

## **High-Risk E-Vehicle Battery Sled Testing**

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Paper Number 15-0248

### **ABSTRACT**

Crash testing of E-Vehicles (electrified vehicles, e.g. electric and hybrid electric vehicles) is required to assure compliance with global safety regulations and standards as well as the even higher requirements set by the car manufacturers themselves. The introduction of E-Vehicle battery systems of as much as 200 to 600 Volt dc presents new safety considerations when performing crash tests. At a crash test, safety by regulations, standards and ratings as well as the limits of durability are investigated. If investigating the limits of durability, scenarios such as release of harmful gases and thermal events must not be disregarded. In order to ensure safe testing conditions, regardless of the severity of impact to be evaluated, new risk analysis, routines and laboratory designs need to be assessed when a new technology, such as high voltage (HV) battery systems, are introduced to the vehicle market.

Autoliv has a long experience in crashworthiness testing and offers car manufacturers assessments of crash safety in laboratories and crash tracks available on all continents. E-Vehicles are being crash tested as well, and for that reason Autoliv have established research and testing capabilities for HV batteries as well as updated routines and laboratory designs. Besides Autoliv's full size crash tracks around the world a new laboratory facility for battery sled testing is now available in Sweden for high-risk durability-limit testing.

### **INTRODUCTION**

Range anxiety is often defined as one of the key limitations of E-Vehicles. It is often considered that the limited range can be extended by means of research on more energy dense battery chemistries. Currently, the Li-ion chemistry is the predominant battery on the market because it currently presents the highest energy density. A great deal of successful research on the constituent materials and molecules have contributed to the introduction of the current Li-ion battery technology. Although this family of battery chemistries have proven to be the key to the present global launch of E-Vehicles, the importance of system and structural design achievements cannot be underestimated.

Another key for the global launch of E-Vehicles is the battery safety. Traditionally the crashworthiness of a battery system installed in an E-Vehicle is solved by locating it in the "safe zone" where mechanical damage from a crash is limited according to crash statistics. Additionally, battery systems are equipped with rigid

housings and other means of structural protection in order to prevent intrusions upon the battery. Crashworthiness testing is a vital part of the safety research that in the years to come will assure that the range anxiety issue will become less of a hurdle. New designs of HV battery systems will permit them to be located closer to frequent deformation zones rather than restricted to the safe zone. The risk that any vehicle crash could reach a worst scenario consequent continuous to diminish as capabilities and routines for safe crash testing and mechanical abuse testing on cars and components are constantly being developed. However, in the world today, there exist only few laboratories for dynamic mechanical abuse testing on HV battery systems, which offers a complete methodology and testing experience in order to replicate the crash environment suffered by such a battery system in a full vehicle crash. The key issue is the concern for the safety of the testing personnel, the facility and the testing equipment since the structural and chemical response of a battery under dynamic sled tests and crash test is not common knowledge. Such a safe testing environment is now offered by Autoliv in Sweden.

### **Issues to be anticipated when performing high-risk battery testing**

#### **The influence of battery material and chemistry**

As mentioned Li-ion batteries offer an out-standing energy and power density in comparison to other battery chemistries (e.g. NiMH and lead acid). The key is the high nominal voltage per cell that is a consequence of the large difference in standard reduction potential between the material of the anode and the cathode. Because of this high nominal voltage water cannot be used as electrolyte solvent in Li-ion batteries. Instead, organic solvents are used together with a salt to form the required electrolyte. Commercial Li-ion batteries use a mixture of alkyl carbonates as solvent and the  $\text{LiPF}_6$  as the salt to form their electrolyte. This salt is completely predominant because of its extraordinary performance in comparison to other salts. If the battery cell is exposed to elevated temperatures (commonly starting within the range from 80 to 170 °C), the material of the two electrodes have a tendency to start reacting with the components of the electrolyte (Huang, Yan, & Jiang, 2008). Under such conditions, the pressure will build up inside a battery cell because of those reactions as well as the gradual vaporization of the organic solvents.

In order to prevent rupture at higher pressures Li-ion cells are designed with soft-spots or venting mechanisms that will release the gases from the cell at a preferred lower internal pressure. This is a safeguard feature which in many scenarios mitigate further escalation of a cell failure. Another safeguard feature is the characteristics of the separators that ensure that only Li-ions can move from one electrode to the other. Commonly, the separator constitutes of a multilayer structure of polyethylene (PE) and polypropylene (PP) with a thickness between 10 to 40  $\mu\text{m}$ . The two polymer melts at 135°C (PE) and 165°C (PP) and the 30°C buffer allow the PP to retain the separator structure while the PE melts and make the separator impenetrable to Li-ions which consequently prevents Li-ion transport at the location of the damage and thus impedes the current in the circuit (Zhang, 2007). Therefore, they are named shutdown separators. Many battery cells are equipped with additional safeguard systems that intend to prevent an escalation of a cell failure, such as Current Interrupt Devices (CID) or poly-thermal switch (PTC).

Nevertheless, all these safeguard systems have an upper limit of operation at which they are overridden. A common cause for a safeguard system to be overridden is when the thermal exposure onto, as well as inside, a battery cell lead to a temperature increase at a rate that is higher than those safeguard systems are capable of handling. Under such circumstances, a battery cell risk to reach a second stage of critical failure that is defined as thermal runaway. Among conventional Li-ion batteries, this may occur at temperature ranging between 170 to 250°C depending on the constituents of the cathode material (Yang, Amiruddin, Bang, Sun, & Prakash, 2006). As of 2014, the two predominant Li-ion chemistries are denoted NMC (based on the use of a cathode material composed of Nickel Manganese and Cobalt) and LFP (based on the use of a cathode material composed of iron phosphate). At best, a thermal runaway remain isolated to the original cell but it is not

unlikely that the heat-up of the first cell increases several hundreds of degrees rapidly that then provokes the neighboring cells into thermal runaway. If propagation of thermal runaway starts between cells it becomes nearly impossible to extinguish until the fuel, (i.e. the cell material) is consumed. This scenario will generate large quantities of gases, as presented by the picture of a faulty battery module in Figure 1a. In the presence of a sufficient source for ignition, the electrolyte vapor might ignite (Figure 1b).



**Figure 1.** Under tough crashworthiness testing conditions, an E-Vehicle battery may experience thermal runaway. Such a critical cell failure cause the faulty cell to heat up rapidly, which may lead to propagation of the failure to neighboring cells. The first indication of a damage battery cell is gas ventilation (a) and the worst scenario of a fire might occur if the organic electrolyte vapors get access to a sufficient ignition source (b).

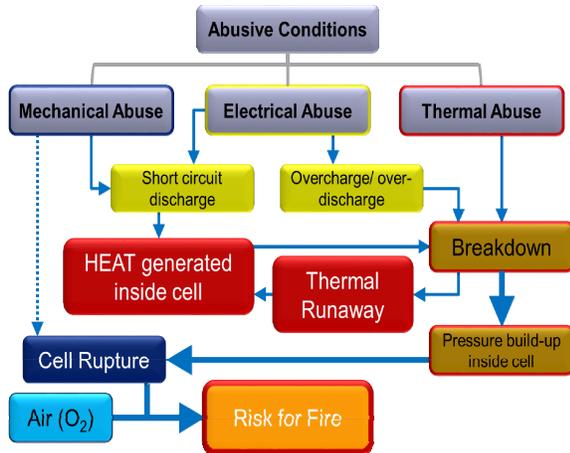
#### **A simplified fault tree analysis for a Li-ion battery cell**

Three major abusive conditions can be illustrated with a simplified fault tree diagram (Figure 2). Those three conditions are:

- Mechanical Abuse
- Electrical Abuse
- Thermal Abuse

A worst-case scenario, in the event of a traffic accident or as a consequence of tough durability testing the mechanical abuse generated onto the battery, would be that the whole failure sequence described above is not impeded. In such a scenario, the mechanical abuse could result in a fault current(s) that heat up the internal components of the battery cells. If the rate of heat-up exceeds the shut-down capacity of the safeguard systems,

thermal runaway might start and the quantity/pressure of electrolyte vapor and gaseous species, which are generated by the decomposition of the cell's material, cause the cell to rupture. At that point, large quantities of gases are emitted to the surrounding and in the presence of a sufficient ignition source; a battery fire might start (Figure 1b).



**Figure 2. Fault tree analysis for a battery cell. There are three major abusive conditions – Mechanical, Electrical and Thermal Abuse. When thermal runaway have started the cell-internal pressure quickly increases and the cell soon rupture and gases are emitted to the surrounding. (Sturk, 2011) Autoliv ©.**

There is of course no fire without a fuel. For the internal breakdown of Li-ion cells, the fuel is the mix of organic electrolyte and the active materials of the electrolytes, while a battery cell external fire is fueled by the electrolyte vapors emitted by a critically damaged battery.

The internal breakdown can progress without visual flames but it will generate much gases. Predominant species is carbon dioxide and carbon monoxide. However, it has been documented that lesser quantities of more toxic species such as hydrogen fluoride or other fluoro-organics are generated. (Hammami, Raymond, & Armand, 2003) (Sturk & Hoffmann, 2013) (NIOSH, 1996) (AFS, 2011) The toxic fluoro-species derive from the breakdown of the salt  $\text{LiPF}_6$ . (Yang, Zhuang, & Ross Jr., 2006) (Wilken, Treskow, Scheers, Johansson, & Jacobsson, 2013) Hence, extensive ventilation of gases from a critically damaged Li-ion battery must be anticipated when preparing for a crash test of an E-Vehicle or a battery component test.

In the event of a battery fire, the composition of gases emitted may alter somewhat, but the risk for harmful fluoro-organics and hydrogen fluoride remains. (Sturk, Hoffmann, & Tidblad, 2015)

## METHOD

Autoliv's battery abuse testing facility is designed for dynamic mechanical abuse testing, i.e. separate acceleration or deformation tests, or a combination of the two. The specifications defining how to perform such a battery test are developed by means of full vehicle crash test with dummy/inert batteries and/or CAE crash simulations on E-Vehicle and battery pack or subsystem in order to assure the best possible replication of the target crash conditions.

### The characteristics and safety feature of the battery sled track

As for all types of crash related testing, sensors and cameras are used to provide qualitative data acquisition during and after test so as to fulfill customer specifications and maintain high level of post-crash safety. In order to offer customers a high-end sled track for battery systems, the 15 meter of track utilize up to 9 meters

for acceleration of the sled that can be propelled, by up to 10 bungee ropes, to a maximum velocity of close to 100 km/h. An empty sled weight 196 kg and the maximum added weight of battery unit is 200 kg. In comparison to regular crash tests some extra sensors and monitoring equipment is added to this test setup because of the need for monitoring the temperature and electrical properties of the battery unit to be tested. (Figure 3)

Additional requirements when performing high-risk battery abuse tests involves a stringent FMEA and routines that ensures that:

- 1) No test operators or other people are exposed to potentially harmful situations or substances caused by the test.
- 2) No collateral or unforeseen damage should be caused to the facility or neighboring facilities or property.
- 3) Any damage to test equipment shall be kept to a minimum.

Based on these priorities Autoliv has equipped the new facility with a test chamber by the barrier-end of the track. This test chamber is surrounded with transparent removable walls that will ensure that no physical parts of the test setup or object will be expelled from the chamber. The chamber offers an enforced environment for fire suppression and forced cooling measures as it limits the air volume, and restrict the area where any critical battery failure may occur. For flame suppression a stationary CO<sub>2</sub> system is dedicated, and for fire suppression and forced cooling water spray is used. Water (with or without additives) is the preferred cooling and fire suppression medium according to research published by (Egelhaaf, Wolpert, & Lange, 2014) and (Sturk, et al., 2014). Besides sensors for electrical characteristics and temperature monitoring a gas-detection warning system ensures an early alert for emissions of species such as carbon monoxide, organic vapors, hydrogen and hydrogen fluoride. All liquids released or leaked during or after a test will be collected and safely handled. For the safety of test operators, multiple cameras allow visual monitoring of the track and test chamber to be viewed from a separate control room with no direct air-contact with the testing room.



**Figure 3.** Autoliv's laboratory for high-risk sled testing of E-Vehicle batteries offers a testing environment with multiple layers of safety. A key safety feature is the enforced test chamber, at the barrier-end of the sled track, which is equipped with gas detection warning, fire suppressions, forced ventilation and collection of liquids. (Autoliv ©)

### **Defining specifications for physical testing**

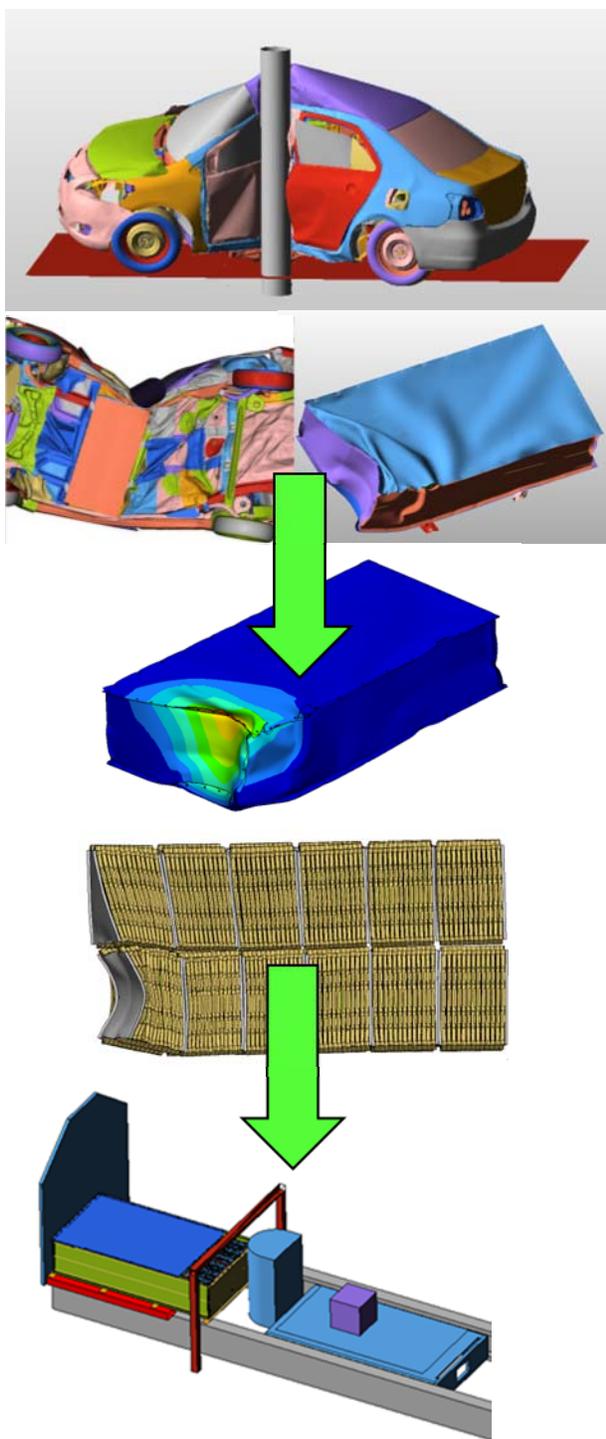
Regardless of the choice of preferred physical testing setup – i.e. separate acceleration or deformation tests, or a combination of the two – the customer specification, upon which the final battery sled test is designed, can be derived from one out of two alternatives:

- A. Battery crash environment characteristics acquired by complete E-Vehicle crash testing with low state of charge (SOC) battery, dummy battery or inert battery system. Tests performed by either Autoliv or the customer.
- B. Battery crash environment characteristics acquired by CAE simulations on complete E-Vehicle crash model. Simulations performed by either Autoliv or the customer.

Alternative A is preferred when a comprehensive simulations model of all relevant parts of the E-Vehicle, the battery system and electronics are not yet fully validated. It shall offer the characteristics of the mechanical abuse that a battery system and its subcomponents experience under the complete vehicle crash. The necessity of replacing the active battery with dummy or inert battery, or using a low SOC is analog to the procedures of conventional crash testing where all liquids, which possess a fire risk (e.g. petrol and diesel), are replaced by inert liquids in prior to crash testing.

Alternative B is preferred when a validated simulation model with sufficient details of the E-Vehicle as well as the battery system is available. This offers a cost effective and fully risk free investigation of the mechanical abuse that may compromise the battery integrity.

Either way, Autoliv will utilize the data acquired to establish a best possible replication of the battery system and/or the subcomponents and run the corresponding simulations with the object to be tested in a detailed model of the battery sled track in order to ensure a high-end of equivalence between the crash scenario and final physical battery sled test (Figure 4). Autoliv's methodology behind this has been publicly presented through the OSTLER project that was cofunded by the European Commission through the 7<sup>th</sup> Framework Programme. (Funcke, et al., 2014)



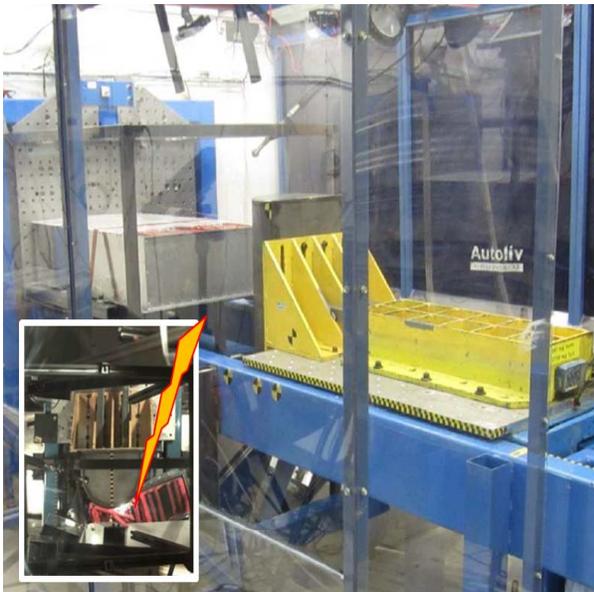
**Figure 4.** CAE simulations on the crash scenario to be investigate offers a more cost effective alternative than complete E-Vehicle testing when the crashworthiness of the battery system and its subcomponents are to be physically tested. (Funcke, et al., 2014)

## RESULTS

As mentioned, when performing a replication of the crash environment experienced by the battery pack in an E-Vehicle crash scenario or when plainly investigating the crashworthiness limits of a battery system, the physical test setup can be optimized for either battery deformation tests or acceleration tests. A combination of them both is also possible. However, it will involve a larger physical setup in order to provide the correct synergy effects of testing the acceleration and deformation characteristics simultaneously. Hence it may put restrictions as to the size of the battery object to be tested.

### Battery Deformation Test

In the OSTLER project a scenario of an E-Vehicle crashing into a pole (sideways) at 50 km/h plus the corresponding damage to the “floor-battery” was investigated (Figure 4). For this physical test setup of the battery sled track, the battery pack was mounted to a rigid barrier and a pole-impactor was mounted on the moving sled. The conversion from the complete E-Vehicle crash characteristics to the physical test setup proved successful and a satisfying match of the compared crash environments was achieved. Figure 5 show the setup prior to testing as well as the arcing-event that occurred during the intrusion of the pole. It is also possible to mount the battery pack or its sub-components on the sled and the impactor or deformation element onto the barrier.



**Figure 5. A battery deformation test with a pole impact. After the characteristics that a battery experience in a specified vehicle crash have been simulated in a CAE model of the track, the physical setup is constructed to offer a crash-matching environment for the battery system and its subcomponents to be tested. (Autoliv ©)**

### Battery Acceleration Tests

Conventional E-Vehicles are traditionally designed to assure the battery system integrity by means passive protective structures. Figure 6a presents a successful FMVSS 305 rear end collision (FMVSS 305, 2015) where the integrity of the battery system proved tough enough to prevent any intrusions. Consequently, in this example a deformation test on battery subcomponent proved not to be needed. In the research project E-Vehicle Safe Rescue, Autoliv performed the corresponding acceleration exposure onto battery modules in order to visualize the high level of robustness of a conventional battery system to the project’s target group of first responders. (Sturk, et al., 2014)

At an acceleration test the battery or sub-component to be tested is mounted on the sled and the dedicated acceleration pulse is achieved by means of different types of breaking elements, such as tubes, bending bar or honey-comb structures.

Regulation UN ECE 100 requires that battery systems are tested for “Mechanical Shock” and show compliance with a set of specifications. In its Annex 8C, figure 1 presents an acceleration pulse corridor with nodes defined by the tables 1-3. (Economic Commission for Europe, 2014) Such a regulatory pulse requirement is physically possible to perform at Autoliv’s battery sled track facility.



**Figure 6.** A battery acceleration test. FMVSS 305 rear impact is a tough test that US market E-Vehicle must comply to; in order to avoid over-engineering of protective structures, the battery and its subcomponents can be tested separately to offer more precise testing feedback on the design. Picture from a video available at (Swedish Civil Contingencies Agency, n.d.).

## SUMMARY

Conventional E-Vehicles of today present a high level of safety but at a cost of range and battery weight since the structural integrity of their battery systems are commonly ensured by passive protection and its location is often restricted to the “safe zone”. Continuous efforts to develop lighter batteries and protective structures demand for dynamic abuse testing that is capable of replicating any foreseeable crash scenarios of future E-Vehicles in order to modify the battery system design without compromising battery crashworthiness.

Moreover, regulations, standards and ratings are addressing battery safety more precisely by every subsequent amendment process. The need for test facilities that are prepared for the increase demand of battery crash testing and all the safety concerns related thereto, are not always fully anticipated by current laboratories on the testing market.

For this reason, Autoliv have developed its new battery laboratory for dynamic mechanical abuse tests on E-Vehicle battery systems and their subunits.

### **General risk factors when testing battery systems**

When performing durability and crashworthiness tests on battery systems and their sub-components it is of utmost importance to have updated routines and fully understand the potential risks associated with provoked batteries in order that any critical battery failure may not compromise the safety of test personnel, the facility and test equipment.

The constituent material of a battery cell influence its failure response in the event of a critical battery failure. As of 2014, the two most common Li-ion chemistries are denoted NMC and LFP based on their respective cathode material. However, all commercial Li-ion battery cells use the salt  $\text{LiPF}_6$  together with alkyd carbonates solvents in their electrolytes. As the electrode materials have advanced to higher levels of stability the electrolyte is often considered as the weak link as it starts to decompose when being exposed to temperatures above  $80^\circ\text{C}$  and risk to start reacting exothermally with the electrode materials if the temperature becomes even higher.

Depending on the choice of active materials in a Li-ion battery, the onset temperature of thermal runaway can be experience in the range from  $170$  to  $250^\circ\text{C}$  for most of the commercial battery cells. At elevated temperatures (i.e. starting at  $80^\circ\text{C}$ ) the cell-internal pressure of these batteries rapidly increases and if the heat-up rate is too fast for the safeguard systems to comply, extensive ventilation of electrolyte vapor and other gases risk to be emitted to the surrounding of the battery. If there exists a sufficient ignition source, a fire could be the worst-case scenario. The gases released during ventilation and the gases during battery fire have proven to be unhealthy to people since they may constitute of species such  $\text{CO}_2$ ,  $\text{CO}$ , various organics, fluoro-organics, and possibly hydrogen fluoride.

### **Efficient and Safe Methodology**

In order to reduce the number of unknown parameters related to a battery system of an E-Vehicle that is exposed to a crash test, it is beneficial to study a smaller system (i.e. the battery system or sub-components) than the complete E-Vehicle. The mechanical interaction between the battery and its surrounding can be extracted from either, complete E-Vehicle crash tests with dummy/inert batteries or low SOC batteries, or stringent CAE simulation models of the vehicle and the battery. By avoiding complete E-Vehicle tests with active high-SOC battery systems, safety during testing is enhanced. This is analog to the requirements of conventional vehicle crash testing when all flammable liquids such as fuels are replaced with inert liquids prior to crash tests. The mechanical characteristics that is extracted from complete (electrically inactive) E-Vehicle crash tests are subsequently transferred into CAE models of the battery sled track together with the model of the battery and/or its sub-components. After optimizations have been done with these models, a physical test setup can be constructed. The final test can be either deformation tests or acceleration tests, or a combination of the two.

Autoliv's methodology, in combination with the new battery-sled-track laboratory, ensures that the unit to be tested experience a good representation of the dedicated crash environment while the risk factors associated with critical battery failure are safely anticipated.

### **FINAL REMARKS**

Autoliv's battery-crash test facility in Sweden can provide dynamic crashworthiness investigative testing on E-Vehicle battery systems and its sub-components in a dedicated laboratory environment. Severe mechanical abuse testing can be pushed beyond the limit of critical battery failure without compromising the safety of test operators as

well as neighboring facilities. Testing beyond this limit is key to develop lighter battery designs for further extension of the range of future E-Vehicles without compromising battery integrity and crashworthiness.

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