



*WATER AND TRACTION BATTERY – IS IT A DANGEROUS COMBINATION?*

Immersion of 400 volt traction battery in  
fresh water and salt water

Lars Hoffmann

RISE Rapport 2018:33

# Immersion of 400 volt traction battery in fresh water and salt water

Lars Hoffmann

**An interim report in the "Rescue Chain" project, a project with financial support from the Strategic Vehicle Research and Innovation Programme (FFI)**



## Background

Water and electricity, can these two elements work together, or is there some unwritten law saying that these two elements must be kept apart for ever? First and foremost, we have conducted this study to establish if it might be dangerous for a fireman, for example, to dive down, or wade, to an electric vehicle (electric or hybrid electric vehicle) that has ended up in a watercourse. Moreover, to provide extra information, an analysis was made of the hydrogen and chlorine gas produced by electrolysis to assess if this mixture could be explosive. In addition to this, a thorough analysis was made of the water in the location where the batteries had been immersed. The tests were conducted during week 42, 15-18 October 2012, and during week 47, 20 November 2013.

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# Foreword

## **Project Group The Rescue Chain**

The Rescue Chain is a VINNOVA funded project, where David Sturk, Autoliv Development AB, is the project owner and, thus, the project manager for the project.

Other participants include Volvo Car Corporation, the Swedish Civil Contingencies Agency (MSB), Presto Brandsäkerhet AB, Trafiksäkerhetscentrum norr (TSCN), Surgery Unit, Umeå University and SP, Technical Research Institute of Sweden. The Rescue Chain is a research project into electric and hybrid electric vehicles' system-specific risk factors and the consequences of any damage in the event of an accident or an electrical system fault, with the aim of developing a training programme for Swedish rescue personnel.

## **Overview**

**For a prompt and competent rescue response, in the event of an accident involving an electric vehicle, new knowledge and training is needed in order to minimise the time to final treatment for the victims of the accident.**

By 2020, it is estimated that there will be several million electric vehicles on the roads worldwide. However, at present there is great uncertainty among rescue personnel concerning suitable actions and priorities when faced with all these types of electric vehicle. The vehicles' battery system not only provides high voltage, high electric capacity and great power and energy density, but also contains large quantities of combustible substances, which gives rise to uncertainty regarding the safety for the personnel who are the first to arrive on the scene. As a consequence, there is an obvious need for new risk analyses when it comes to handling accidents that involve such systems.

The main purpose of the "Rescue Chain" research project is to develop some basic material, in the form of a training programme for Swedish rescue personnel, based on an overview of the existing recommendations, as well as stress and traffic-related damage tests of the aforementioned battery systems. Based on assessments of accident patterns, documented accidents involving electric vehicles and technical basic data, accident scenarios giving rise to extensive damage to battery systems, and how the systems reacted to this damage, have been studied.

A number of types of commercial battery are commercially available but, thanks to the high energy and power density of Li-ion batteries, the aforementioned are the most commonly used for electric vehicles currently in production. For this reason, the emphasis during this project has been placed on Li-ion battery cells and systems. Apart from collision tests involving loads that mirror real traffic accidents, stress tests have been conducted regarding short-circuiting (internal/external), immersion in water (varying salt concentration), the resistance of insulation materials, spark formation, fire/combustion energy, gas analysis as well as assessment of various extinguishing agents for fire-fighting.

# Summary

By means of these tests, where Li-ion batteries have been immersed in both fresh water as well as 3 % salt water, it was demonstrated that it is completely safe to be both in the water and in the direct proximity of a battery, in this case, with 400 volt direct current. This conclusion holds, on the condition that the exposed individual, in the direct proximity of the battery, does not actively touch any of the battery's poles. Analogous to this, it can be assumed that nor does an electric vehicle, which for some reason has entered a watercourse consisting of either fresh water or seawater, constitute a danger for those bathing in the immediate vicinity of the electric vehicle.

However, this assumes that an individual who is diving or bathing does not touch exposed parts of the traction system (explanation, e.g. open battery case and directly taking hold of live exposed parts of the traction battery and its cells). However, these parts are normally built into the vehicle's protective structures and are hard to access by inadvertent contact.

The commercially available, factory produced, electric vehicles made by serious designers and automotive companies have a monitoring system in their systems that immediately switch off the power supply from the traction battery to the electric vehicle's traction system.

This provides additional personal protection for anyone (e.g. fireman) who has the task of helping passengers who have entered a watercourse along with their electric vehicle.

During immersion in salt water, a pungent chlorine gas was generated, which can be thought to collect inside a vehicle's air pockets; whether these gas mixtures are flammable or not has not been studied during these tests.

No drastic events could be observed during any of these tests, however, one should be aware that a battery, which for some reason has been immersed in water and has not discharged, can still have a hazardous voltage level after many months. This is something that the rescue service, automotive mechanics and car recyclers in particular should be informed.

# 1 Method

## 1.1 Measurement set-up

Because the tests' implementation has its limitations regarding the bath volume and, not in the least, the bath's area to size, the test, for natural reasons, has its limitations.

Of course, it would have been interesting to perform this test in a large swimming pool, for example. However, the project did not have the budget to carry out tests of this size, and, moreover, there are few, if any, who want to lend out their pool for such a trial.

The bath is built from stainless steel sheet and has a volume of 600 litres.

The measurements were carried out using measurement electrodes made from acid resistant metal, preinstalled on a wooden board, as shown in the sketch below. This wooden board was also equipped with a supporting steel band, in which the test object was placed to maintain the distance in the immersed position.

In test series two, it was not possible to use this wooden board, because there wasn't sufficient space for the test object due to its width. Instead, in this test the voltage between the battery's poles and the bath's metal was measured as well as the field strength in the liquid 100 mm from the battery at 1000 mm separation.

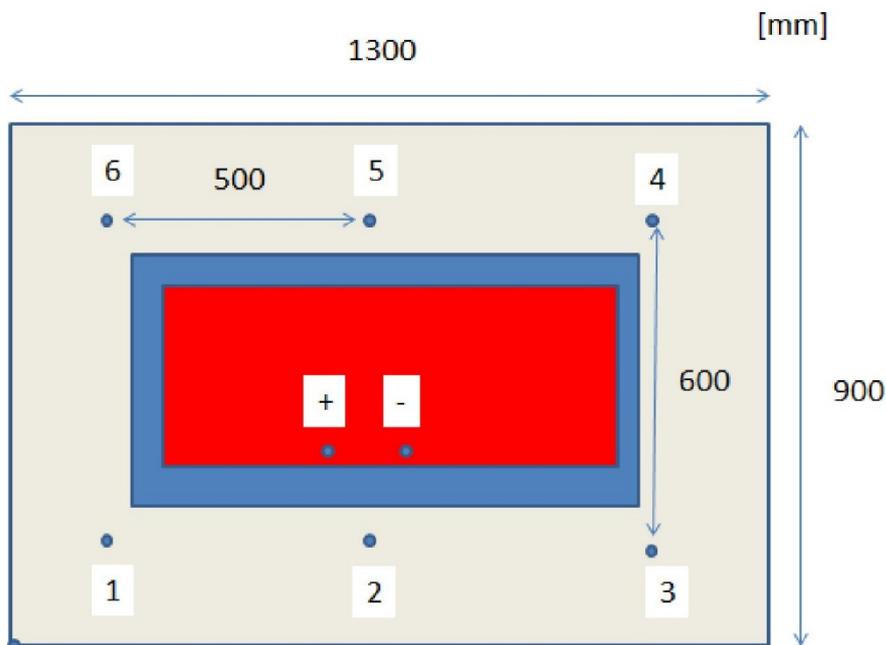


Figure 1, Sketch showing the measurement set-up prior to immersion in water, to measure electric field strengths in the water.

## 2 Results

### 2.1 Test 1

#### 2.1.1 Technical data:

- Hybrid battery for a prototype electric vehicle
- Rated voltage: 396 volt
- Electrical energy content: 2.4 kWh
- Number of cells: 108, split into four modules
- Capacity per cell: 7 Ah
- Rated current: 210 Ampere
- Battery type: LiFePO<sub>4</sub>
- Packaging, Pouchcell (Swedish: Kaffepåscell)

#### 2.1.2 Chemical characterisation, first trial

Chemical characterisation of three aqueous solutions contain sodium chloride (NaCl), in which a charged Li-ion battery had been immersed, which resulted in a discharge of the battery,

Performed in the Battery and hybrid electric platform (PX 11654)

Arrived at SP KMoo: 18/10/2012

Submitted by: Lars Hoffman, ELle

Analysis date: 18/10/2012 - 12/11/2012

#### 2.1.3 Methods

pH was determined potentiometrically, with a glass electrode.

Dissolved fluoride (F<sup>-</sup>) was determined by ion chromatography with conductivity detector.

Test for the presence of free chlorine (in the form of elementary (Cl<sub>2</sub>), hypochlorous acid (HClO) or hypochlorite (ClO<sup>-</sup>)) was done according to ISO 7393/1. Because free chlorine can decompose slowly, the test should be done immediately but, in this case, the test was done after six days, with the samples being stored for six days at room temperature.

Dry substance content (DS) was determined by mixing equal volumes of the three solutions and weighing the mixture before and after drying at 105 C.

General analysis was done on both the deposit that was collected on a filter (0.45 µm) and on the dried sample, where the solution had been dried at 105 C, using X-ray fluorescence (XRF) according to method SP 4343. The method is a semi-quantitative analysis of the outer layer and is applicable for approx. 70 of the 80 generally occurring elements in the periodic table (sodium and heavier elements) and gives an approximate estimate of the concentration. Important elements that are not measured are boron, carbon, nitrogen, oxygen and fluorine.

## 2.2 Test 1

### 2.2.1 Voltages Fresh Water

	U1	U2	U3	U4	U5	U6
Voltage [Vdc]	3.2	1.6	0.9	0.26	1.1	2.1
	U1	U2	U3	U4	U5	U6
Voltage [Vdc]	1.4	2.7	1.0	0.8	0.9	1.3
	U GND+	U GND-				
Voltage [Vdc]	161.3	188.4				

Voltage before test: 357

Volt Voltage after test: 353

Volt Test time: 7 min and 10

## 2.2.2 Voltages 3 % Salt Water

	U1	U2	U3	U4	U5	U6
Voltage [Vdc]	0.2	4.1	5.6	0.5	1.3	2.3
	U12	U23	U34	U45	U56	U61
Voltage [Vdc]	2.6	2.2	1.2	2.6	0.2	0.1
	U GND+	U GND-				
Voltage [Vdc]	41	17				

Voltage before test: 356 Volt, 140 Volt after half-time

Voltage after test: 62 Volt

Test time: 7 min and 25 sec

## 2.2.3 The water's effect before and after

The fresh water only causes negligible damage to the battery, however, the balancing electronics and the internal communication between main processor and the modules' measurement processors are damaged.

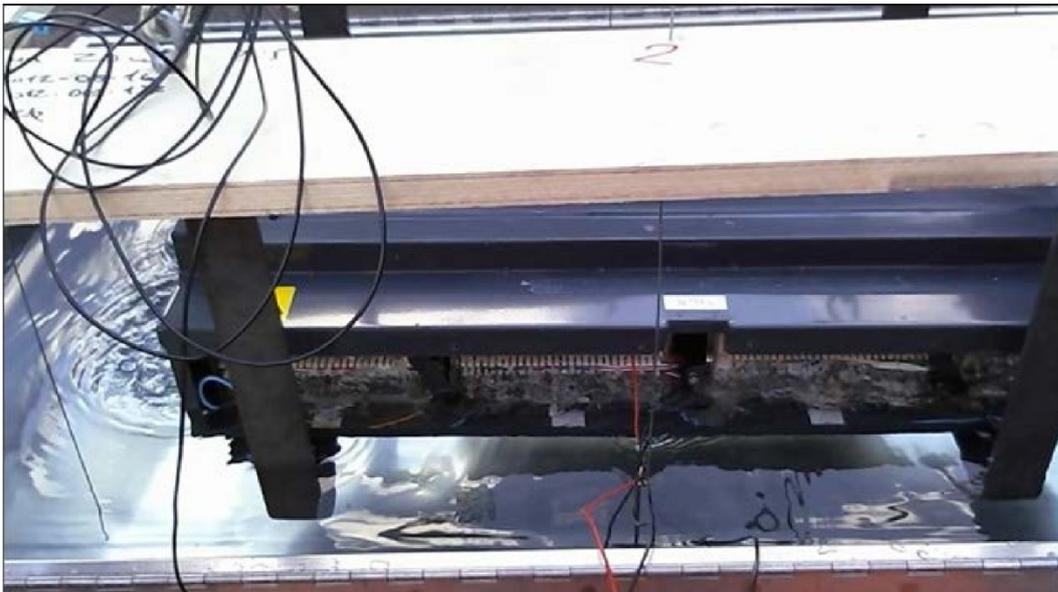


Figure 2. Before immersion in water.

Immersion in salt water is a more vital test, where the water looks as if it is boiling due to the gas generated at the cells' plus (cathode) and minus (anode) connections. Much of this gas disappears into the atmosphere, but the chlorine gas's pungent smell is immediately noticeable from a distance. During immersion in salt water, a pungent

chlorine gas is formed, which can be thought to collect inside a vehicle's air pockets; whether or not these gas mixtures are flammable has not been studied during these tests.



Figure 3. Immersion in 3% Salt Water

After the end of the test, the salt water does not look particularly inviting, and colour changes are visible, mainly due to a cocktail in which various metal ions had precipitated due to the electrolysis that occurs. Primarily, Zinc, Iron, Copper and Aluminium ions were detected in the salt water after the test, but there are other contaminants as well, see annex Chemical Characterisation.



Figure 4. After Immersion in 3 % Salt Water

During the course of the test, the fault current turns out to be so large that the internal conductors and their insulation material melt under the water surface. After the test, the traction battery is totally devoid of all electrochemical energy, however, the battery is hot for understandable reasons. The cells still contain organic electrolyte, which could act as a fuel during a fire.

## 2.3 Test 2

### 2.3.1 The water's effect before and after

### 2.3.2 Technical data:

- Battery for a prototype electric vehicle
- Rated voltage: 375 Volt
- Electrical energy content: 11.2 kWh
- Capacity per cell: 15 Ah
- Rated current: 200 Ampere
- Battery type: LMO/NMC Carbon
- Packaging, Pouch cell (Swedish: Kaffepåscell)

### 2.3.3 Chemical characterisation, second trial

Chemical characterisation of three aqueous solutions contain sodium chloride (NaCl), in which a charged Li-ion battery had been immersed, which resulted in a discharge of the battery,

Performed in the Battery and hybrid electric platform (PX 11654)

Received by SP KM: 12/03/2013

Submitted by: Lars Hoffman, ELle Analysis date: 04/12/2013 - 21/12/2013

### 2.3.4 Methods

pH was determined potentiometrically, with a glass electrode.

Dissolved fluoride (F<sup>-</sup>) was determined by ion chromatography with conductivity detector.

Determination of free chlorine or hypochlorite was done by titration, according to ISO 7393/1, and the concentration is expressed as mass Cl<sub>2</sub> per Volume

Test for the presence of free chlorine (in the form of elementary (Cl<sub>2</sub>), hypochlorous acid (HClO) or hypochlorite (ClO<sup>-</sup>)) was done according to ISO 7393/1. Because free chlorine can decompose slowly, the test should be done immediately, but, in this case, the test was done after six days, with the samples being stored for six days at room temperature.

Dry substance content (DS) was determined by mixing equal volumes of the three solutions and weighing the mixture before and after drying at 105 C.

General analysis was done on both the deposit that was collected on a filter (0.45 µm) and on the dried sample, where the solution had been dried at 105 C, using X-ray fluorescence (XRF) according to method SP 4343. The method is a semi-quantitative analysis of the outer layer and is applicable for approx. 70 of the 80 generally occurring elements in the periodic table (sodium and heavier elements) and gives an approximate estimate of the concentration. Important elements that are not measured are boron, carbon, nitrogen, oxygen and fluorine.

Two water samples were taken during the second trial, both of the samples were taken from the water that exited the battery when it was lifted up out of the bath approx: 30 min after the battery had been submerged into the water. The first water sample was taken from the fresh water test, and the second water sample was taken from the salt water test. We expected to find ions from copper, aluminium, zinc, tin, nickel and iron. Furthermore, we wanted to see the presence of chlorines, partly as elementary chlorine, Cl<sub>2</sub>, but also in compounds along with hydrogen and oxygen. Moreover, we wanted to see if there was any possibility of finding any type of fluorides in these water samples. The way the electrolysis affect the pH value of the water was also of interest. The water samples were examined three weeks after the batteries were immersed in water, for which reason, free chlorine may have dropped during this time. For a more detailed reading, consult the full report from Eskil Sahlin, SP Chemistry, Annex 2

Table 1 Determination of pH, dissolved fluoride (F), free chlorine and dry substance concentration (DS)

	Fresh water	3% Salt Water
pH	9.2	6.4
F	<0.4 mg/l	<1 mg/l
Free chlorine	<0.5 mg/l	<0.5 mg/l
DS (weight-%)	-	2.6

### 2.3.5 Test series two

In test series two, it was not possible to use the wooden board, because there wasn't sufficient room for the test object due to its width. Instead, in this test the voltage between the battery's poles and the bath's metal was measured as well as the field strength in the liquid 100 mm from the battery at 1000 mm separation.

The second test, immersing a traction battery in water, was performed 20 November 2013. This test was conducted on a production battery, which is found today in commercially available products, due to confidentiality, no images or other detailed information can be given of this.

This test was intended to answer the question of what happens when two fully charged batteries are immersed in fresh water and in 3% salt water, equivalent to the salt concentration off the Swedish west coast.

Both batteries were prepared in advance with extra temperature sensors in order to read off any temperature rise in the battery. In addition, they were started up with external computer communication in order to simulate an electric vehicle in operation; in other words, both of these traction batteries were in the operating mode when we immersed them in the water bath.

The batteries are equipped with the original sheet metal enclosure, which means it takes some time before the water can penetrate fully and, moreover, we have fitted contacts on all sockets, slowing water penetration.

The first test in fresh water; within five seconds, the protection system has opened the traction battery's main switches, the battery is rendered harmless and only field strengths under 0.5 Volt per metre could be measured in the water. The traction battery is allowed to lay in the water for 30 minutes and, during this time, nothing happens. It is decided to lift up the battery and store it separately. Measurements will be conducted on a weekly basis to check the battery voltage and to see if this declines. However, during more than two months' storage, the voltage only drops marginally, by only a few Volts.

The second battery, which was dipped in salt water, has a more lively outcome, however, the same thing happens, the protection system disconnects the battery more or less immediately and, as in the first case, the electric fields in the water are less than 0.5 Volt per metre. Nevertheless, the gas formation is large and the pungent chlorine gas is noticeable immediately.

Chlorine gas is generated next to the cells' plus pole, while hydrogen gas is formed at the cells' minus pole.

A number of different products are formed from both of these elements later, but most of the gas disappears into the atmosphere, see Annex 5.2 Chemical Characterisation.

One observation from the second test on a battery in salt water was that, after 15 minutes, the cells were total devoid of electrical energy, which had converted into thermal energy in the salt water.

The salt water's start temperature was 4 °C and after 15 minute, the water temperature in 400 litres of water had risen to 23 degrees.

The heat generated was enormous and inside, under the battery case, temperatures exceeding one hundred degrees were measured.

Salt water is a good conductive liquid and, after 30 minutes the traction battery was lifted up, and it was observed that its service fuse had tripped at 200 A. Afterwards, we could observe that the service fuse had tripped pretty immediately when the salt water penetrated the battery.

No drastic events could be observed during any of these tests, however, one should be aware that a battery, which for some reason has been immersed in water, can still

have a hazardous voltage level after many months. This is something that the rescue service, automotive mechanics and car recyclers in particular should be informed.

### 2.3.6 Voltages, fresh water

The field strengths that could be measured in the test with fresh water turned out to be less than 0.5 Volt per metre, 100 mm from the battery.

### 2.3.7 Voltages, 3 % salt water

As in the test with fresh water, the measured field strengths were also low in this test.

The field strengths that could be measured in the test with salt water turned out to be less than 0.5 Volt per metre, 100 mm from the battery.



Figure 5, The battery's inbuilt system opens the main contactors immediately, the measurement instrument to the left is connected after the main contactors and the instrument to the right, before this.

## 3 Conclusions

### 3.1 Test 1

Conclusions based on test 1

In the first test, the immersion in water was carried out with a fully, on the whole, open battery. No one is going to produce an electric vehicle in this way, however, the reason the test was performed in this way was to observe the absolutely worst possible conditions.

Nevertheless, it can be considered to be completely safe to wade or dive to an electric vehicle that has ended up in the water, however, on the condition that the general public or specially trained person does NOT touch, or in any way mechanically tamper with, the traction system or intentionally come into contact with any live parts or exposed parts. However, this is, on the whole, impossible on an electric vehicle built by a vehicle manufacturer who complies with global regulations.

However, there is a small, but reasonable, chance that amateur built, or small-scale production of, electric vehicles, which are not made according to the globally agreed requirements, could be exposed in a situation where the rescue service may need to act.

Those who design these electric vehicles have not implemented the same measures, in some cases, to limit access to exposed and, thus, live parts. For this reason, the trial with a completely open battery was of great technical interest.

In the above case, it is important not to touch any exposed part of the battery or its propulsion system.

## 3.2 Test 2

Conclusions based on test 2

The protection systems that are installed in a battery designed to meet the global requirements, which the mass production, vehicle makers have, function trouble-free and disconnect the battery within a couple of seconds, from its main contactors and demobilises the battery and its dangerous voltage.

If a battery is immersed in salt water, not only does gassing occur due to the current rush, caused by the fault current in the conductive water, but a great deal of heat is also generated. This can be localised using a thermal camera, which the rescue service normally has in its mobile equipment.

## 3.3 General conclusions

Based on test 2

Electric vehicles that end up in salt water have, on the whole, discharged their electric energy within 15 minutes, by which time, the rescue service has not usually managed to reach the scene.

The knowledge that there might be chlorine gases or hydrogen chloride contaminants present in the vehicles' air pockets is, thus, highly important.

Electric vehicles that end up in fresh water certainly disconnect their main contactors but they can, even so, have a full electrical charge many months after immersion in water.

Batteries that end up in salt water are subjected to a temperature rise, which can be easily detected with a thermal camera, on the condition that these surfaces are accessible with a thermal camera.

From an electrical engineering safety perspective, wading or diving to an electric vehicle in order to save lives is safe, because the field strengths are so low that they do not even come up to the sensibility threshold value. To feel any sensation from an electric current requires higher voltages and, above all, currents, for more detailed reading, please refer to IEC 60479-1,

Effects of current on human beings and livestock.

# 4 Appendices

## 4.1 SP report Test 1



### RAPPORT

Date	Designation	Page
Eskil Sahlin SP Chemistry, Materials and Surfaces - Chemistry 010-516 52 65 Eskil.Sahlin@sp.se	12/11/2012	1(1)

#### Chemical characterisation

Chemical characterisation of three aqueous solutions contain sodium chloride (NaCl), in which a charged Lithium ion battery had been submerged, which resulted in the discharge of the battery, Performed in the Battery and hybrid electric platform (PX11654)

Arrived at SP KM00: 18/10/2012

Submitted by: Lars Hoffman, ELU Analysis

date: 18/10/2012 - 12/11/2012 Methods

pH was determined potentiometric with a glass electrode.

Dissolved fluoride (F-) was determined by ion chromatography with conductivity detector.

Test for the presence of free chlorine (in the form of elementary (Cl<sub>2</sub>), hypochlorous acid (HClO) or hypochlorite (ClO<sup>-</sup>)) was done according to ISO 7393/1. Because free chlorine can decompose slowly, the test should be done immediately but, in this case, the test was done after six days, with the samples being stored for six days at room temperature.

Dry substance content (DS) was determined by mixing equal volumes of the three solutions and weighing the mixture before and after drying at 105° C.

General analysis was carried out on both deposits that was collected on a filter (0.45 µm) and also on dried sample, where the solution was dried at 105° C, using X-ray fluorescence (XRF), according to method SP 4343. The method is a semi-quantitative analysis of the outer layer and is applicable for approx. 70 of the 80 generally occurring elements in the periodic table (sodium and heavier elements) and provides a rough estimate of the concentration. Important elements that are not measured are boron, carbon, nitrogen, oxygen and fluorine.

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SP Chemistry, Materials and Surfaces -  
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Performed by

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## 4.2 SP test report Test 2



### RAPPORT

Date  
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Designation Page  
 23/12/2013 PX22710-05

1 (2)

Lars Hoffman  
 SP ELJe

#### Chemical characterisation of liquids

##### Object and assignment

Chemical characterisation of liquids submitted by the principal. Received

by SP KM: 03/12/2013

Analysis date: 04/12/2013 - 21/12/2013

Sample ID	Sample marking / Sample description
22710-05:1	Fresh 20131113/ Water solution with weak precipitation present
22710-05:2	Salt 20131113 / Water solution with obvious precipitation present

#### Methods

pH was determined potentiometric with a glass electrode.

Dissolved fluoride (F) was determined by ion chromatography with conductivity detector.

Determination of free chlorine (in the form of elementary chlorine (Cl<sub>2</sub>), hypochlorous acid (HClO) or hypochlorite (ClO<sup>-</sup>)) was made by titration according to ISO 7393/1 and concentration is expressed as mass Cl<sub>2</sub> per volume. (Because free chlorine can decompose slowly, the test should be done immediately but, in this case, the test was done three weeks later.)

Dry substance concentration (DS) was determined by weighing the liquids before and after drying at 105 °C.

General analysis using X-ray fluorescence (XRF) was carried out according to method SP 4343 on dried sample, where the solution was dried at 105 °C. The method is a semi-quantitative analysis and is applicable to approx. 70 of the 80 generally occurring elements in the periodic system (sodium and heavier elements) and gives an approximate estimate of the concentration. Important elements that are not measured are boron, carbon, nitrogen, oxygen and fluorine. Levels are reported for dried sample.

Determination of iron (Fe), aluminium (Al), zinc (Zn), copper (Cu), tin (Sn) and nickel (Ni) in solution was made using inductive coupled plasma-optic emission spectrometry (ICP-OES) after acidification of the sample.

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## Results

### Determination of pH, dissolved fluoride (F<sup>-</sup>), free chlorine and dry substance concentration (DS)

	Fresh 20131113	Salt 20131113
pH	9.2	6.4
F <sup>-</sup>	<0.4 mg/l	<1 mg/l
Free chlorine <sup>nb</sup>	<0.5 mg/l	<0.5 mg/l <sup>c</sup>
DS (weight-%)	Not determined	2.6

- The solutions were three weeks old when the analysis was done.
- The concentration is expressed as mass Cl<sub>2</sub> per volume.
- A weak red tint can be seen initially when titrating sample "Salt 20131113", which shows that free chlorine is present in the sample, but the level is under the report limit (0.5 mg/l).

### General analysis using XRF

	Dried 20131113	Salt 20131113
Chlorine, Cl (weight-%)		approx. 60
Sodium, Na (weight-%)		approx. 35
Iron, Fe (weight-%)		approx. 2
Aluminium, Al (weight-%)		approx. 2
Zinc, Zn (weight-%)		approx. 2
Copper, Cu (weight-%)		approx., 1
Tin, Sn (weight-%)		approx. 0.3
Nickel, Ni (weight-%)		approx. 0.2

Only levels > approx. 0.1 weight-% are reported. Levels that are reported are for dried sample.

### Determination of Fe, Al, Zn, Cu, Sn and Ni using ICP-OES

	Fresh 20131113 (solution)
Iron, Fe (mg/l)	4.2
Aluminium, Al (mg/l)	8.0
Zinc, Zn (mg/l)	14
Copper, Cu (mg/l)	5.5
Tin, Sn (mg/l)	2.2
Nickel, Ni (mg/l)	2.2

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SP Chemistry, Materials and Surfaces - Chemistry

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