back	
Performing Organization Name and Address: Hughes Associates, Inc. 3610 Commerce Dr., Suite 817 Baltimore, Maryland 21227	Contract No.: DTNH22-11-P-01363
Sponsoring Agency Name and Address: U.S. Department of Transportation National Highway Traffic Administration Office of Vehicle Safety Compliance (NVS-220) 1200 New Jersey Ave., SE Washington, D.C. 20590	Type of Report and Period Covered: Final Inspection Report June 9, 2011 to November 24, 2011

Abstract

In 2011, NHTSA's New Car Assessment Program (NCAP) and Office of Vehicle Safety Compliance (OVSC) contractors performed Federal Motor Vehicle Safety Standard (FMVSS) testing of the Chevrolet Volt to obtain NCAP ratings and to verify compliance with the FMVSS No. 214 side impact pole test requirements. Under these programs, two side impact pole tests were conducted on the Volt; a 5th percentile female dummy and a 50th percentile male dummy. The distinction is made between the test dummies because the impact location of the pole depends on the location of the dummy's head which varies for different size dummies.

During the May 12, 2011 test with a 5th percentile female dummy conducted at MGA in Burlington, Wisconsin, the battery was physically damaged during the crash by part of the car structure that intruded into the side of the battery. Approximately three weeks after the side impact test, the vehicle caught fire which spread to adjacent vehicles. A forensic inspection was conducted to determine the origin and potential cause of the fire.

Based on all of the physical evidence and analysis conducted during this effort, the following scenario can be stated with a reasonable degree of certainty. During the crash test, the transverse stiffener located under the driver's seat penetrated the tunnel section of the battery compartment and intruded into the side of the lithium-ion battery. The physical damage to the battery and the battery cooling system was the root cause of this incident. Although it is difficult to determine the exact mechanism and series of events that lead to the fire, it is more likely than not that the damage to the cells at this location created an internal short that resulted in the forceful release of flammable gases (vaporized electrolyte) into the occupant compartment of the vehicle. These gases were eventually ignited by the reaction and generated enough pressure to expel the windshield and ignited the contents of the occupant compartment. The fire eventually consumed the Volt and spread to the adjacent vehicles.

CONTENTS

MGA/NHTSA CAR FIRE INSPECTION

1.0 INTRODUCTION

A fire occurred at the MGA Research facility in Burlington, Wisconsin over the weekend of June 3–6, 2011. Since the fire occurred over the weekend, there were no witnesses to the fire. The following vehicles were damaged in the fire:

2006 Ford F150
2011 Lexus RX350
2011 Chevrolet Volt
2011 Dodge Charger
1995 Chevrolet Z71 (this vehicle is owned by an employee, not involved in crash testing)

The vehicles were located at the northern portion of the testing facility. The Ford F150, Lexus, and Chevrolet Volt were parked front to back (all three vehicles were parked facing west). The Chevrolet Volt and Dodge Charger were parked front to front (the Charger was parked facing east). The Dodge Charger and the Chevrolet Z71 were parked back to back (the Z71 was parked facing west), all on the southwest side of the roadway. Vehicles were placed there with a forklift after having been crash tested (side impact test on the driver's side). The Ford F150, Lexus RX350, and Chevrolet Volt were crashed 3 weeks prior to the fire and the Ford F150 was tested in February 2011. Per the standard test procedures, the 12V batteries of all four vehicles were fully charged at the time that they were tested. The cars were spaced about 2–3 feet apart. A photograph of these vehicles is provided as Figure 1.0-1.

Figure 1.0-1. Fire Scene Photograph

The initial forensic inspection was conducted on June 13–16, 2011 at the MGA facility in Burlington, Wisconsin. The inspection was conducted by Jeff Morrill of MorrFire Investigations, LLC and Jerry Back of Hughes Associates, Inc. to determine origin and cause of the fire by examining all four burned vehicles, and to determine the involvement of the Chevrolet Volt and its propulsion battery. The inspection was overseen by the following NHTSA representatives:

- Brian Smith – NHTSA
- Emily Reichard – formerly a contractor now a NHTSA employee

The fire inspection identified the 2011 Chevrolet Volt as the likely origin of the fire [1]. For the remainder of this report, the term "battery" will refer to the lithium-ion propulsion battery in the Volt.

There were two separate Chevrolet Volt battery inspections conducted after the initial fire inspection. After the fire origin was postulated, the Chevrolet Volt was taken from the location where the fire had occurred and moved inside where the battery was removed from the vehicle and the conditions of the vehicle and battery were documented. The battery was then shipped to NHTSA's facility in East Liberty, Ohio where a thorough inspection of the battery was performed. During this battery inspection, the battery was disassembled and each cell was inspected for damage. A detailed description of both inspections is provided in this report.

2.0 VEHICLE OF ORIGIN

The initial inspection concluded that the conditions of the adjacent vehicles and the exterior of the Chevrolet Volt are consistent with the fire originating in the Chevrolet Volt [1]. In addition, there were obvious differences in the damage to the Volt when compared to the other vehicles involved in the fire. The most notable was that the windshield and rear view mirror assembly had been blown out of the car and were lying on the street next to the vehicle with little (if any) heat damage to these components. The lack of heat damage suggests that this overpressure event occurred before the occupant compartment of the Volt caught fire. This overpressure event was followed by a fire within the occupant compartment of the Volt that eventually destroyed the four vehicles at the MGA facility between June 3–6, 2011.

Based on the fire scene evaluation, the individual vehicle inspections, the evaluation of fire-damaged and non-fire damaged vehicle components, the following scenario can be stated to a reasonable degree of fire science certainty:

1. An incipient pressure event occurred within the interior of the Chevrolet Volt. This over-pressure event displaced the vehicle windshield, interior rear-view mirror components, exterior rear-view mirror components, and vehicle trim.
2. After the pressure event, a thermal event occurred within the interior of the Chevrolet Volt.
3. The ensuing fire damaged the driver's side rear hatch pneumatic cylinder causing it to 'launch' from the rear of the vehicle forward, under the roof sheet metal, to its resting place forward and to the passenger's side of the Chevrolet Volt.
4. The passenger's side rear hatch pneumatic lift cylinder failed in place causing localized mechanical damage.

5. The ensuing fire caused the passenger's frontal air bag module to be released from the dash mounting bracket, drop to the passenger's side floor, and remain there until it over-pressurized and mechanically damaged the passenger's side front floor and roof directly over the passenger's side front seat.
6. The fire spread through radiation and convection forward to the 2011 Dodge Charger and further to the 1995 Chevrolet Z71 and rearward to the 2011 Lexus RX350 and further rearward to the 2006 Ford F150.
7. The fire consumed most of the combustible material from the 2006 Ford F150, the 2011 Lexus RX350, the 2011 Chevrolet Volt, and the 2011 Dodge Charger. The 1995 Chevrolet Z71 was superficially damaged.

An initial inspection of the crash damage to the Volt revealed that the transverse stiffener located under the driver's seat had penetrated the tunnel section of the battery compartment and damaged the lithium battery and the battery's liquid cooling system. For discussion purposes, the battery compartment includes the tunnel section located between the two front seats and the transverse section located under the back seat. It is more likely than not that this damage to the battery, battery compartment, and battery liquid cooling system caused the fire that destroyed the four vehicles at the MGA facility between June 3–6, 2011.

3.0 DETERMINATION OF THE SPECIFIC ORIGIN AND CAUSE

There were two separate inspections of the Chevrolet Volt and the battery. During the initial inspection at MGA, the battery was removed from the vehicle and the conditions of the vehicle and battery were documented. The battery was then shipped to NHTSA's facility in East Liberty, Ohio where a detailed inspection of the battery was performed. During this battery inspection, the battery was disassembled and each cell was inspected for damage. A detailed description of both inspections is provided in the following sections of this report.

3.1 Chevrolet Volt Observations/Conditions

The Chevrolet Volt was crash tested (Side Impact Pole Test) on May 12, 2011. Per the test report [2], the side impact produced a leak in the battery cooling system that was identified while the car was being rotated during the post test inspection. The voltage of the lithium battery as documented in the crash test report corresponds to a 58% state of charge at the time of the test.

The initial fire inspection conducted at the MGA Research facility in Burlington, Wisconsin, included removal of the battery and the inspection of the battery compartment. It also included a general assessment of the battery based on the damage to the battery cover. The battery cover is made of fiberglass and encases the sides and top of the battery (reference Figure 3.1-1). The battery cover is bolted to a metal plate that serves as the foundation for the battery. The battery cover was not removed until the battery was inspected at the NHTSA facility in East Liberty, Ohio.

Figure 3.1-1. Fiberglass Battery Cover (new)

The initial inspection revealed that the transverse stiffener located under the driver's seat had penetrated the tunnel section of the battery compartment and damaged the lithium battery. A photograph of the damage to the outside of the tunnel is shown in Figure 3.1-2.

Figure 3.1-2. Crash Test Damage to the Outside of the Battery Compartment (Tunnel Section)

An inspection inside of the tunnel revealed that the transverse stiffener and tunnel structure had been pushed about 3 inches into the battery compartment and penetrated the side of the battery cover. A photograph of the inside of the tunnel section of the battery compartment showing the intrusion is provided as Figure 3.1-3 (left photograph).

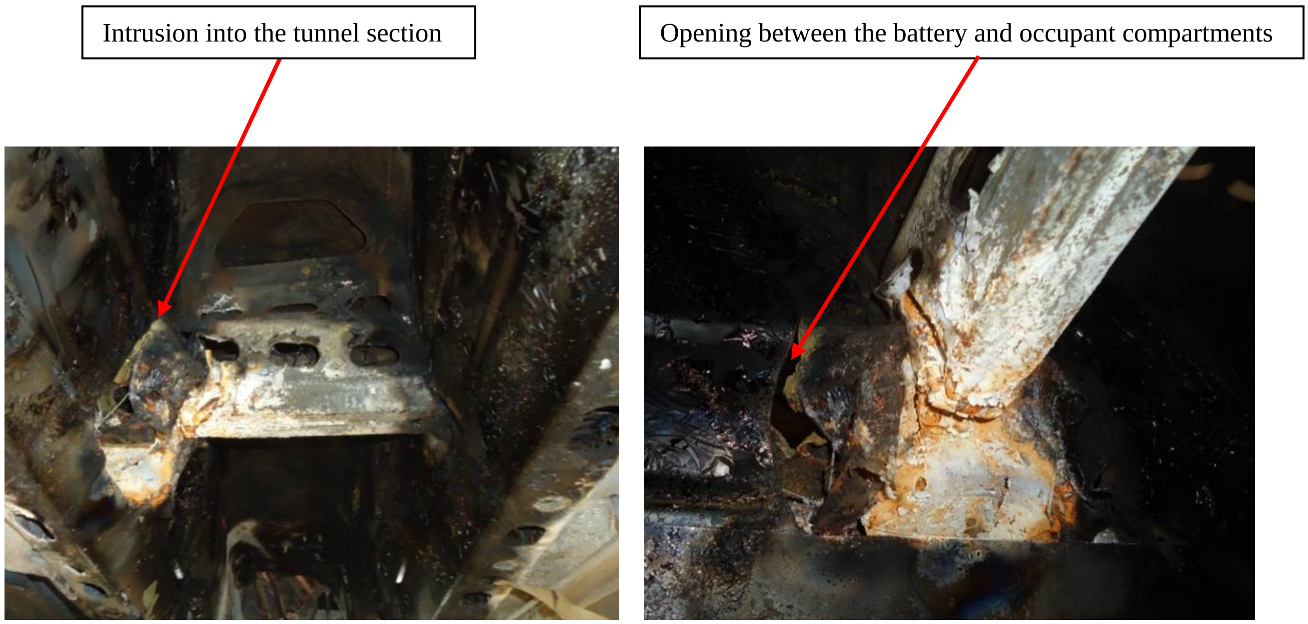


Figure 3.1-3. Crash Test Damage to the Inside of the Battery Compartment (Tunnel Section)

A further inspection of the inside of the battery compartment revealed two other significant findings. The first was that the crash damage produced an opening between the battery compartment and the occupant compartment of the vehicle as shown in the photograph to the right in Figure 3.1-3. This opening would allow gases released by the battery during cell venting to enter the occupant compartment of the vehicle. It also provides a path for fire to spread from the battery to the combustible contents of the occupant compartment.

The second finding is associated with the thermal damage inside of the tunnel. The paint around the damaged area had been completely consumed and the steel was discolored indicating a higher thermal exposure and potential exposure to the reactive chemicals within the battery (electrolyte and or electrolyte combustion products). In short, this area in the tunnel was exposed to different and more severe conditions than the other areas inside of the battery compartment.

The outer cover of the battery and the battery itself were damaged at this location and exhibited signs of higher thermal exposures. The fiberglass structure had been breached at this location and all of the resin within the structure had been consumed by the fire. This is evident by the white colored glass fibers in the damaged area as shown in the photograph provided as Figure 3.1-4. The battery cells in this area were also physically damaged during the crash test and will be discussed in the following section of this report.

Figure 3.1-4. Battery Cover Damage at the Impact Location

There were at least seven areas between the occupant and battery compartments that were breached during the event. It was concluded that these holes were produced as a result of the battery arcing (shorting) to the car chassis. It was determined that some of the battery connections had melted off during the fire energizing part of the battery support structure. A photograph of one of these arcing holes is provided in Figure 3.1-5. Additional information of this arcing is provided in the following section of this report.

Figure 3.1-5. Holes in the Tunnel Section of the Battery Compartment Produced by Arcing

3.2 Battery Removal and Initial Observations at MGA

As stated previously, the battery was removed from the car at the MGA facility in Wisconsin. A photograph of the battery shortly after it had been removed is provided as Figure 3.2-1. The fiberglass cover is still on the battery in the photograph. Although the detailed assessment was not conducted until the battery reached the NHTSA facility in East Liberty, Ohio, a few observations of the battery were noted and are listed as follows:

1. The greatest fire damage to the battery occurred in areas with the best access to oxygen. Specifically, the greatest fire damage occurred at the ends of the battery and in the crash damaged areas near the center of the battery. There are openings into the battery compartment at these locations providing a path for oxygen to support the fire.
2. For the most part, all of the resin had been baked or burned out of the fiberglass battery cover. There were a limited number of areas of the cover that were still somewhat rigid but the majority of the battery cover had the consistency of non-rigid fiberglass cloth.
3. All of the visible battery electronic components (wires, circuit boards, etc) were completely consumed by the fire.
4. There were at least seven holes in the battery cover created by arcing between the battery and the car chassis. These areas are indicated by the color spots (green and pink) on the photograph in Figure 3.2-1.

Figure 3.2-1. Battery Cover Photographs

3.3 Battery Assessment at VRTC

The battery forensic inspection was conducted on June 20–23, 2011 at NHTSA Vehicle Research and Test Center (VRTC) located in East Liberty, Ohio. The inspection was conducted by Lance Turner and Galen Ressler of General Motors and by Jerry Back of Hughes Associates. The inspection was overseen by Brian Smith and Emily Reichard of NHTSA.

An illustration of the battery is provided in Figure 3.3-1. The battery is “T” shaped and consists of 288 LG P1 pouch cells arranged in three modules. One side of each cell is adjacent to a cooling fin that contains a glycol/water solution designed to thermally manage the cell environment (both cooling and heating). From a numbering standpoint, the cells adjacent to the fins are; fin # times 2 minus 1 and fin # times 2. The first module (Module 1) is located in the tunnel between the two front seats and contains 90 cells and 45 cooling fins. The second module (Module 2) is located in the tunnel just in front of the backseat and contains 72 cells and 36 cooling fins. The third module (Module 3) is located under the back seat of the vehicle and contains 126 cells and 63 cooling fins. The modules are shown from left to right in Figure 3.3-1. A photograph of an individual cell and cooling fin are provided as Figure 3.3-2.

As a general description of the LG P1 cell, each cell is about 5 inches wide, 7 inches tall and about ¼ inch thick. Each cell consists of 33 layers of alternating sheets of different metals referred to as current collectors. There are 16 cathode sheets (lithium manganese coated aluminum) and 17 anode sheets (carbon coated copper) in a LG P1 cell. These sheets are separated by a thin, ceramic coated film of plastic (polyethylene) referred to as a separator. The lithium ions travel between the anode and the cathode through a liquid referred to as an electrolyte (lithium hexafluorophosphate ($LiPF_6$) dissolved in a carbonate solution). The cell casing consists of a polymer coated aluminum pouch.

The battery is equipped with a voltage and temperature monitoring system. The system consists of four circuits boards referred to as Voltage Temperature Sub Modules (VTSMs). The VTSMs are located on the top of each battery module. These sub modules and associated connections are potential short circuiting locations of the battery is exposed to battery coolant. The locations of the VTSMs are shown as the numbers on Figure 3.3-1.

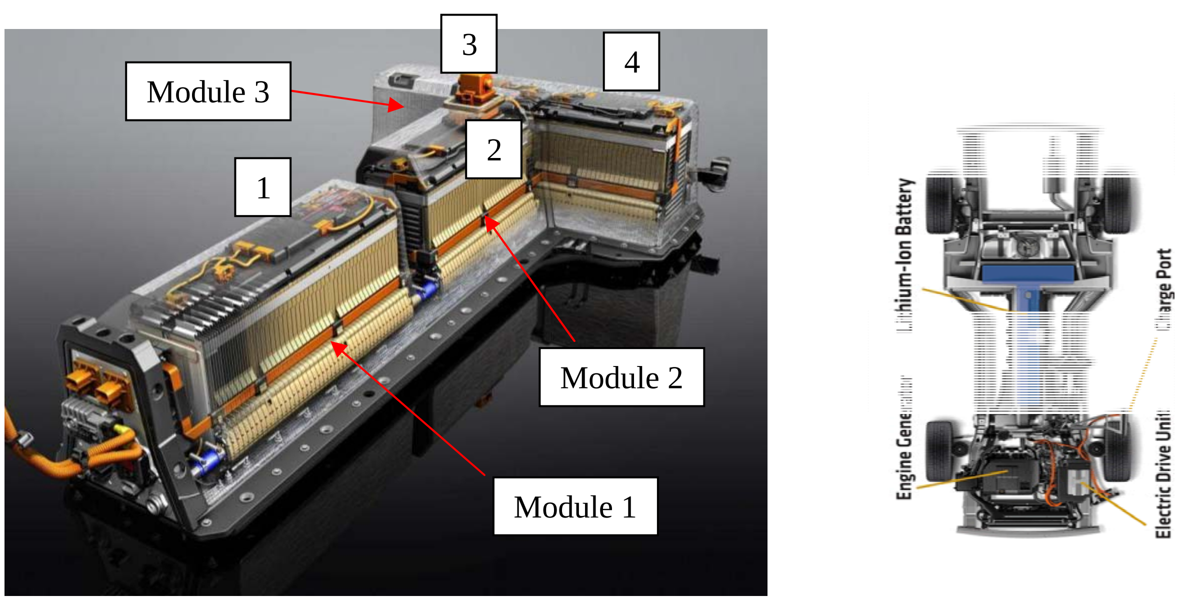


Figure 3.3-1. Battery Configuration and Location

Figure 3.3-2. LG P1 Cell and Cooling Fin

A photograph of a module is provided as Figure 3.3-3. Each module consists of a row of cells and cooling fins that are sandwiched together. The modules are held together using a rod assembly at the bottom and metal strap around the top (shown in white in Figure 3.3-3). There is a metal plate (black) located at each end of the module for strength. The cooling lines that contain the glycol/water solution are located in a plastic housing that is located at the bottom perimeter of each module. There are a number of circuit boards and electrical connections on the top of each module located under a plastic cover (black). The main power leads run along the side of each module about 1/3 of the way up (orange). Each lead consists of a number of copper straps encased in an orange plastic sheath.

Figure 3.3-3. Example Module (Typical Module Configuration)

3.3.1 Approach

The battery was disassembled at NHTSA VRTC during the period June 20–23, 2011. The modules were removed one at a time and the condition of each cell and cooling fin were documented. A procedure for removing the modules and documenting the findings was developed by GM. During the process, each cell and cooling fin is removed in sequence and numbered. Damaged cells were photographed in place (for the most part) but each cooling fin was removed, cleaned, numbered and photographed.

The modules were removed in a sequence from the highest to lowest number 3, 2, and 1. The first module inspected was Module 3 which is located under the back seat of the vehicle and contains 126 cells and 63 cooling fins. The fins were numbered starting on the driver's side of the vehicle (No. 1-63). The second module (Module 2) is located in the tunnel just in front of the backseat and contains 72 cells and 36 cooling fins (No. 64-99). These fins were numbered from the back of the vehicle to the front. The final module (Module 1) is located in the tunnel between the two front seats and contains 90 cells and 45 cooling fins (No. 100-144 also numbered back to front).

Precautions were taken to prevent additional damage when removing the cells and fins from the module. However, to start the removal process, a saws-all was required to cut away the cooling lines and the support rods that run along the bottom of each module. A photograph showing the disassembly of the battery is provided as Figure 3.3-4.

Figure 3.3-4. Overall Battery Condition Photograph

3.3.2 Observations

This section provides a high-level overview of the condition of the battery, modules, cooling fins and cells as observed during the inspection. Additional detail describing the area of origin and potential causes is provided in the following section.

A photograph of the battery after the cover had been removed is shown in Figure 3.3-5 (right photograph). As a reference, an unburned battery is shown in the photograph on the left (Figure 3.3-5). As shown in this figure, the battery was still fairly intact after the fire.

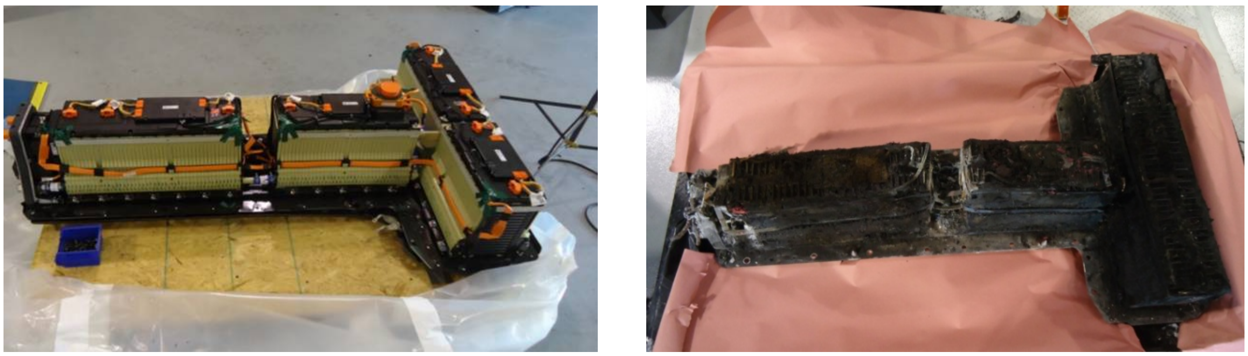


Figure 3.3-5. Overall Battery Condition Photograph

The first thing that was noticed was that the battery had been structurally damaged during the crash test. As shown in Figure 3.3-6 (left photograph), the battery was bent in the middle at the crash impact location. Specifically, the junction between Modules 1 and 2 had been pushed over about an inch toward the passenger side of the car and the cooling line that runs down the driver's side of the battery had been breached. This breach in the cooling system would have allowed the battery coolant to flow into the battery compartment and potentially create a short in the battery circuitry. In addition, the back of Module 1 had been dented-in at least an inch physically damaging the last few cells in the module (reference Figure 3.3-6 right photograph). The front of Module 2 had also been damaged by the impact but to a lesser degree.

Consistent with the damage to the battery cover, the greatest fire damage to the battery itself occurred in areas with the best access to oxygen. Specifically, the greatest fire damage occurred at the front of Module 1 and the crash damaged areas near the center of the battery between Module 1 and Module 2. The ends of Module 3 near the vent holes also showed more fire damage than in the center.

As a general observation, all of the visible combustible electronic components (wires, wire insulation, circuit boards, plastic housings, etc) were completely consumed by the fire. There was a limited amount of unburned plastic material located around the cooling line on the sides of the battery. This unburned material was melted and was covered with a layer of char which may have prevented the material from being completely consumed by the fire.

Figure 3.3-6. Physical Battery Damage

Prior to the discussion of the individual cells, a basic understanding of cell heating and likely consequences is required. There are three potential mechanisms or combinations of mechanisms that could have caused the cells in the Volt battery pack to heat-up:

1. An internal short within the cell caused by physical damage produced during the crash test,
2. An external short in the battery circuitry resulting in high current flow, and
3. External heating produced by burning materials near the cells and/or battery.

Independent of the cause, as the temperature of a cell increases; the electrolyte and organics begin to vaporize increasing the pressure within the cell. For a pouch cell, when the pressure within the cell reaches the critical value, the gases typically vent out of the casing near the positive and negative terminals (tabs) located at the top of the cell. This is structurally the weakest point in a typical pouch cell and is the only region of the cells in the Volt battery pack that is not supported by adjacent materials (i.e., battery casing, adjacent cells or cooling fins).

If the cell experiences an internal short due to damage to the separator, the cell may either vent out of the top or burn through the side of the cell casing depending on the nature of the internal short and the construction of the cell. In any case, the vented gases are flammable and can be easily ignited by external heat sources.

With respect to actual inspection, other than near the ends of each module, the cells were fairly intact except that all of the organics contained within the cells had been consumed leaving only the metallic anode and cathode sheets (reference Figure 3.3-7 left photograph). The organics contained within the cells located in the center of each module appeared to have vented out of the top of the cell (reference Figure 3.3-7 right photograph). As a general observation, the cooling fins appear to limit cell to cell propagation down the length of the module. However, the heat generated by the fire and the shorting of the modules caused all of the cells in the battery to react and burn.

The cells at the ends of each module showed significant damage near the top of the cells. There were a few cells at the end of the modules that had vented out of the side and burned a hole through the cooling fin as opposed to venting out of the top of the cell. These end locations have better access to oxygen (due to openings in the tunnel) and as a result, would have been hotter due to increased burning at this location. The increased heating to the end cells may have made them react more violently and/or weakened the cell casings and cooling fins at these locations. Additional discussion of these end cells is provided in Section 3.3.3.

There were at least seven areas where the battery had arced to the inside of the battery compartment during the fire. This arcing was the result of the structural metal bands that run around the top of each module becoming positively charged during the fire. There were multiple areas where the battery leads had shorted and fused to this metal band or module end plates once the insulation on the lead had been consumed by the fire. Figure 3.3-8 (left photograph) shows a positive lead fused to the front plate of Module 2. The right photograph shows the damage to the band produced by the arcing. As stated previously, this arcing typically cut an opening into the side of the battery compartment (i.e., an opening between the battery and occupant compartments). This arcing caused the cells to heat-up adding additional energy the overall event.

Figure 3.3-7. Typical Cell/Module Remains

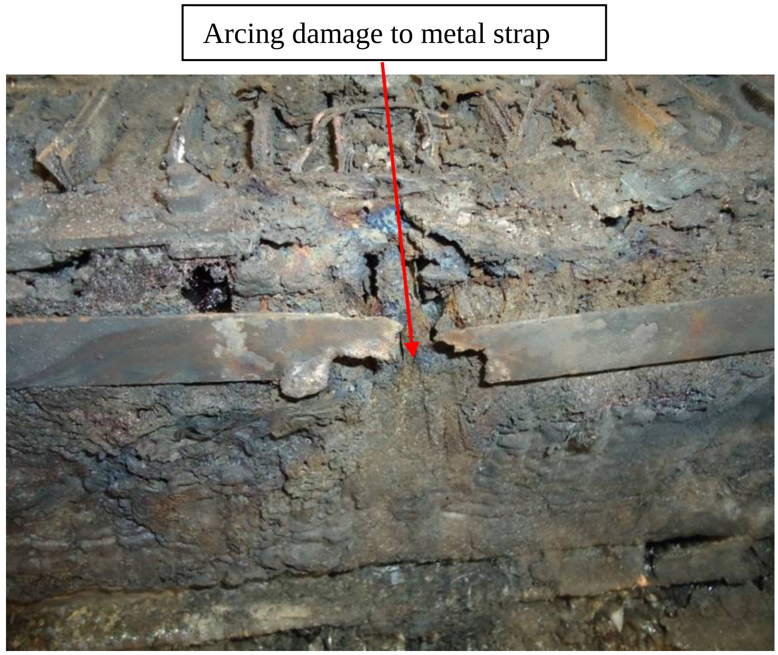


Figure 3.3-8. Typical Arcing Scenario/Remains

3.3.3 Cell Level Damage

The back end of Module 1 and the front end of Module 2 were both physically damaged during the crash test. An inspection of the battery revealed that the back of Module 1 had been dented-in at least an inch physically damaging the last few cells in the module. The front of Module 2 had also been deformed by the impact but to a lesser degree.

The entire battery was disassembled during inspection (i.e. all of the cells and cooling fins were removed and inspected) and the findings are summarized in the following sections. The discussion focuses primarily on the areas of the modules with physical damage and the fire damaged areas observed at the end of each module.

<u>Module 1 Findings</u>

Module 1 is located in the tunnel section of the battery compartment between the two front seats and contains 90 cells and 45 cooling fins. Per the GM procedures, the fins were numbered from 100–144 starting at the back of the module (the rear of the vehicle). The module was disassembled from the back to the front which started at the area where the crash damage was observed.

An inspection of the first few cells (cells 198–204, cooling fins 100–102) revealed that the anode and cathode metallic sheets and the separators had been damaged during the crash test. A side view and front view of this area is provided in Figure 3.3-9. Upon removal of the cells, a distinctive crease was observed in the anode and cathode sheets of these cells and is shown in the photograph in Figure 3.3-10. The cooling fins also showed a similar amount/type of damage.

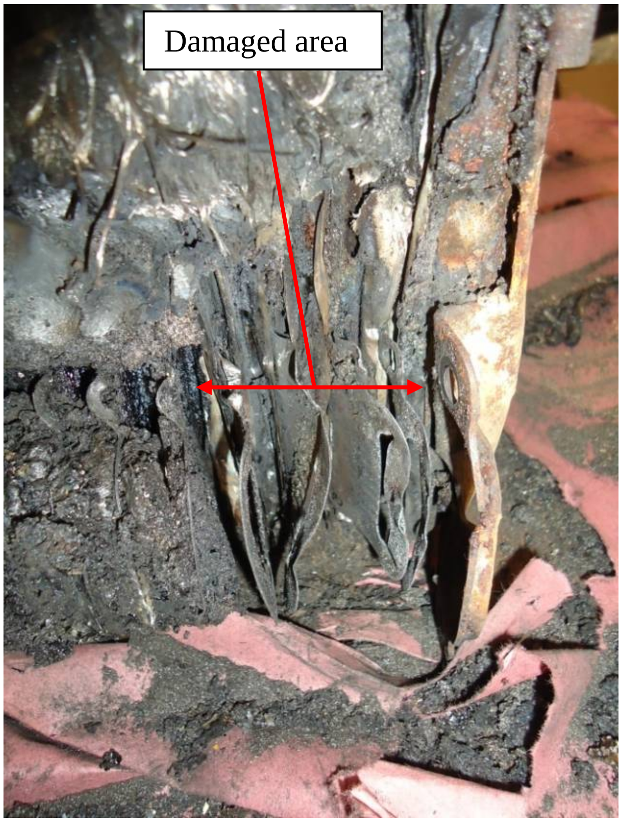
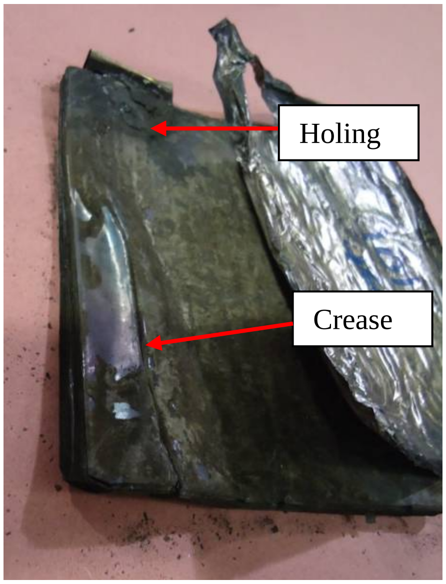


Figure 3.3-9. Side and Front View of Cells 198-204



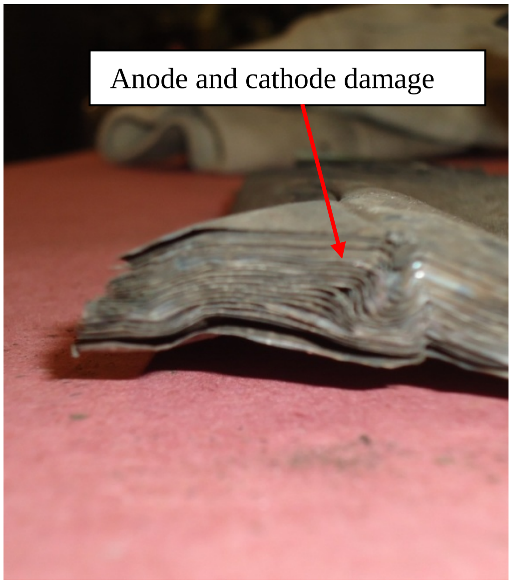


Figure 3.3-10. Example of Physical Damage to Cells 198-204

Cells 198–204 all burned through the cell casings and in many cases burned through the cooling fins separating the cells. There was holing through the anode and cathode sheets within the cells at these locations indicating that an internal short took place inside of the cell. Specifically, there was no oxygen to support combustion at these locations but the copper anode sheet was penetrated. Since copper melts at approximately 1080^{o}C, this must have been the result of an electrical short within the cell.

The holing and burn through locations were typically above the portions of the cells that were damaged during the crash test as shown in Figure 3.3-11. However, the location of the holing and burn through of the end cell group was near the middle of the cell. In general, the holing and burn through locations did not line-up between the cells indicating that this was not an event that cascaded longitudinally through the pack and may have been separate events.

It should be noted that the burn patterns through the cells at the damaged end of Module 1 were different than at the ends of the other modules. The burn patterns through the cells at the damaged end of Module 1 can be described as holing through and between the cells as opposed to a “V” pattern observed at the top of the cells at the other ends of the modules.

Even with the advances made by GM/LG on cell construction and chemistries, there is a good possibility that the physical damage to cells 198–204 (i.e., damage to the separator(s) within the pouch cells) that occurred during the crash test produced an internal short within the cell(s) that resulted in the release of flammable vapors (electrolyte) that were eventually ignited and initiated the fire within the Chevrolet Volt.

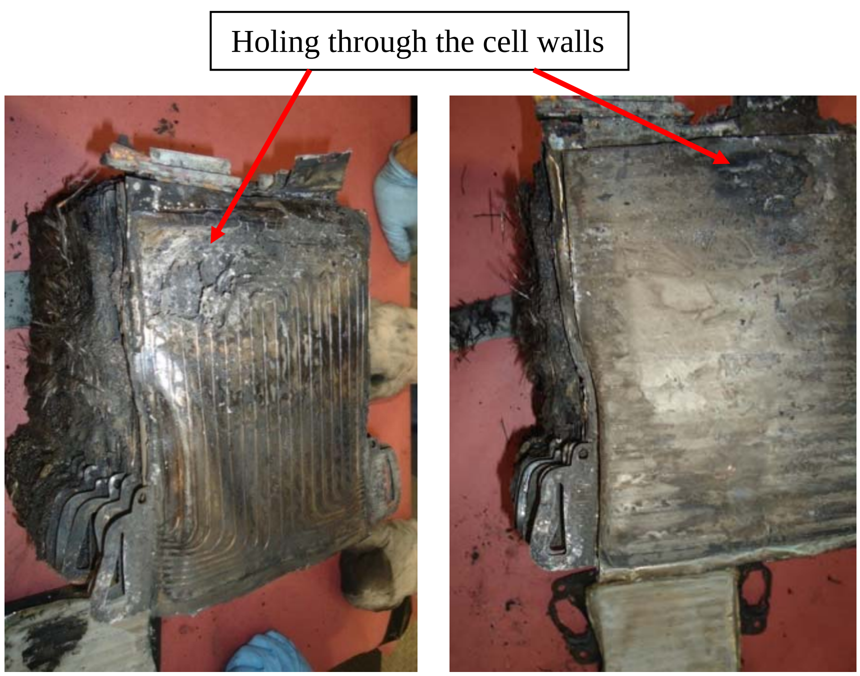


Figure 3.3-11. Remains of Cells 198–204

Module 2 Findings

Module 2 is located in the tunnel section of the battery compartment in front of the back seat and contains 72 cells and 36 cooling fins (No. 64–99). Per the GM procedures, the fins were numbered from 64–99 starting at the back of the module (the rear of the vehicle).

The initial inspection of battery pack indicated that the last few cells in Module 2 (cells 188–197, cooling fins 94–99) could have been damaged during the crash test. A side view of this area is provided in Figure 3.3-12. Upon removal of the cells, it was determined that the damage to the cell components (anode, cathode and separator) was superficial and did not appear to have caused an internal short within the cells; although the cells did undergo a thermal reaction during the event.

Figure 3.3-12. Side View of Cells 188–197

Cells 188–197 all burned through the side of the cell casing near the top of the cell and in many cases burned through the cooling fin indicating that a thermal reaction took place either inside or just above the cell. The burn through location was typically at the top of the cell between the cell terminals and produced a "V" shaped burn pattern as shown in Figure 3.3-13. In order for the copper current collector to have been destroyed, the exposure temperatures must have exceeded the 1080^{o}C melting point of copper.

The reaction of the cells at the front end of Module 2 was likely caused by external heating. The heating produced by the fire in Module 1 could have been adequate to melt the separator(s) near the top of cells 188–197 causing them to react and burn. In addition, the external shorting of Module 2 (shown in Figure 3.3-8) may have generated additional heat adding to the vulnerability of these cells.

Module Ends

The cells at the front end of Module 1 and both ends of Module 3 also had “V” shaped burn patterns similar to the one shown in Figure 3.3-13. Consistent with the findings of the previous discussion, these patterns were likely caused by external heating from a fire burning at these locations. Although these reactions were most likely caused by an external short, these are still considered to be “cell level” reactions since the current collector sheets were burned completely through at these locations.

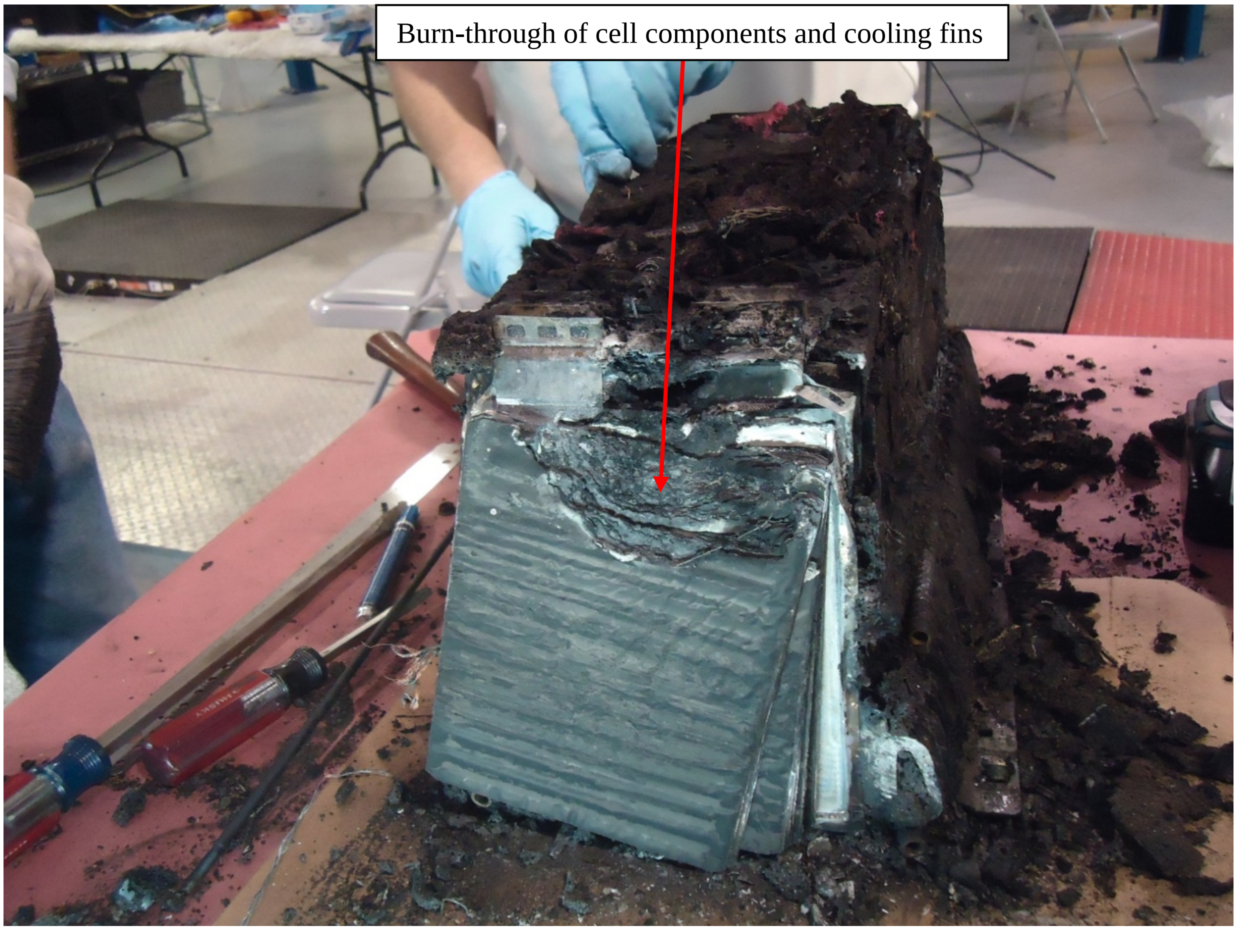


Figure 3.3-13. Remains of Cells 188–197 (“V” pattern)

3.4 Potential Origins and Causes

3.4.1 External Shorting

The battery cooling system was damaged during the side impact test allowing the coolant to leak into the battery case. During the post test rollover of the vehicle, the circuit boards and connectors located on top of the battery could have been wetted by the coolant. The exposure of the VTSM circuit boards and connectors on the top of the battery to the glycol battery coolant can produce electrolysis that can deposit a film of carbon on the surface of the electronics. This film can develop into an external short that generates heat and causes a current flow through the battery.

External shorting of the VTSM boards and/or connectors could initiate a fire in one of two ways. The first would be to slowly melt the plastic housing near the short until the plastic drips down onto the hot surface at which point it may ignite initiating the event. However, this ignition scenario does not provide the means to produce the overpressure in the occupant compartment that expelled the windshield from the car during the MGA fire. The second way would be to generate heat within the damaged cells due to current flow produced by the shorts on the VTSM boards and connectors. The second way is discussed further in the following section.

3.4.2 Cell Damage and Internal Shorting

Most standard, off-the-shelf lithium-ion batteries/cells react violently when physically damaged. Damage to the separator between the anode and the cathode can produce an internal short that can potentially generate enough heat to cause a cell to vent and/or catch fire [3, 4]. The current flow across the internal short produces heat that can cause the electrolyte and organics within the cell to vaporize. Once the critical pressure is produced inside of the cell, the cell ruptures, allowing the rapid release of the flammable gases contained within the cell. At this point, the reaction speeds up, generating even more heat which can ignite the remaining combustibles inside of the cell and/or the flammable gases venting from the cell.

At a cell level, the heating/vaporization rate and the total amount of gas produced are a function of the capacity of the cell, the state of charge of the cell at the time of the damage, and the degree of damage to the separator creating the internal short. As a result, this process can occur quickly or take days to complete, depending on the conditions. Less volatile chemistries and improved cell designs show promise for reducing this hazard. These general observations concerning off the shelf lithium-ion batteries do not reflect specific measures GM has taken to address the inherent risks of lithium-ion batteries.

Even with the advances made by GM/LG on cell construction and chemistries, there is a good possibility that the physical damage to cells 198–204 (i.e., damage to the separator(s) within the pouch cells and holing of the cell casings) that occurred during the crash test produced an internal short within the cell(s) that resulted in the release of flammable vapors (electrolyte) that were eventually ignited and initiated the fire within the Chevrolet Volt.

As stated previously, the exposure of the VTSM circuit boards and connectors on the top of the battery to the glycol battery coolant can produce electrolysis that can deposit a film of carbon on the surface of the electronics. This film can develop into an external short that generates heat and causes a current flow through the battery. The localized heating of the external short has the potential to ignite adjacent combustible materials. The current flow can cause additional heat generation within the damaged cells and can potentially cause damaged cells to react. In addition, removing all of the energy from the pack can cause adverse cell reactions depending on the rate the energy is removed and the health of the cells within the pack.

The overpressure event that occurred in the occupant compartment of the Chevrolet Volt at MGA was most likely caused by the ignition of flammable gases that were present in the occupant compartment at the onset of the fire. Due to the obstructed flow path between the battery and the occupant compartment of the vehicle (i.e. there was only a small hole through the battery cover and in the side of the tunnel and, the tunnel penetration was covered by padding and carpeting), a forceful cell venting scenario is the only conceivable way to produce a flammable gas mixture in the occupant compartment of the vehicle prior to ignition. An external short in the battery circuitry that causes localized heating that eventually leads to ignition of the plastic housings lacks the pressure to transfer unburned flammable gases into the occupant compartment of the vehicle. Regardless of the failure mechanism, the physical damage to the battery and battery cooling system produced during the side impact test was the root cause of this incident.

4.0 FINDINGS AND CONCLUSIONS

The conditions of the vehicles involved in the fire at the MGA facility are consistent with the fire originating within the Chevrolet Volt. There were significant differences in the damage to the Volt when compared to the other vehicles involved in the fire. The most notable was that the windshield and rear view mirror assembly had been blown out of the car and were lying on the street next to the vehicle with little (if any) heat damage to any of these components. The lack of heat damage to these components suggests that this overpressure event was the precursor to the fire that destroyed the four vehicles at the MGA facility between June 3–6, 2011.

During the initial inspection at the MGA facility, the battery was removed from the Chevrolet Volt and the conditions of the vehicle and battery were documented. The initial inspection revealed that the transverse stiffener located under the driver's seat had penetrated the tunnel section of the battery housing during the side impact test and damaged the lithium battery. The crash damage produced an opening between the battery housing and the occupant compartment of the vehicle. This opening would allow gases released by the battery during cell venting to enter the occupant compartment of the vehicle. The paint around the damaged area had been completely consumed and the steel was discolored which indicated a higher thermal exposure, and potential exposure to the reactive chemicals within the battery (electrolyte and or electrolyte combustion products) at this location. In general terms, this damaged area was exposed to different and more severe thermal conditions than the other areas inside of the battery housing.

After the initial inspection, the battery was then shipped to NHTSA's facility in East Liberty, Ohio where the battery was disassembled and each cell inspected for damage. The inspection revealed that the majority of the cells in the battery vented their organics out the top of the cell due to global heating of the battery pack and were fairly intact after the fire/event. The cells located in the front of Modules 1and 2 and at both ends of Module 3 vented out of the side of the casing near the top of the cell producing a "V" shape burn pattern between the cell terminals. These end locations have better access to oxygen (due to openings in the tunnel) and as a result, would have been hotter due to increased burning at these locations. The increased heating to the end cells made them react differently than the cells located deep within the battery/pack.

The back end of Module 1 and the front end of Module 2 were physically damaged during the crash test. An inspection of the battery revealed that the back of Module 1 had been dented-in about an inch physically damaging the last few cells in the module. The front of Module 2 had also been deformed by the impact but damage to the cells was minimal.

An inspection of the last 5 or 6 cells in Module 1 revealed that the anode and cathode metallic sheets and the separators had been damaged during the crash test. There is a good possibility that this physical damage produced an internal short within the cell(s) that resulted in the release of flammable gases (electrolyte) that were eventually ignited during the reaction. The heating of this internal short could have been increased due to the damage of the VTSM cards caused by the exposure to the battery coolant during the rollover portion of the test. All of the other scenarios that were considered were much more complex and consisted of numerous events that needed to occur sequentially in order for the fire to have occurred.

Occam's Razor is the scientific precept that all things being equal, the simplest solution is usually the correct one. An internal short caused by the physical damage to the battery produced during the crash test is the simplest and most likely solution and the cause of the fire. Regardless of the failure mechanism, the physical damage to the battery and battery cooling system produced during the side impact test was the root cause of the incident.

In summary, based on all of the physical evidence and analysis conducted during this effort, the following scenario can be stated with a reasonable degree of certainty. During the crash test, the transverse stiffener located under the driver's seat penetrated the tunnel section of the battery compartment and intruded into the side of the lithium-ion battery. The physical damage to the battery and the battery cooling system was the root cause of this incident. Although it is difficult to determine the exact mechanism and series of events that lead to the fire, it is more likely than not that the damage to the cells at this location created an internal short that resulted in the forceful release of flammable gases (vaporized electrolyte) into the occupant compartment of the vehicle. These gases were eventually ignited by the reaction and generated enough pressure to expel the windshield and ignited the contents of the occupant compartment. The fire eventually consumed the Volt and spread to the adjacent vehicles.

At the time of this inspection, this case was the only example of a post crash battery fire known by this author to have occurred in an electric vehicle battery. Since then, additional Chevrolet Volt full battery pack tests have been conducted that include both physical damage to the battery and the exposure of the electronics to coolant. These tests have produced both electrical arcing and fires.

The opinions contained in this report are based on the information available at the time the analysis was performed. These opinions are based on a reasonable degree of certainty for experts in the fire protection engineering field. If additional information becomes available, the author reserves the right to re-evaluate these opinions.

Gerard G. Back
Senior Engineer
410-737-8677 x239
jback@haifire.com

5.0 REFERENCES

[1] Morrill, J., "NHTSA 060411 Fire Inspection," MorrFire Rpt. #02215, July, 2011.

[2] Report Number: SPNCAP-MGA-2011-081, U.S. Department of Transportation, Washington, DC, May 18, 2011.

[3] Power Sources Technology Group, Sandia National Laboratories, "Li Ion Battery Abuse Tolerance Testing – An Overview," presented to *AQMD*, July 12, 2006.

[4] Orendorff, C.J., Roth, P., and T. Lambert, "Lithium-Ion Cell Safety Issues of Separators and Internal Short Circuits," *218th ECS Meeting*, Las Vegas, NV, October 10–15, 2010.

Report No. GTL-DOT-11-VOLTBAT

CHEVROLET VOLT BATTERY PACK TESTS

Prepared by

GENERAL TESTING LABORATORIES, INC.
1623 LEEDSTOWN ROAD
COLONIAL BEACH, VIRGINIA 22443

January 20, 2012

FINAL REPORT

Prepared For

U. S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
ENFORCEMENT
OFFICE OF VEHICLE SAFETY COMPLIANCE
1200 NEW JERSEY AVE., SE
WASHINGTON, D.C. 20590

Technical Report Documentation Page

<table>
<tr><td>1. Title and Subtitle
Chevrolet Volt Battery Pack Tests</td><td>2. Report Date:
January 20, 2012</td></tr>
<tr><td rowspan="2">3. Author(s)
Alan Aylor, General Testing Laboratories, Inc.
Gerard Back, Hughes Associates, Inc.
Clint Winchester, NSWC – Carderock Division</td><td>4. Performing Organ. Rep#
GTL-DOT-11-VOLTBAT</td></tr>
<tr><td>5. Contract or Grant No.(s)
DTNH22-12-P-01452
DTNH22-12-P-01464</td></tr>
<tr><td>6. Performing Organization Name and Address
General Testing Laboratories, Inc.
1623 Leedstown Road
Colonial Beach, Va 22443</td><td>8.Type of Report and Period Covered:
November 4 2011 to January 6, 2012</td></tr>
<tr><td colspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
National Highway Traffic Safety Admin. Enforcement
Office of Vehicle Safety Compliance (NVS-220)
1200 New Jersey Ave., S.E.,
Washington, DC 20590</td></tr>
</table>

Prepared By: General Testing Laboratories, Alan Aylor

Prepared By: Hughes Associates, Gerard Back

Prepared By: NSWC – Carderock, Clint Winchester

Date: January 20, 2012

FINAL REPORT ACCEPTANCE BY OVSC:

Accepted By: Charles Case

Accepted Date: 1/20/2012

CONTENTS

Executive Summary

A test program was established to narrow down the potential causes of the MGA fire and to identify the variables that may have contributed to the event. The test program was conducted at General Testing Laboratories in Colonial Beach, Virginia. Six tests were conducted on Chevrolet Volt battery packs, not entire vehicles.

The first three tests consisted of damaging the battery in a similar manner as that occurred during the side impact vehicle test conducted on the Chevrolet Volt at the MGA facility in May, 2011. A separate battery was used for each test. A battery cooling system representative of that installed in the Volt was attached to the battery during each test. This allowed the coolant contained in the system to flow into the battery housing as during the MGA test.

During each of the first three tests, after the battery was impacted, the battery was x-rayed and rotated around the longitudinal centerline, 360 degrees, at 90 degree increments. Once the battery was rotated 90 degrees, the battery was held in that position for five minutes prior to rotating to the next position. This is representative of the post crash rollover procedures conducted by MGA on the Chevrolet Volt during the test in May.

After the first two batteries were tested, they were placed in a shed for surveillance for a period of four weeks. The shed was heated to control temperature between 70°F and 90°F. Less than a week into the four week surveillance period, the battery damaged during Test 2 caught fire and destroyed the contents of the shed including the battery from Test 1. During Test 3, while the battery was at 180° of rotation, an event occurred that jetted sparks and flames from the battery housing in the area of the impact block for about a second.

To further investigate the anomalies observed during these first three tests, an electrolysis experiment was conducted on the battery coolant using a variable power supply and two copper wires. The current flow through the coolant and associated electrolysis rapidly produced metallic compounds and carbon particles that floated on the coolant surface during the experiment. Compounds like these are believed to have created the external shorts in the wiring and circuit boards that occurred during the post test surveillance period.

In the remaining three tests (Tests 4-6), the parameters believed to have contributed to the MGA event were further isolated. In tests 4 and 5 coolant was introduced into undamaged batteries and then subjected to a rollover. Test 5 was a repeat of Test 4 with the battery externally grounded to the frame to create the current path. Test 6 consisted of impacting to damage the battery but without the rollover that exposes the wiring and circuitry to the coolant solution.

After the tests 4-6 were completed, the batteries were placed in separate heated sheds for surveillance. Less than a week into the surveillance period, the Test 5 battery caught fire due to shorting of a connector on the passenger side end of battery Module 3. The fire was quickly suppressed by discharging water into the battery case. Water flow into the battery case was continued until the test team returned to the facility (approximately 18 hours later). The batteries for Test 4 and Test 6 produced minor heating during the surveillance period but never caught fire.

The results of these tests demonstrate that intrusion damage to the battery with coolant leakage followed by a rollover has the potential to expose energized battery components to the battery cooling solution. A fire hazard is produced when the electrically conductive liquid cooling solution comes in contact with the energized battery components (terminals and circuits). The ensuing fire can occur relatively quickly or take weeks to develop. There are little if any precursors to the fire event (i.e. there are no warning signs that an event is about to occur).

Although two of the batteries caught fire during this test program and one battery experienced an arcing event, the conditions that occurred at the MGA facility in May 20, 2011 were never truly replicated. Specifically, the conditions to over pressurize the occupant compartment of the vehicle and displace the windshield without causing heat damage and/or smoke deposition were never produced.

1.0 INTRODUCTION

A fire occurred at the MGA Research facility in Burlington, Wisconsin over the weekend of June 3–6, 2011 involving a 2011 Chevrolet Volt.

NHTSA initiated a program to determine the cause of Chevrolet Volt fire. This program consisted of a thorough forensic examination of the burned vehicle and battery, a supplemental Chevrolet Volt crash test and a series of battery pack tests conducted at General Testing Laboratories (GTL) in Colonial Beach, Virginia. This report summarizes the battery pack tests and monitoring conducted at GTL during November and December 2011 and January 2012.

2.0 TEST ITEM DESCRIPTION

Six 2011 Chevrolet Volt Battery packs were tested during this program. For the remainder of this report, the term "battery" will refer to the lithium-ion propulsion battery in the Volt. Three of the batteries were removed from NHTSA vehicles and three were new batteries supplied by General Motors. The table below identifies each battery by test number.

Test Number	Description
1	Removed from Vehicle
2	Removed from Vehicle
3	Removed from Vehicle
4	New
5	New
6	New

All batteries were inspected for mechanical and electrical soundness and were fully charged to a nominal 390 volts 87% state of charge (SOC) prior to testing.

An illustration of the battery is provided in Figure 2.1. The battery is "T" shaped and consists of 288 LG P1 pouch cells arranged in three modules. One side of each cell is adjacent to a cooling fin that contains a glycol/water solution designed to thermally manage the cell environment (both cooling and heating). The first module (Module 1) is located in the tunnel between the two front seats and contains 90 cells and 45 cooling fins. The second module (Module 2) is located in the tunnel just in front of the backseat and contains 72 cells and 36 cooling fins. The third module (Module 3) is located under the back seat of the vehicle and contains 126 cells and 63 cooling fins. From a numbering standpoint, the cells adjacent to the fins are; fin # times 2 minus 1 and fin # times 2. The cooling fins are numbered from the back of the battery working forward (i.e. fin 1 is on the driver's side end of Module 3). The modules are shown from left to right in Figure 2.1. A photograph of an individual cell and cooling fin are provided as Figure 2.2.

As a general description of the LG P1 cell, each cell is about 5 inches wide, 7 inches tall and about ¼ inch thick. Each cell consists of 33 layers of alternating sheets of different metals referred to as current collectors. There are 16 cathode sheets (lithium manganese coated aluminum) and 17 anode sheets (carbon coated copper) in a LG P1 cell. These sheets are separated by a thin, ceramic coated film of plastic (polyethylene) referred to as a separator. The lithium ions travel between the anode and the cathode through a liquid referred to as an electrolyte which is a carbonate solution containing lithium hexafluorophosphate ($LiPF_6$). The cell casing consists of a polymer coated aluminum pouch.

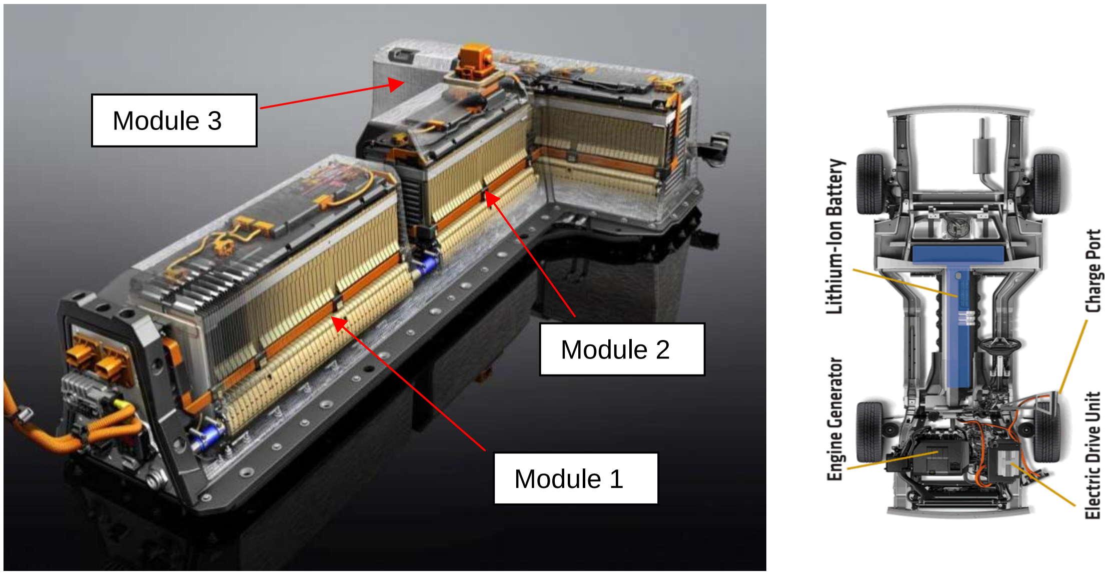


Figure 2.1 Battery Configurations and Location

Figure 2.2 LG P1 Cell and Cooling Fin

The battery is equipped with a voltage and temperature monitoring system. The system consists of four circuits boards referred to as Voltage Temperature Sub Modules (VTSMs). The VTSMs are located on the top of each battery module. The locations of the VTSMs are shown as the numbers on Figure 2.1.

The main power lines, referred to as bus bars, run along the outside of each module and can be seen in Figure 2.1 as the orange stripes along the sides of each module.

3.0 BATTERY INSTRUMENTATION

With the exception of voltage measurement, all of the instrumentation described in this section was installed by The Naval Surface Warfare Center – Carderock Division.

3.1 VOLTAGE

Battery voltages were monitored during and after testing by utilizing the GM Can Bus and data acquisition software recorded on a separate computer for each battery.

3.2 TEMPERATURE

Type K thermocouples were installed at the following locations.

Thermocouple Number	Location
1	Top of forward electronics (VITM)
2	Top of positive bus bar forward of module 1
3	Top of black connector for VTSM* 1 Module 1
4	Center Top of VTSM 1 Module 1
5	Center Bottom of VTSM 1 Module 1
6	Top on negative bus bar between Modules 1 and 2
7	Top of black connector for VTSM 2 Module 2
8	Center Top of VTSM 2 Module 2
9	Center Bottom of VTSM 2 Module 2
10	Top of black connector for VTSM 3 Module 3 Passenger Side
11	Center Top of VTSM 3 Module 3 Passenger Side
12	Center Bottom of VTSM 3 Module 3 Passenger Side
13	Top of black connector for VTSM 4 Module 3 Driver Side
14	Center Top of VTSM 4 Module 3 Driver Side
15	Center Bottom of VTSM 4 Module 3 Driver Side

*VTSM refers to “Voltage and Temperature Sub Module”

The thermocouples were monitored using an Argent 34970A data acquisition/switch unit. The data was continuously recorded throughout the testing and long term monitoring. This digital data has been supplied under separate cover.

3.3 VIDEO

The batteries used in tests 1, 2 and 3 had three internal miniature video cameras and led lights installed inside the batteries.

The testing was also monitored with stationary and hand held video cameras as required. For long term monitoring additional video cameras were installed in the storage sheds. All video was recorded on hard drives and has been delivered under separate cover.

3.4 GAS DETECTION

For the gas analysis portion of testing, Carderock used a Crowcon TriplePlus+ gas detector. It was configured to measure four gases: methane (CH_4), ammonia (NH_3), sulfur dioxide (SO_2), and volatile organics (VO). Methane concentration was expressed using lower explosive limit values, and the remaining gases NH3, SO2 and VO had their concentrations recorded in parts per million (ppm).

The test setup required a 50 foot polyethylene tubing to extend from the battery cases to the Crowcon inlet port. A pump was installed inside of the Crowcon, which pulled the air source from the testing location to the internal sensors. When the gases reached the sensor, they exited the Crowcon through the inlet port. The outlet port was instrumented with a polyethylene tubing long enough for the exhaust to exit safely.

Tests 1-3

For the first three tests, the Crowcon used a very small pump that was unable to bring air from the battery to the sensors. In this case, the tubing from the battery case, sealed by putty, went directly to the Crowcon (Figure 3.1). The data from these tests were unreliable. This is attributed to the small pump. The pump was not powerful enough to handle the resistance caused by the 50 feet of tubing necessary to extend from each of the batteries to the Crowcon.

Figure 3.1 Battery-Crowcon Configuration for Tests 1-3

Test 4-6

The next series of tests used a different configuration. Because the internal pump wasn't sufficient, another vacuum pump was added to the end of the system. This ensured that battery out-gassing would reach the sensors inside of the Crowcon. In this case, the polypropyelene tubing extended from inside of the battery case to the inlet port of the Crowcon, and the second vacuum pump was attached to the outlet port of the Crowcon (Figure 3.2).

Figure 3.1. Battery-Crowcon Configuration for Tests 4-6

The three batteries were continuously monitored and recorded for gas production, after impact. All three batteries had equal lengths of tubing, which were combined, using brass compression fittings; these fed into one polypropylene tube, which went to the Crowcon and then to the Vacuum Pump.

The data collected from the Crowcon was accessed using the Portables PC software, provided by Crowcon. The gas data was continuously recorded during testing and long term monitoring. The data has been supplied under separate cover.

4.0 TEST SETUP

4.1 IMPACTOR BLOCK

NHTSA designed an impactor block to replicate the damage that the Volt battery received during the 214 pole test that resulted in a fire. NSWC – Carderock fabricated three of these impactor blocks and supplied them to GTL for the battery impact testing. See photograph at Figure 4.1.

Figure 4.1 Impactor Block

The impactor block was shaped to simulate the side of the tunnel and stiffener that penetrated the battery during the test at MGA. The impactor block was made of HY100 steel plate. The block was installed on the driver's side of the battery at the junction between Modules 1 and 2. Two 1" diameter rods were connected to the impactor block, run through the opening between the two modules and through a wood block assembly on the opposite side of the battery. Crimp rings were installed on the rods in the center of the wooden block to keep the device in compression after impact. A photograph of the impactor block assembly is shown in Figure 4.2. Photographs of the impactor block in position both before and after impact are shown in Figure 4.3.

Figure 4.2 Impactor Block Assembly

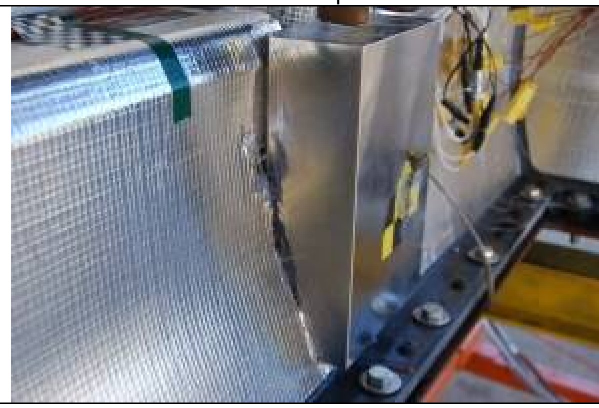
Before Impact	After Impact
	

Figure 4.3 Sample Impactor Block Penetration

4.2 BATTERY CRADLE

NSWC Carderock designed and fabricated three cradles to support the batteries during testing, rollover, and long term monitoring.

The primary design features of the Chevrolet Volt battery cradle allow the battery pack and tray to maintain system level structural integrity during component level testing. Due to the nature of the test series, the composite shell of the battery pack was required to be completely unobstructed from both driver and passenger sides. Factory installation requires the battery pack to be fastened to the chassis of the vehicle from the underside of the pack, distributing the load of the battery pack to the chassis by means of fasteners and metallic standoffs which are integrated into the composite shell at each of the structural bolt locations. The cradle designed to constrain the pack during this test series was required to support the pack from the underside rather the top, by means of a steel frame deemed structurally comparable to the chassis of the Chevy volt. The installation of the pack to the frame, utilized the factory installed standoffs as well as additional standoffs on the underside of the pack to mimic the distribution of stresses seen by the battery and tray during factory installation. During the test, the composite cover would be attached using factory hardware followed by the fastening of the fully assembled battery pack to the cradle, utilizing all of the factory bolt locations.

The battery cradle was designed to transfer forces seen by the pack through the cradle by means of half inch steel transfer plates mounted to the forward and rear sections of the battery pack, perpendicular to the forward- rear axis of the pack. The battery cradle was supported vertically and horizontally during testing by GTL’s battery impact support fixture to provide adequate axial energy transfer to the battery during the test.

Additional test procedures required the battery to be rotated 360 degrees about the forward rear axis of the pack. To accomplish this, two 1000 pound rated engine stands were attached to the steel transfer plates, about the assembly's center of gravity, on the forward and rear ends of the cradle. The use of such engine stands allowed for full rotation of the test item as well as locking in position at 90 degree intervals. Throughout the procedure both engine stands remained attached for safety, transportation and storage purposes. See photograph at Figure 4.4.

Figure 4.4 – Battery Cradle with Engine Stand & Battery

4.3 SUPPORTS

GTL designed and fabricated supports that were attached to its fixed impact barrier to hold the battery during testing. See photograph at Figure 4.5. These supports also acted as a stop for the impacting moving barrier.

Figure 4.5 – Battery supports

4.4 MOVING BARRIER

GTL utilized its SAE J972 moving rigid barrier common carriage with a flat impact surface attached for impact testing of the batteries. A cone shaped jack stand was attached to the barrier face, herein after referred to as the “Stinger”. See photograph at Figure 4.6. The stinger has a 3 inch diameter acme threaded nose that provides a means to adjust the amount of stinger protrusion outward from the moving barrier face. See photograph at Figure 4.7.

Figure 4.6 – Stinger attached to moving barrier face

Figure 4.7 - Stinger

4.5 COOLING SYSTEM

A cooling system was assembled to simulate the one that is installed in the Chevrolet Volt and was attached to the battery during each test. This allowed the coolant contained in the system to flow into the battery housing as observed during the MGA test. The cooling system consisted of a heat exchanger, a coolant reservoir, a coolant pump and the associated hoses to connect all of the components together. A photograph of the battery cooling system is shown in Figure 4.8.

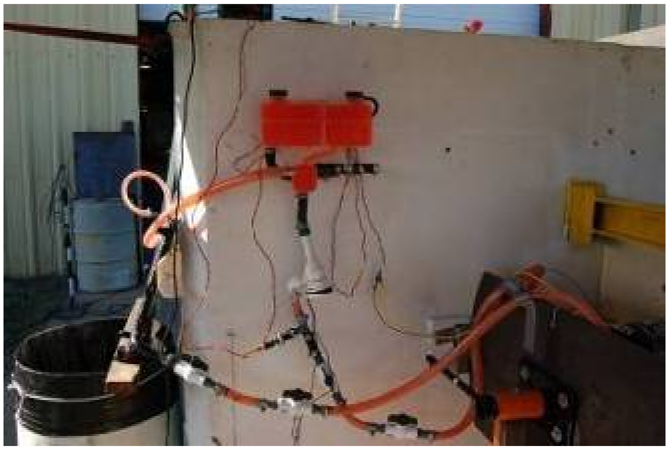


Figure 4.8 Battery Cooling System Test Setup

The first three tests were conducted with a 50/50 mixture of commercially available Prestone DEX-COOL and de-mineralized water. The Prestone DEX-COOL is approved by GM for use in GM vehicles. The final three tests were conducted with a 50/50 mixture of GM DEX-COOL and de-mineralized water purchased from a General Motors dealer.

5.0 TEST PROCEDURE

The charged battery and cradle assemblies were placed on the fixed barrier support fixture. Next the impact block and guide system were positioned on the battery. The cooling system was connected and coolant was circulated through the battery until there was no evidence of entrapped air in the coolant. The circulation pump was then turned off.

The voltage monitoring, thermocouples and gas detection instrumentation was connected to the battery and checked out. See photograph at Figure 5.1.

Figure 5.1 Thermocouples & Gas Detection Instrumentation connected to Battery

The distance from the moving barrier stops to the impact block was measured and the Stinger was adjusted to produce the desired penetration of the impact block into the battery. The moving barrier was accelerated to test speed using GTL's crash test monorail and tow system. Speed was measured using GTL's 3 foot speed trap and Systron Donner counter to measure time. Speed was measured approximately one foot prior to impact of the Stinger into the impact block. The impact block traveled forward into the battery until the moving barrier bottomed out on the battery supports/stops. After impact the battery was photographed and the instrumentation was checked.

The battery remained on the support fixture for approximately one hour while it was being x-rayed. After completion of x-rays the battery/cradle was removed from the support fixture and an FMVSS 305 type rollover was initiated. The battery was manually rolled over taking approximately one minute to rotate each 90° increment and pausing for five minutes at the 90°, 180° and 270° increments.

Coolant fluid leaking from the battery was collected during rollover. After completion of the rollover, the battery/cradle assemblies with instrumentation attached were moved to storage sheds for long term monitoring. The sheds were heated to control temperature between 70°F and 90°F.

5.1 ROLLOVER PROCEDURES

For tests that included rollover, the battery was rotated around the longitudinal axis 360 degrees at 90 degree increments as shown in Figure 5.2. The battery was rotated toward the passenger side of the vehicle. Once the battery was rotated each 90 degree increment, the battery was held in that position for five minutes prior to rotating to the next position. This is representative of the post crash procedures used by MGA on the Chevrolet Volt during the test in May 2011.

0 degrees	90 degrees	180 degrees	270 degrees	360 degrees

Figure 5.2 Battery Rollover Photographs

5.2 LONG TERM MONITORING

After the test procedures were completed, the batteries were placed inside of sheds for long term monitoring. The batteries were stored and monitored for a period of four weeks. The instruments installed on each battery were scanned at one minute increments for the entire period.

Each shed was equipped with at least one video camera to visually monitor the battery and the conditions in the shed. Each shed was also equipped with a photo/ion smoke detector connected to an auto-dialer. In the event of an alarm, the auto-dialer would notify lab personnel of the incident. During the last three tests (Tests 4, 5 and 6), the data acquisition system was also programmed to provide an audible alarm if the battery temperatures exceeded 40^{o}C. In addition a hose fitting and shut off valve was added to the battery case so that the battery case could be flooded with water in case of a fire event.

6.0 TEST OBJECTIVES

Six tests were conducted during this program. All six tests were conducted on Chevrolet Volt battery packs, not complete vehicles. A brief description of rationale for the test is provided in the Table below. Additional details are provided in the following paragraphs.

Battery Pack Test Description and Rationale

Test No.	Rationale
1	Reproduce the battery damage and conditions that occurred during the side impact test and roll over at MGA
2	Reproduce the battery damage and conditions that occurred during the side impact test and roll over at MGA
3	Reproduce the battery damage and conditions that occurred during the side impact test and roll over at MGA
4	Reproduce the conditions that occurred during the roll over at MGA (i.e. the exposure of the electronics to the coolant) without the battery being damaged
5	Reproduce the conditions that occurred during the roll over at MGA (i.e. the exposure of the electronics to the coolant) without the battery being damaged but the negative bus bar was shorted to ground
6	Reproduce battery damage that occurred during the side impact test at MGA without exposing the components to the coolant

The first three tests consisted of reproducing the battery damage and conditions that occurred during the side impact test conducted on the Chevrolet Volt at the MGA facility in May, 2011. A separate battery was used for each test.

During the remaining three tests, the parameters believed to have contributed to the MGA event were further isolated. Specifically, during Test 4, the battery was not physically damaged but the electronics were exposed to the coolant solution by pouring a known quantity of coolant solution in the battery case and rotating the battery as described above. Test 5 was a repeat of Test 4 except that the battery negative bus bar was externally grounded to the frame to create a current path. Test 6 consisted of physically damaging the battery without exposing the wiring and circuitry to the coolant solution.

After the test procedures were completed, the batteries were stored and monitored for a period of four weeks. As a refresher, the MGA fire occurred about three weeks after the side impact test was conducted.

7.0 BATTERY PACK TEST RESULTS

7.1 BATTERY PACK TEST RESULTS OVERVIEW

An overview of the six tests conducted during this program is provided in the table below.

Test # / Date	Type of Test	Intentional Grounding	Coolant in Battery Case: How Introduced	Coolant in Battery Case: Amount (L)	Test Speed (MPH)	Impactor Displacement Setting (Inches) **NOTE 1**	Notable Observations
1 11/16/11	Impact with Rollover	None	Leakage due to impact	2.871	7.58	2 ½	Destroyed during the 11/24 fire initiated by Test 2 battery
2 11/17/11	Impact with Rollover	Impact Block Grounded to Battery Frame	Leakage due to impact	2.951	6.80	2 15/16	Battery caught fire on 11/24. a week after the test. Fire originated in Module 3
3 11/18/11	Impact with Rollover	Same as Test 2	Leakage due to impact	4.041	6.38	3 9/16	Spark and Flames jetted from the pack at the 180° mark of rollover. Battery disassembled. No surveillance period
4 12/05/11	Rollover	None	Poured through Flooding Port	2.341	N/A	N/A	Minor Heating, Discolored VTSM 1 wiring
5 12/05/11	Rollover	Negative Bus Bar Grounded to Battery Frame	Poured through Flooding Port	3.20	N/A	N/A	Rapid electrolysis observed at the 180°-270° mark. Battery caught fire on 12/12/11, a week after the test.
6 12/06/11	Impact with Rollover	Same as Test 2	Leakage due to impact	5.07	6.86	3 ¼	Minor Heating, One Cell Group dropped to .2 volts.

NOTE 1: X-rays were used as a non-invasive method of assessing the post impact internal structural deformation to the battery. The x-rays were compared to the previous x-rays of the MGA side impact damaged battery that resulted in a fire. This information along with physical measurements were used as an aid in making adjustments to the impactor displacement and moving barrier speed for each test.

The first three tests consisted of damaging the battery and conducting a post test rollover in a similar manner to the side impact test conducted on the Chevrolet Volt at the MGA facility in May, 2011. Once the batteries were damaged during the first two tests and the test procedures were completed, the batteries were placed in a shed under surveillance for a period of four weeks. Less than a week into the four week surveillance period, the battery damaged during Test 2 caught fire and destroyed the contents of the shed including the battery from Test 1.

During Test 3, while the battery was inverted, an event occurred that jetted sparks and flames from the battery housing for about a second. An assessment of the battery remains from the first three tests indicated that the exposure to the coolant solution during the post damage roll-over was creating external shorts in the battery wiring and circuitry.

For the remaining three tests, the parameters believed to have contributed to the MGA event were isolated. Specifically, during the fourth test, the battery was not physically damaged but the electronics were exposed to the coolant solution. The fifth test was a repeat of the fourth with the battery externally grounded to the frame to create the current path produced by the physical damage to the battery in the MGA side impact test. The sixth test consisted of physically damaging the battery without exposing the wiring and circuitry to the coolant solution.

After the test procedures were completed for Tests 4, 5 and 6, the batteries were placed in separate sheds for surveillance. Less than a week into the surveillance period, the battery from Test 5 caught fire due to shorting of a connector on the passenger side end of battery Module 3. The fire was quickly suppressed by discharging water into the battery case. The battery was submersed until the test team had returned to the facility (approximately 18 hours later). The batteries from Test 4 and Test 6 produced minor heating during the surveillance period but never caught fire. The details of each test are provided in the following sections.

7.2 TEST 1 AND TEST 2 DETAILED RESULTS

Test 1 and Test 2 were designed to reproduce the physical damage and conditions that occurred during the side impact test conducted at the MGA facility in May. Test 1 was conducted on November 16th and Test 2 was conducted on November 17th, 2011.

There were only two minor differences between the two tests. During Test 1, the impactor block was not intentionally grounded to the mounting frame as was the case for Test 2. In addition, the degree of physical damage was slightly increased for Test 2 by adjusting the depth of impact and increasing the test impact velocity. A photograph and an X-ray of the damage for the two tests are provided in Figures 7.1 and 7.2.

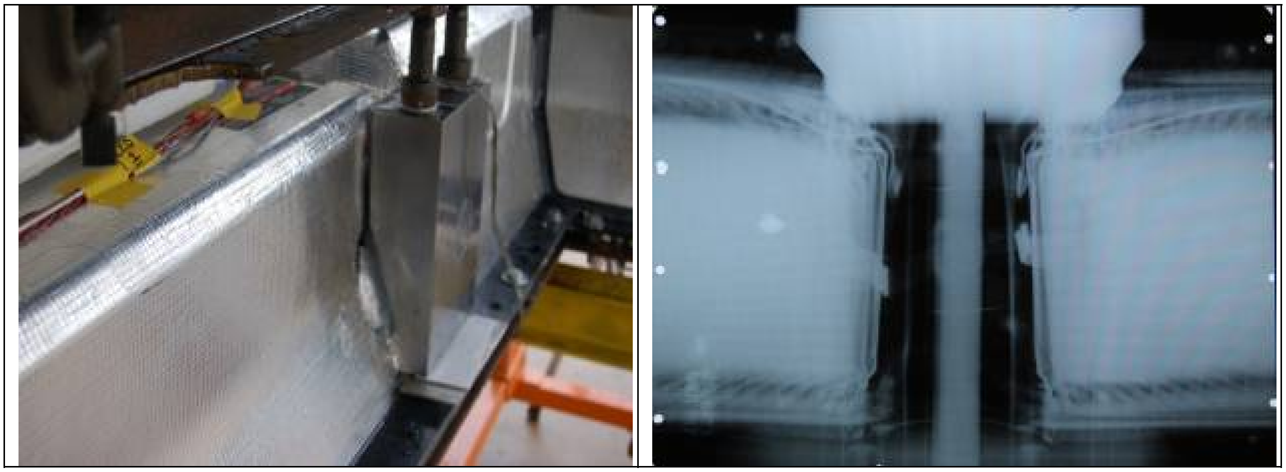


Figure 7.1 - Test 1 Battery Damage and X-Ray

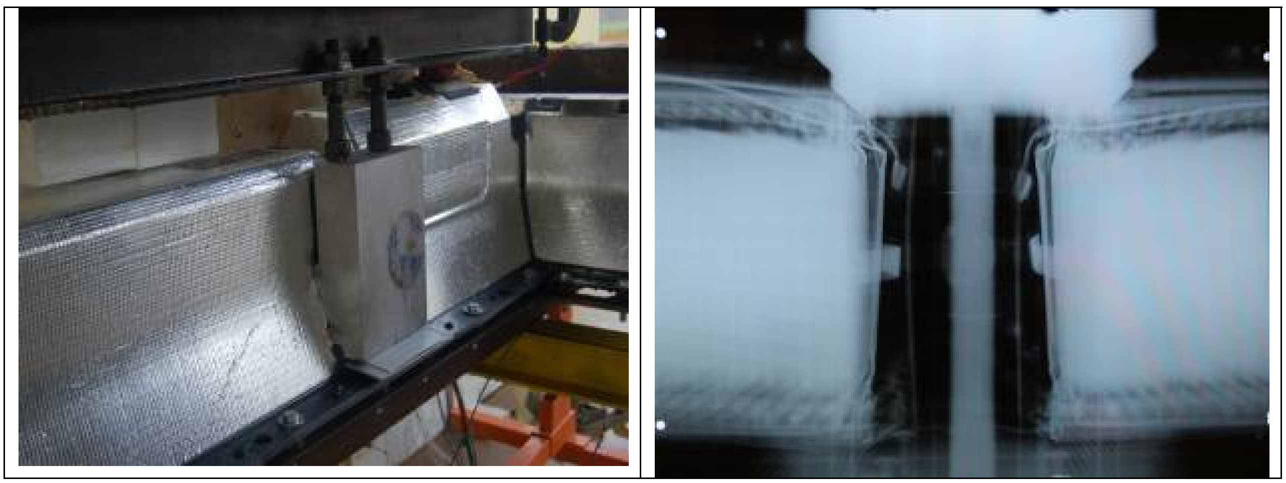


Figure 7.2 - Test 2 Battery Damage and X-Ray

Other than the physical damage to the battery and cover, there were no signs of an ensuing reaction while the batteries were located on the test deck prior to being moved into the shed. There were no indications of either arcing or smoking within the battery case.

After the batteries were physically damaged and the test procedures were completed, the batteries were placed in a shed for surveillance for a period of four weeks. Less than one week into the four week surveillance period, the battery from Test 2 caught fire and destroyed the contents of the shed including the battery from Test 1. The details of the fire and the forensic examination of batteries are provided in the following sections.

7.2.1 TEST 1 AND TEST 2 BATTERY FIRE
7.2.1.1 Event Description

The orientation of the two batteries within the shed is shown in Figure 7.3.

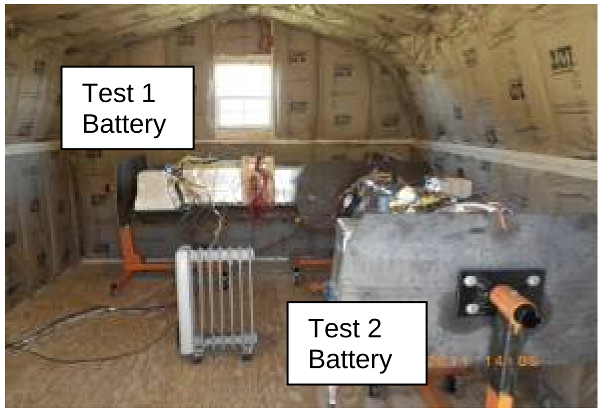


Figure 7.3 – Storage Configuration for Batteries from Tests 1 and 2

The fire occurred in the late afternoon on November 24, 2011 (Thanksgiving Day). There were no indications visually or empirically that a reaction was about to happen up to about an hour before the event. The following is a high level overview of the events that occurred on that day.

1. The cameras installed inside the Test 2 battery show smoke logging within the case at 4:30 PM
2. The thermocouples on the Test 2 battery began to increase about 4:35 PM
3. The thermocouples on the Test 2 battery heat from back to front (Section 3, Section 2 then Section 1)
4. Smoke detector triggered auto-dialer at about 4:38 PM
5. Video camera in shed shows smoke coming from the Test 2 battery about 4:40 PM
6. Video camera in shed is completely obscured with smoke by 4:45 PM
7. Video camera in shed shows sight of flames in the shed about 4:50 PM
8. About 4:50 PM, the cameras installed in the Test 2 battery began to malfunction
9. At 4:55 PM, the thermocouples in battery began heating faster
10. Ambient temperatures in the shed begin to increase shortly after 4:55 PM
11. Just before 5:00 PM temperatures spike in the batteries and shed and video is lost
12. GTL Tech/FF arrives on site shortly after 5:00, heavy smoke coming from shed eves
13. Doors of shed blew open shortly after arriving on scene (whoosh sound heard as door blew open). This overpressure blew out the back window of the shed with pieces located over 10 ft away
14. Interior of shed significantly charred when door blew open indicating that the fire had been burning for a while prior to the pressure event. Test 2 battery fully involved, Test 1 battery heating but not involved.
15. Only the Test 2 battery is involved at the time of the initial attack
16. Flames jetting from drivers side end of Module 3 and opening in cover observed at that location
17. Fire spreads to the Test 1 battery
18. Fire is extinguished about 7:30 PM
19. Fire burned for about 2 hours and 30 minutes total

Figure 7.4 – Photograph Showing Early Stage of Fire

Figure 7.5 – Photograph Showing Final Attack on Fire

Before	After
	

Figure 7.6 – Photograph Showing the Contents of the Shed Before and After the Event

7.2.1.1 Forensic Investigation of the Shed and Contents

The forensic investigation of the shed was performed on November 26th 2011.The investigation was conducted by Jerry Back of Hughes Associates Inc. and Ron Orlando of General Motors.

The forensic investigation is consistent with the measurements, video footage and observation solicited from the fire fighters that combated the fire. The damage to the shed structure, based on visual observations and char depth, supports the fire originating in Battery from Test 2. The area above and adjacent to the open end of Battery from Test 2 experienced the greatest damage during the event.

There were a number of potential ignition sources located in the shed other than the two batteries. These included a power distribution box, a duplex outlet, an electric light installed on the ceiling and an electric heater located in the center of the space. All of these components were inspected and showed no signs of shorting or arcing and were eliminated as potential ignition sources.

The damage is consistent with the following scenario: The fire originated in the Battery in Test 2. The fire then spread to the paper facing on the insulation installed on the inner surfaces of the shed. As the paper facing was consumed, the oxygen concentration in the shed dropped causing the fire to become oxygen limited. The fire then smoldered for about 10 minutes prior to the overpressure that blew open the door.

There are two potential causes for the over-pressure event; a rapid influx of air into the shed and/or a single or multiple cell rupture in Section 3 of Battery from Test 2. The likelihood of a rapid influx of air is extremely low based on the conditions of the shed before and after the event. In short, there were no openings into the shed to allow a rapid influx of air. In addition, there was little if any wind the day of the fire.

A single or multiple cell level event (i.e. rapid venting of electrolyte) is the most likely scenario. This would also explain the opening in the case at the driver's side end - Module 3 of Battery from Test 2. A photograph of the opening is provided in Figure 7.7.

Figure 7.7 – Photograph Showing Cover Damage on the Driver's Side end of Module 3

7.2.1.3 Forensic Investigation of Batteries from Tests 1 and 2

As a general statement, a significant amount of the combustible materials in both batteries were consumed during the fire. A photograph showing to two batteries is provided as Figure 7.8.

Figure 7.8 – Photograph of Batteries from Tests 1 and 2 (Battery from Test 2 is closest to the photographer)

The battery from Test 2 that initiated the fire inside of the shed was disassembled in an attempt to determine the exact origin of the fire. All of Module 3 and the impact damaged ends of Modules 1 and 2 were disassembled cell by cell in the same manner as the forensic investigation conducted on the battery involved in the MGA fire.

The forensic investigation of the battery fromTest 2 placed the origin of the fire on the top of the module. However, the exact origin of the fire could not be determined. The electrical shorting caused by the coolant solution that was observed during the other tests conducted during this program suggest that the fire could have originated in any of the circuitry (i.e. VTSM cards and/or cable connections) located on the top of Module 3.

The battery forensic investigation also concluded that a number of cells vented during the fire, due to the elevated temperatures inside of the battery case adding to the severity of the fire. This conclusion was based on the damaged observed to a limited number of cells throughout the module. Specifically, there were a number of cells where the copper current collector sheets had been melted and/or consumed just below the cell tabs. Since copper melts at approximately 1080^{o}C, this could only occur if the electrolyte was venting out of the cell at this location. The aluminum current collector sheets and cooling fins were also destroyed at these locations (i.e. aluminum melts at approximately 660^{o}C). A photograph of this damage is provided as Figure 7.9.

As stated previously, it is also believed that this cell venting blew apart the battery cover at the end of Module 3 during the fire and may have blown open the doors to the shed when the fire department first arrived on scene.

Figure 7.9 – Photograph Showing Cell Level Damage within Module 3

7.3 TEST 3 DETAILED RESULTS

During Test 3, while the battery was inverted, an event occurred within the battery pack that jetted flames and sparks (incandescent particles) out of the pack for about a second.

The impact penetration was slightly increased for each test in an attempt to reproduce the damage to the battery produced during the crash test conducted in May at the MGA facility in Wisconsin. The amount of battery coolant (ethylene glycol/water mix 50/50) leaked into the pack was also greater than that leaked during the first two tests. A photograph and an X-ray of the damage for this test is provided in Figures 7.10.

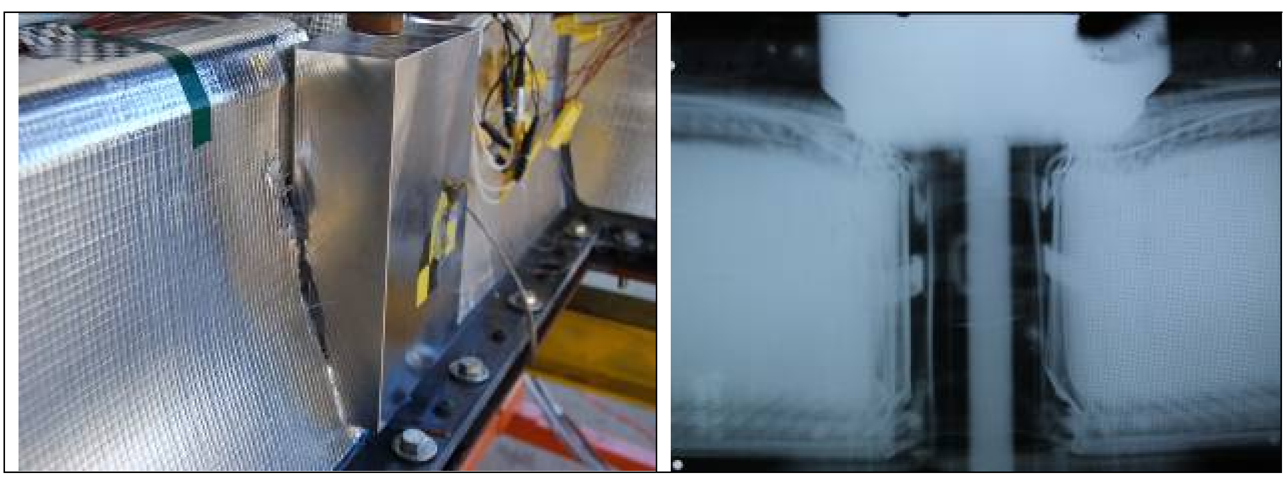


Figure 7.10 – Test 3 Battery Damage and X-Ray

The event occurred during the rotation of the battery after the impact (about an hour after the impact). The battery was x-rayed after the impact. The battery pack was then tilted about 1 degree downward (the front end of the battery was 1 degree lower than the back end) to simulate the conditions during the rotation at MGA in May. The battery was then rotated at 90 degree increments (toward the passenger side) and held at that orientation for five minutes prior to continuing the rotation. The battery was upside-down at the time of the event. It was estimated that a majority of the coolant was located in the front section of the battery (Module 1) at the time of the event. A photograph of the event is provided as Figure 7.11.

Figure 7.11 – Photograph Showing Flames and Sparks from Test 3 Battery

The observations made are listed as follows:

1. There was no unusual activity on the cameras or instrumentation prior to rotating the battery to the 180 degree mark.
2. Shortly after the battery was rotated to the 180 degree mark, two thermocouples installed on the front section of the battery began to rising at about 2-5 degrees C per minute.
3. Consistent with the previous two tests, GM's battery monitoring system began to malfunction/short out during this period due to the exposure of the electronics to the coolant.
4. About 5 minutes after the rotation to the 180 degree position, the battery housing began to fill with smoke as the temperatures continued to rise.
5. Smoke was observed leaking out of the pack at the impact location.
6. The area was then cleared and the rotation to the 270 degree mark was delayed until all parties believed the area around the battery was safe.
7. During this period, the two thermocouples that were rising began to heat faster, about 5-10 degrees C per minute.
8. About 10-20 minutes later (about 25 minutes after reaching the 180 degree mark), the event occurred.
9. Sparks and flames jetted from the pack for about a second.
10. During the event, most of the thermocouples installed on the battery measured a temperature spike.
11. Almost immediately after the event, the smoke began to clear from the pack and the thermocouple began to return to normal with the exception of one installed on

the top of Module 1 of the battery pack. This thermocouple remained near 40°C (104°F) until the battery was disassembled the following week.

12. Once the battery was stable and all temperatures dropped below 40°C, the test sequence was continued and the battery was rotated to 270 degrees and held there for 5 minutes and then rotated back to the upright position (the 360 degree mark).
13. Once the battery was upright, smoke was again observed exiting the impact location.
14. The battery was left at that location overnight and then the following morning, moved inside a test camber for further monitoring and disassembly.

7.3.1 INSTRUMENTATION CHECK

The first assessment conducted on the battery was to determine the potential involvement of the instrumentation, cameras and lighting installed in the battery pack to monitor the test. This assessment was conducted after the cover was removed from the battery. The findings are summarized as follows:

1. All 15 thermocouples worked properly after the test. There were no breaks in wiring or leaks to ground.
2. The accelerometers and wiring were still operational with no observable damage or leaks to ground.
3. Two video cameras were damaged during the event but the other two were still operational after the event. There were no breaks in wiring or leaks to ground.
4. All of the LED lights were operational after the event. There were no breaks in wiring or leaks to ground in 3 of the 4 lights. The 4th LED strip had a slight nick in the coating but showed no sign of any abnormal electrical activity at this location. It should be noted that these LED lights operate off of 12V with virtually no current draw.

It was concluded by the NHTSA team and agreed to by GM that the devices installed in the battery pack to monitor the test had no contribution to the event.

7.3.2 BATTERY DAMAGE OBSERVATIONS

Impact damage looked similar to that of the MGA battery with the back end of Module 1 and the front end of Module 2 slightly crushed and pushed about an inch toward the passenger side of the vehicle. The cooling system was also breached at this location allowing the coolant to flow out of the pack into the battery enclosure.

At the time the cover was removed, all three modules were determined to be almost fully charged. Module 1 had just under 120V, Module 2 had just over 96V and Module 3 had approximately 170V. All three modules were discharge using an electrical heater provided by NSWC-Carderock. During the discharge of Module 1, a limited number of cells were observed to heat to about 90°F near the damage location. During the discharge, it was also determined that Module 1 was partially discharged and was being drained by the damaged electrical circuitry of the battery, probably VTSM1 located on top of Module 1.

The post-test inspection of the battery revealed that there were four areas where arcing occurred;

1. In and above the electronics at the front end of Module 1,
2. On VTSM 1 located above the center of Module 1,
3. At the front end of Module 2 near the impact location, and
4. At the negative end of Module 3 (drivers side end).

These locations are shown in Figure 7.12. and are discussed in the following paragraphs.

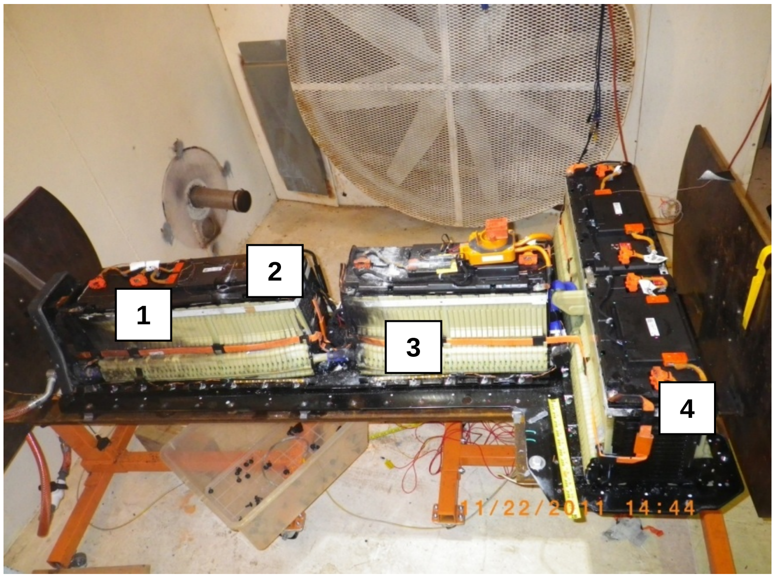


Figure 7.12 Test 3 Arcing Locations

The front of Module 1 had arcing damage near the positive battery terminal and was stained with smoke and combustion products as shown in Figure 7.13. In addition, the front end plate of Module 1 had arced to the bottom support frame.

Figure 7.13 Arcing Damage to the Front of Module 1

The plastic cover over VTSM1 had a small penny size area where the plastic had started to melt. Circuitry below the cover was visibly damaged and was warn to the touch and was still generating a small amount of heat at the time that the battery was disassembled. A photograph of VTSM 1 is provided as Figure 7.14.

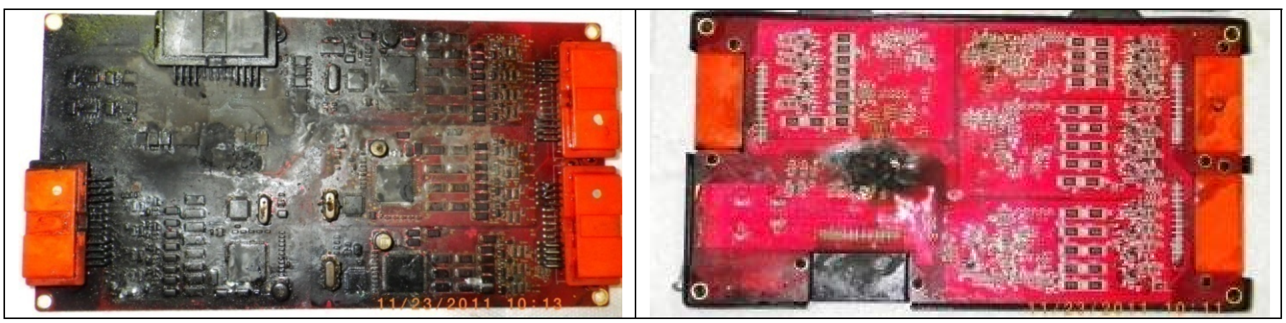


Figure 7.14 Arcing and Heating Damage to VTSM 1

The greatest amount of electrical activity occurred at the front end of Module 2 as shown in Figure 7.15. As shown in the figure, most of the arcing occurred at the impact location. The negative bus bar that runs from Module 3 to the front of the battery was damaged by the impact and had arced to the front end plate of Module 2. The bottom of the end plate that supports the cooling line had arced to the impactor block and was completely destroyed in the process.

Figure 7.15 Arcing Damage to the Front of Module 2

The final area of damage was in Module 3 at the negative terminal as shown in Figure 7.16. There was evidence of arcing between the cells and the terminal at this location. Specifically, there was an opening in the cover plate directly below the junction between the terminal and the negative bus bar where the activity occurred.

Figure 7.16 Arcing Damage at the Driver's Side End of Module 3

Generally speaking, the arcing was attributed to both the structural damage to the battery caused by the impact, and the shorting of various components due to the exposure to the electrically conductive coolant solution.

7.3.3 ARCING SCENARIO DESCRIPTION

The submersion of the electronics in front of, and on top of Module 1 caused a number of short circuits that altered the voltage potential and polarity of the battery pack. These short circuits generated heat and smoke that were observed by the cameras installed inside of the battery cover. The submersion of the electronics also produced electrolysis gases that along with the smoke became logged within the case. Within a few minutes of submersion, significant arcing occurred at numerous locations (at the front ends of both Module 1 and Module 2). The primary arcing location was in the front of Module 2. The arcing occurred between the negative return and the end plate of Module 2 and the impactor that was grounded to the battery frame. The arcing ignited the combustible smoke and electrolysis products logged in the case causing flames to momentarily jet from the case when the arcing occurred.

To further investigate the shorting that was observed during these first three tests, an electrolysis experiment was conducted on the battery coolant using a variable power supply and two copper wires. The current flow through the coolant and associated electrolysis rapidly produced metallic compounds and carbon particles that floated on the coolant surface during the experiment. These compounds are believed to have created the external shorts in the wiring and circuit boards during the post test surveillance period.

7.4 TEST 4 DETAILED RESULTS

There were not any major electrical or thermal events noted within the battery from Test 4. The thermocouples located on the top of VSTM 1 and 3 showed continuous slow heating from 26°C to 34°C. The temperature fluctuated about 33° for the last few days of the monitoring period.

On January 6, 2012, 31 days from the test date, the battery was removed from the storage shed, deenergized, and retained at GTL.

Post test visual inspection of the battery revealed discoloration(brown to black) on the wires and orange jacket leading from the orange connector on the battery to VSTM 3. See photograph at Figure 7.12.

Figure 7.12 Discoloration of wires and orange jacket

7.5 TEST 5 DETAILED RESULTS

Test 5 was a repeat of Test 4 with the exception that the negative bus bar running between modules 1 and 2 of the battery was grounded to the frame.

During the rollover portion of the test, between 180 degrees and 270 degrees, the coolant must have submersed the positive and negative terminals located on the driver's side of Module 1 causing rapid electrolysis of the coolant. A vigorous boiling sound could be heard as the battery was rotated through this orientation. The electrolysis abruptly stopped as the battery approached the 270 degree orientation and no other adverse effects were observed. A photograph showing the battery at the 270 degree mark is provided as Figure 7.13. Smoke can still be seen in the area where the shorting and electrolysis is believed to have occurred.

Figure 7.13 Test 5 with the Battery at the 270 degree orientation

Less than a week into the four week surveillance period, the Test 5 battery caught fire due to shorting of a connector on the passenger side end of battery Module 3. The location of the fire is shown in Figure7.14. The fire was quickly suppressed by discharging water into the battery case. The battery was submersed by flowing water through the battery case until the test team returned to the facility, approximately 18 hours later.

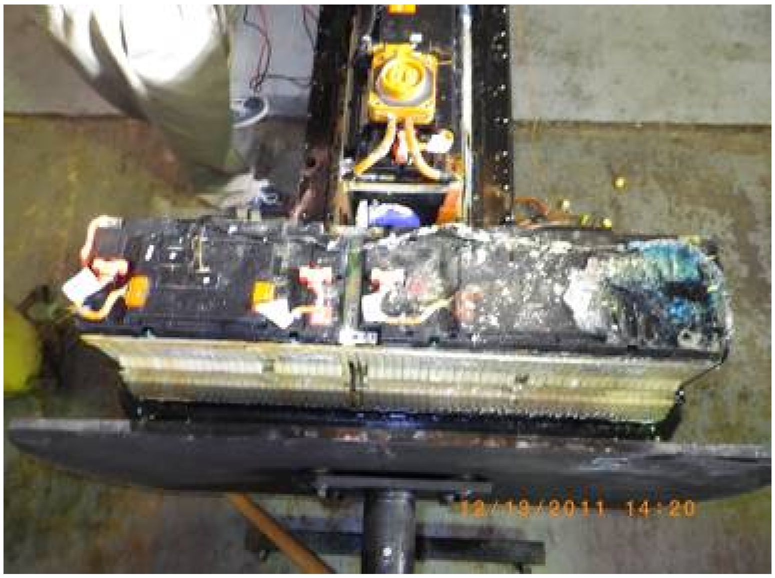


Figure 7.14 Fire Damage to Passenger Side End of Module 3

Due to the rapid suppression of the fire, the exact origin of the fire could be determined. The forensic investigation of the battery revealed that the fire originated at the passenger side end of Module 3. Specifically, the fire originated at/in the connector on the battery between the voltage monitoring system bus bar and the cable for VTSM 3 as shown in Figure 7.15.

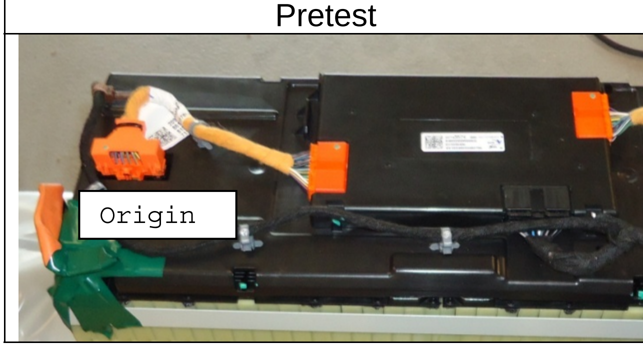
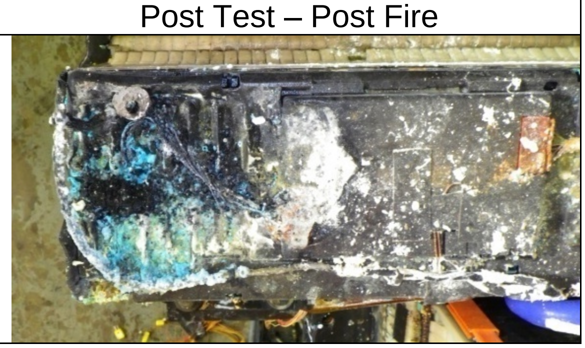
Pretest	Post Test – Post Fire
	

Figure 7.15 Fire Origin of Test 5 – Passenger Side End of Module 3

During the forensic inspection, Module 3 of Battery from Test 5 was disassembled cell by cell in the same manner as the forensic investigation conducted on the battery from Test 2.

The forensic inspection of the cells was consistent with the fire originating at the connection between the voltage monitoring system bus bar and the cable for VTSM 3. Specifically, there was no damage to any of the cells other than directly under the connector and there was no damage to VTSM 3. A photograph of VTSM 3 is provided as Figure 7.16.

Figure 7.16 VTSM 3 – No Apparent Fire Damage

The voltage temperature monitoring system leads that run through the bus bar were destroyed between the connector location and the passenger's side end of Module 3. These leads are fairly low gauge copper wires. Since copper melts at approximately 1080^{o}C, this could only occur under high current flow conditions or if the electrolyte was vented out of the cell(s) directly below the leads. A photograph of these leads is provided as Figure 7.17.

Figure 7.17 Fire Damage to the Bus Bar Leads

7.6 TEST 6 DETAILED RESULTS

There were not any major electrical or thermal events with the battery in Test 6. The thermocouples located on the top of VSTM 1 and 3 showed continuous slow heating from 26°C to 34°C. The temperature fluctuated about 33° for the last few days of the monitoring period.

One of the cell groups on the end of Module 1 located in the impact area slowly lost charge during the monitoring period. Voltage at the end of the monitoring period had dropped to 0.21 volts. A photograph and an X-ray of the damage for the test is provided in Figure 7.18.

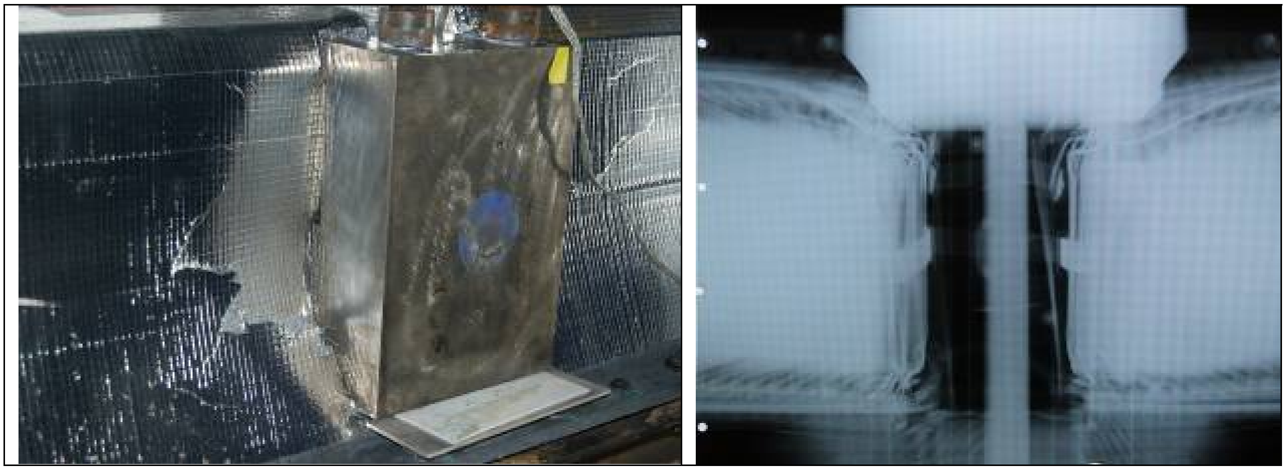


Figure 7.18 - Test 6 Battery Damage and X-Ray

On January 6, 2012, 30 days from the test date, the battery was removed from the storage shed, de-energized, and retained at GTL.

8.0 CONDUCTIVITY TEST OF BATTERY COOLANT

The impact of electrical conductivity of the glycol-water coolant mixture used in the battery coolant system of the Chevrolet Volt battery was highlighted during GM contracted Exponent testing and fire-event investigation of the MGA Volt vehicle fire. The tests performed by Exponent demonstrated that with highly doped glycol-water solutions (9% by weight table salt added) that dendrite growth could be established that would cause carbonization of the underlying supporting plastic in the battery BMS electronics between cells and series connections of cells within a few hours to days of exposure.

Literature values for glycol, and glycol-water solutions are available [1]. These are provided by glycol manufacturers, by various automotive test and documentations sites and MSDS sheets, and various activities including SAE publications. The values for conductivity of deminearlized water and ethylene/propylene glycol are cited as 1500 to 2500 S/cm.

During the initial three Volt battery tests, off-the-shelf Prestone 50-50 DEX-COOL/WATER (GM approved) was utilized as the coolant fluid addition to the battery coolant circulation lines. This material met the specifications provided by GM representatives for the Chevrolet Volt battery to DOT/NHTSA representatives.

After the Test 3 arcing event, followed by the Test 2 fire event 11/24/11, a crude test was conducted on the conductivity of the DEX-COOL solution at relatively high voltages to approximate possible battery driven effects within the volume and spacing of the Volt battery protective cover. Discussions by GM representatives also indicated that the use of the Prestone 50/50 mixture with “demineralized” water was inadequate and that the GM specified coolant mixture utilized ”deionized” water.

A high voltage power supply (Sorenson 600-8) capable of providing 1200 watts of total power (1200 watt limiting power at combination of voltage and current) was utilized to evaluate the effects of moderate battery voltage through a test sample coolant from the Volt batteries. An impromptu set of electrodes were fashioned from AWG 12 wire cabling, exposing approximately 1” length with an electrode-to-electrode separation of approximately 1”. With the power supply set to 350 VDC and 4 ampere limit, a clean plastic container of DEX-COOL 50/50 was decanted and exposed to the electrodes. The coolant-electrode reaction was immediate with formation of bubbles, and dissolution of exposed copper wire. Approximately 150 ml of coolant was discolored and observed to have significant concentration of particulates floating after 30 seconds of exposure. Peak current was observed to be approximately 2.5 Amperes. 350 VDC was chosen as a moderately low voltage for the Volt battery. After 30 seconds, electrical arcs were visible through the coolant and mixture of water vapor and glycol were rising from the exposed material. Temperature of the sample had increased in temperature dramatically.

The exposure was repeated with a fresh sample at various voltages from 12 VDC stepping to 100, 200 and 300 VDC. At increasing voltages, increasing levels of reactions were observed. No tests were conducted above 350 VDC. Battery voltage for the GTL test series were 390 VDC. Voltage for the MGA test event battery is estimated at 370 VDC.

Two samples of OEM supplied materials were provided by GM representatives. OEM GM source 50-50 mixture of glycol-water was obtained by DOT/NHTSA representative from GM maintenance and repair dealership shop. “Neat” undiluted Prestone DEX-COOL was also obtained.

The first batch of GM factory provided materials were provided in re-used 1-gallon plastic containers. A quick test of this material using the same technique described above resulted in the over-loading of the power supply from providing too much power and exceeding the 4 ampere limit imposed. This test was repeated twice, with similar results. This material was not used for additional tests.

A second batch of GM factory material was sent by GM representatives. Again, the containers used to provide this sample were 1-gallon plastic containers (labeling indicated original use was for cleaning solution and solvents). This material was tested and was found to be no worse (no more conductive) than the original Prestone non-Hybrid vehicle quality DEX-COOL 50/50 mixture of material.

GM OEM high purity DEX-COOL certified for use in HYBRID VEHICLE SYSTEMS was obtained by NHTSA/DOT personnel. This material was found to be equivalent at high voltages as the off-the-shelf Prestone DEX-COOL coolant mixtures.

A comparative test of conductivity was conducted on the five basic coolant fluids available; Prestone DEX-COOL, GM Supplied Coolant #1, GM Supplied Coolant #2, and GM OEM HYBRID DEX-COOL. Neat (undiluted) DEX-COOL although available was not tested in this sequence. These were compared with Distilled water acquired from local hardware store. These tests were conducted with a HANNA total dissolved solid/conductivity water quality test meter. The HANNA meter, Model HI9835, was provided by GM representatives.

(A) Distilled Water: 12.25 to 13.00 microSiemens
(B) Prestone Pre-mix 50/50 DEX-COOL: 1900 - 2030 microS (used in initial tests)
(C) OEM Sample #1 (original very conductive in HV test): 3600 microS
(D) OEM Sample #2 (resend, last Fridays, issue): 1880 - 1900 microSiemens
(E) Prestone 50/50 HYBRID Electrical System DEX-COOL Mix from GM Dealer): 1950 - 1960 microS (used in subsequent Tests #4-6)

NOTE: The HANNA HI9835 electrode assembly was disassembled, washed and cleaned with purchased distilled water in between conductivity tests to prevent contamination effects.

These values ranges and levels match the observed high-voltage effects when exposed to 350 VDC. It should be noted that “neat” undiluted DEX-COOL (glycol) was observed to behavior very differently than literature values would allow inference when exposed to the 350 VDC source. Gylcol undiluted is reported to be more conductive that the 50/50 water mixture typically used or sold. During the high-voltage exposure tests, the glycol was observed to be initially less conductive, lower current flow, than any of the 50/50 glycol water mixtures. The reaction however did become seemingly more violent than any 50/50 mixture with apparent gassing or boiling of the glycol, ejecting substantial portions of the test sample out of the sample container.

A literature survey and review located a potential alternative source for the deposition of carbon films detailed by Exponent [2] have demonstrated that application of high voltages in a water glycol solution can support formation and deposition of graphite by electrolysis reactions. Although these experiments were driven for approximately 12 hours at a 3 to 4 times the applied voltage exposures anticipated in the VOLT battery coolant exposure, the lower-voltage and extended exposure times may be an alternate explanation for some behaviors observed.

9.0 CHEMICAL ANALYSIS

BAE Systems was contracted to provide chemical analysis on the following samples:

SAMPLE	DESCRIPTION
A	50/50 DEX COOL PREMIX OTS PRESTONE
B	NEAT DEX COOL OTS PRESTONE
C	OEM DEX COOL DI 50/50 MIX
D	OEM DEX COOL DI 50/50 MIX
D RESIDUE	INSOLUBLE SOLIDS IN SAMPLE D
E	SWAB INSIDE OF IMPACTOR
F	Q-TIP DRIVER SIDE RESIDUE OF BATTERY FROM TEST 3
G RESIDUE	SECTION 3 BURN/ARC AREA
G PLASTIC	GRAY PLASTIC
H	SWAB SECTION 2 FRONT END PLATE
I	SWAB SECTION 1 FRONT END PLATE
J	SWAB BDU DRIVER SIDE SAMPLE BURN AREA
K	SWAB VTSM 4 WATERLINE MATERIAL #14 CARD COVER
L	Q-TIP SWAB OF GREEN BLACK RESIDUE ON CONNECTOR OF BATTERY ASSEMBLY INTERCONNECT

The report of this analysis can be found as Attachment 1 to this report.

10.0 FINDINGS AND CONCLUSIONS

The results of these tests demonstrate that intrusion damage to the battery with coolant leakage followed by a rollover has the potential to expose energized battery components to the battery cooling solution. A fire hazard is produced when the electrically conductive liquid cooling solution comes in contact with the energized battery components (terminals and circuits). The fires that occurred during this test series took approximately a week to develop. It is conceivable that these fires could have occurred sooner under different circumstances (i.e. wetting of areas with higher voltage potentials and situations that expose the electronics to the coolant for a longer period of time). It should also be noted that there were no indications that a fire was about to occur prior to about an hour before ignition (i.e. there are no warning signs).

Although two of the batteries caught fire during this test program and one battery experienced an arcing event, the conditions that occurred at the MGA facility in May 20, 2011 were never truly replicated. Specifically, the conditions to over pressurize the occupant compartment of the vehicle and displace the windshield without causing heat damage and/or smoke deposition were never produced.

11.0 REFERENCES

[1] Electrical Conductivity of Typical Automotive Engine Compartment Fluids And A Method for Determining Their Effects When Inadvertently Present in Electrical Connectors of Powertrain Control Modules; Proceedings of the 57th International Wire and cabling Symposium; NK Medora et al.

[2] Deposition of carbon films by electrolysis of a water-ethylene glycol, Suzuki et al, Journal of Material Science, 30 (1995) 2067-2069