SAAB

Mechanical, climatic and EMC testing of battery driven systems for military use.

Electrical safety, fuses and DC arcs.

2021-04-20 Clas Tegenfeldt

Scope

- This presentation is about the special needs when testing military products.
- It focuses on electrical safety during environmental testing.
- Chemical issues and fire hazards are excluded and covered by other presentations.

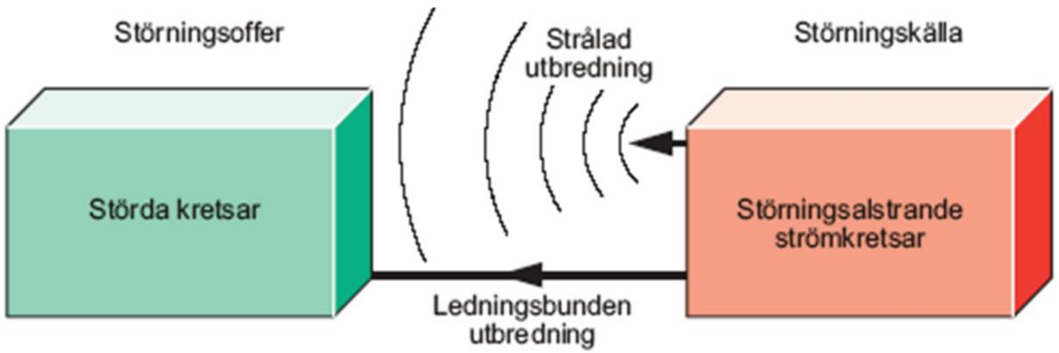
- Clas Tegenfeldt
- Started with electronics 1976, computers (punch cards on central mini computers) 1980
- Fyra årig teknisk El-Tele 1984
- Software consultant
- Master of electrical and electronics engineering (Y), 1991
- PhD studies, color computations, visualization of 3D data sets from PET, SPECT (nuclear medicine), MR and CT modalities.
- Microwave measurement instrument development
- EMC consultant since 1995

Agenda

- Civil versus military products
- Environmental testing
  - Climatic
  - Mechanical
  - EMC
- What can happen?
- Electrical safety
  - High DC voltages
  - Batteries with kWh stored
  - Arcing
  - Fuses
  - Earthing/bonding
  - Work routines
  - Gloves and protective clothing

EMC – Electromagnetic Compatibility
To be or not to be – disturbed

- Field and radiation are consequences of function as well as an obstacle for function
- Do not interfere, law and order
  - *Allocation* of spectra – intentional radiators must be protected. Different frequency ranges used for different kind of systems, FM radio, TV, cellular, radar etc.
  - Laws, directives and licenses. CE-marking etc.
  - Standards are *tools* for laws, guarantees, contracts and requirements, design testing, verification and qualification.
- Power quality, electrical safety for installations and humans
  - Overvoltage, dips and fallouts, spikes, overtones and noise.
  - Protective earth, fuses, residual current monitoring and breaking, potential equalisation methods
  - Radiation protections, workplace laws and directives
- Do not interfere with yourself, quality of function
  - System inter- and intra-compatibility.
  - Transmitter-channel-receiver
  - Separation of signals, shielded cables, filters etc.
- Accept and reject interference, quality in environments
  - Filters, protection circuits, ESD, overvoltage protection, drop out energy storage, overcurrent limiting, shielding
  - Ignore false signals and information, coding, redundancy
- TEMPEST/RÖS, Protect information, separation, encryption etc.



EMC

- EMC – Electromagnetic Compatibility
- How to make sure devices work with other devices without disturbances of function, even in large systems.
- Transmitter-channel-receiver
  - Restrict emissions
  - Control the channel
  - Accept interference
- EMC is not only some testing to pass.
- Radiofrequency allocation agreements and control of licenses
- Standards to enable trade of devices to be used in some electrical power network, communication network etc. In some sense use the same width of railway track to enable trains to cross a continent, or making a telephone call to whomever. Plug and play.
- From surface treatments, to connectors, cables, components, electronic design to system design and topology, to law and regulations.

EMC, vad och varför

- **EME** är electromagnetic environments, dvs. elmiljö. **EMI** är electromagnetic interference, dvs. störning av något slag, strålat i luft eller ledningsburet. **EMC** är kompatibiliteten, dvs. att få allt att fungera som tänkt i system i alla elmiljöer.
- **ESD** är statisk elektricitet, **EMP** är elektromagnetisk pult, **CE** är kabelburen emission, **CS** är påförd belastning på kabel, **RE** är utstrålad emission, **RS** är påstrålning.
- Kabelburet
  - CE102, vanligaste torsken.
  - CE101
  - CS114, grymt sa grisen
  - CS115
  - CS116, avlägsen blixt via kabel
- Påstrålat
  - RS101
  - RS103, koka fläsk
- ESD
  - Funktionskrav, function during
  - Robusthetskrav, function after
  - Personburen 8 kV, explosivt 25 kV, helikopter 300 kV
- Blixt
  - Direktblixt, ledningsburet, höljen, skärmar
  - Indirekt blixt
    - Magnetfält
    - Inducerat ledningsburet
  - Blixt är inte ”likström” utan har bredbandigt energiinnehåll.
- RÖS
  - Röja plats
  - Röja aktivitet
  - Röja information

EMC is quality

Clas Tegenfeldt, clte/ORTOCA

Differences between civil and military products

- A civil product as an electrical vehicle may be in continuous use a long time.
- Reliability is a required by customers, but service and repairs are acceptable.
- A self steering car is very safety critical, and an electrical vehicle must be safe for service personnel or first responders even after a crash. If something is not working safely it is taken out of service.

- Military products are often never used, as it should be. However, they shall work when needed. High reliability demands without possibility for service.
- Military products has to work in very hostile environments, even exposed to countermeasures from a foe.
- Military products are often extremely safety critical. But the requirement is that it shall work.

Differences between civil and military products

- The same testing, eg. transport vibration, may differ widely due to the purpose of the requirement or why the testing is performed.
- Design tests
- Test to fail
- Verification or qualification

The environments, despite one world, is different between civilian and military use. The limits are different and shelf time, life time and useage time differs widely.

- What does “transportation” mean for a product meant to be on a shelf 25 years? Then to be used?
- What is “life” for such a product? Fatigue?
- What civilian directives rules a military product? What test standards?
- Why is there military standards for environmental requirements and testing?

Environmental Requirements

- The same product may have requirements for transportation by sea, land and air, be used in a wide range of conditions and perhaps various climates...
- Various vibrations such as MIL-STD-810G method 514.7 for ships, helicopter, propeller airplane, jet airplane, trucks, railway.
- 516.7
- Shocks, bumps, linear acceleration etc.

- Ambient temperature of -40C to +70C or even higher.
- Core battery temperature of 0C - +60C
- MIL-STD-810G Method 501.6

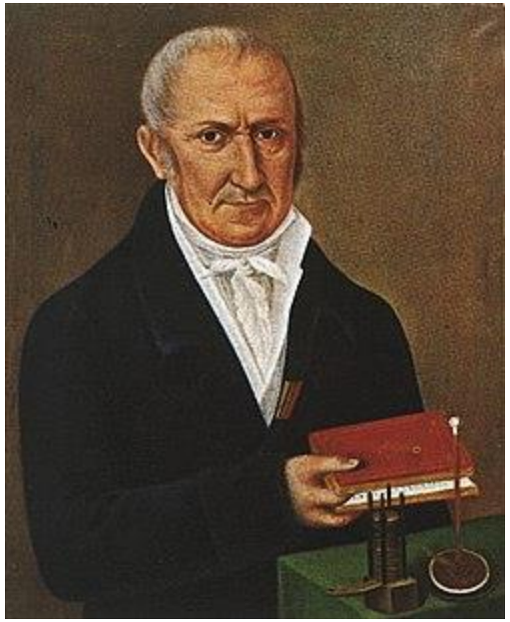
- Pressure at altitude, MIL-STD-810G method 500.6
- Rapid pressure changes

- etc. etc.

Battery types

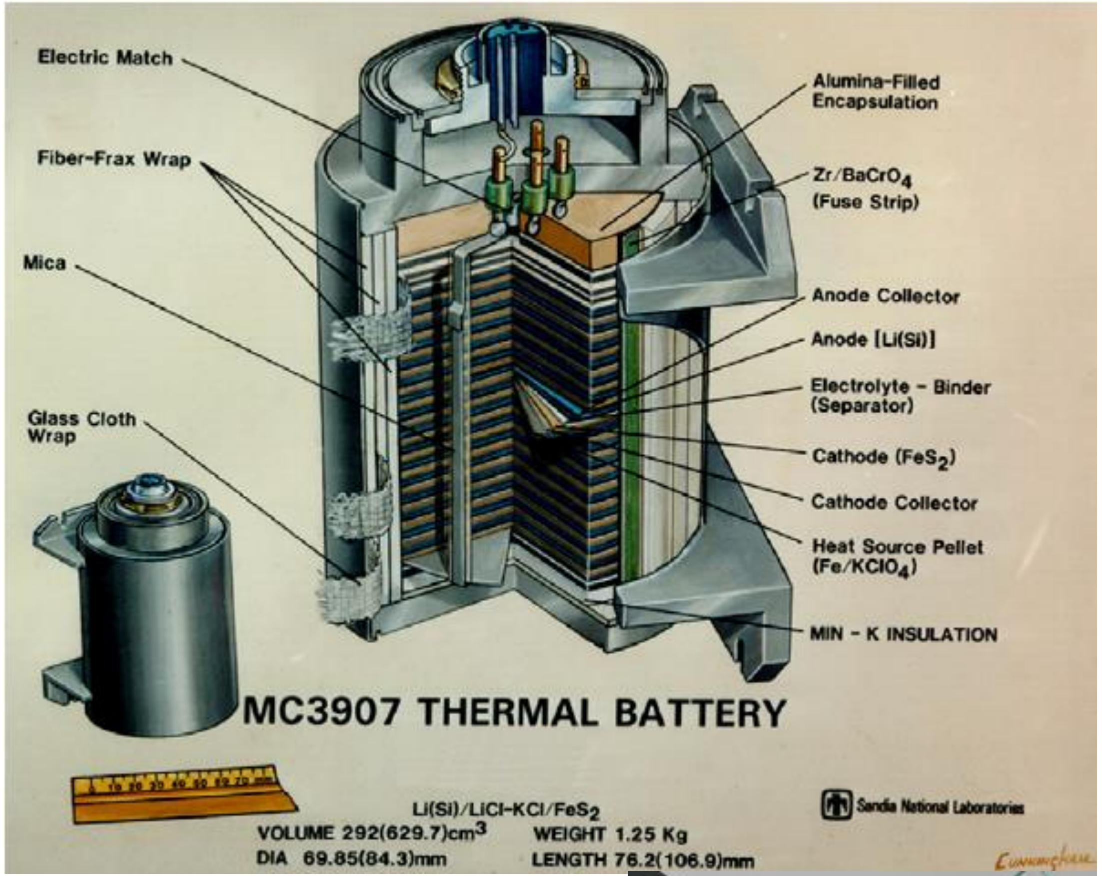
- Batteries use chemistry to store an electrical charge for later use. The chemical process may be reversible and make it possile to repeatedly recharge a battery.
- The exact battery type will be different due to demands such as maximum number of recharge cycles, such as for mobile phones; high capacity for vehicles; long time low power use such as for fire alarms or batteries for memories or clock circuits.
- For military products in storage 25 years and then used, the demands are hard to fulfill.

- Luigi Galvani
  1780 Discovered galvanic electricity and showed that an EMK with metals in an electrolyte could contract frog leg muscles.
- Alessandro Volta
  1800 Made the first practical battery. Used Ag and Zn.



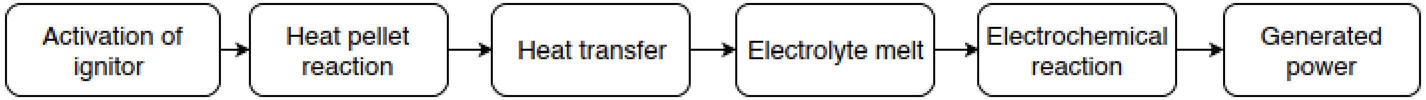
Thermal batteris

- Thermally activated (“thermal”) batteries are primary batteries that use molten salts as electrolytes and employ an internal pyrotechnic (heat) source to bring the battery stack to operating temperatures.
- Often Lithium salt mixture.
- An **igniter** sets off the pyrotechnic reactions.
- Can be stored almost indefinite without self-discharging.
- High reliability
- High-power capabilities.
- One-time use only.
- Cannot be stopped after initiation!
- Ignition and reaction releases heat which can be a problem. Over 1000 degrees inside, often 200-300C on the outside.

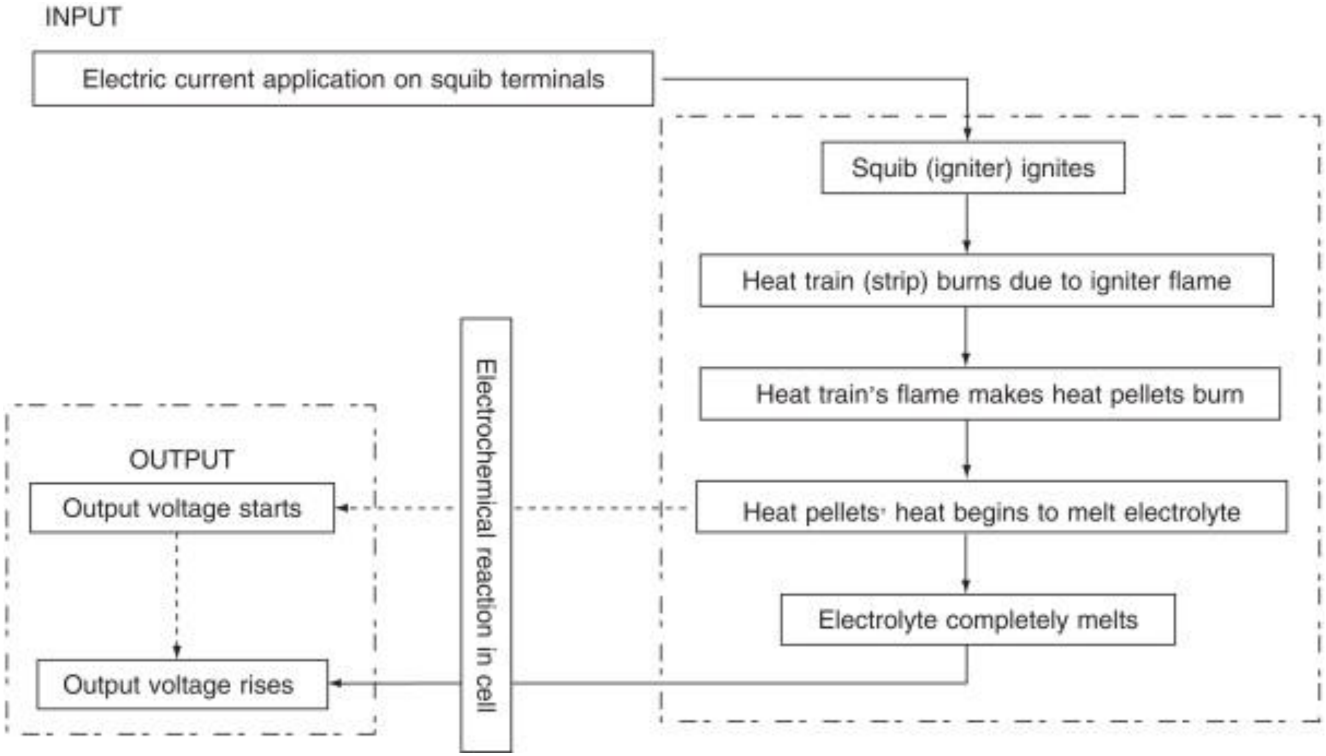


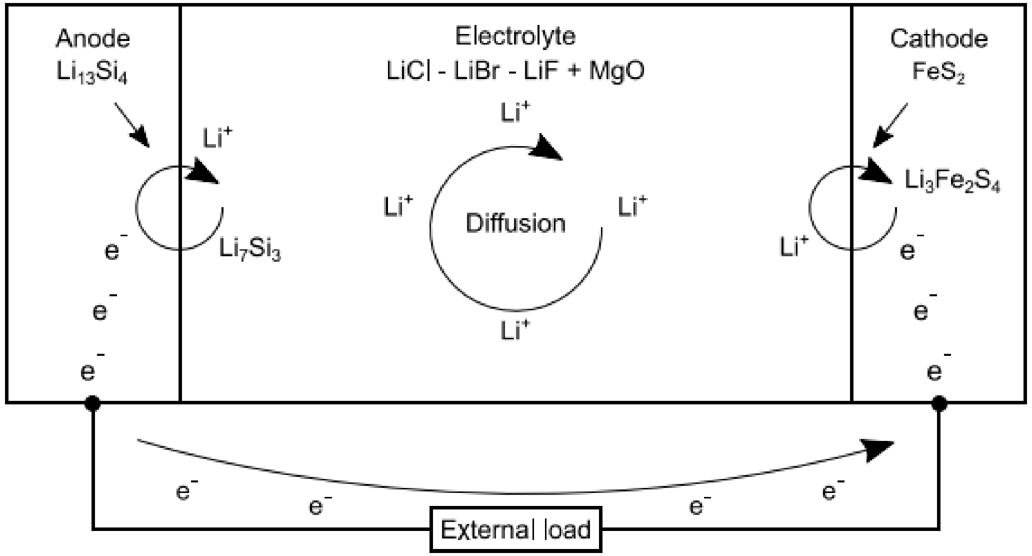
- Developed by German scientists during World War II for use in V-2 rockets.
- Dr G. O. Erb

Thermal battery



- Internal heat can reach 1000°C.
- Too low temperature and the salt goes solid and the battery stops.
- Too high temperature and it is a thermal run away condition.
- Proper thermal insulation is critical.

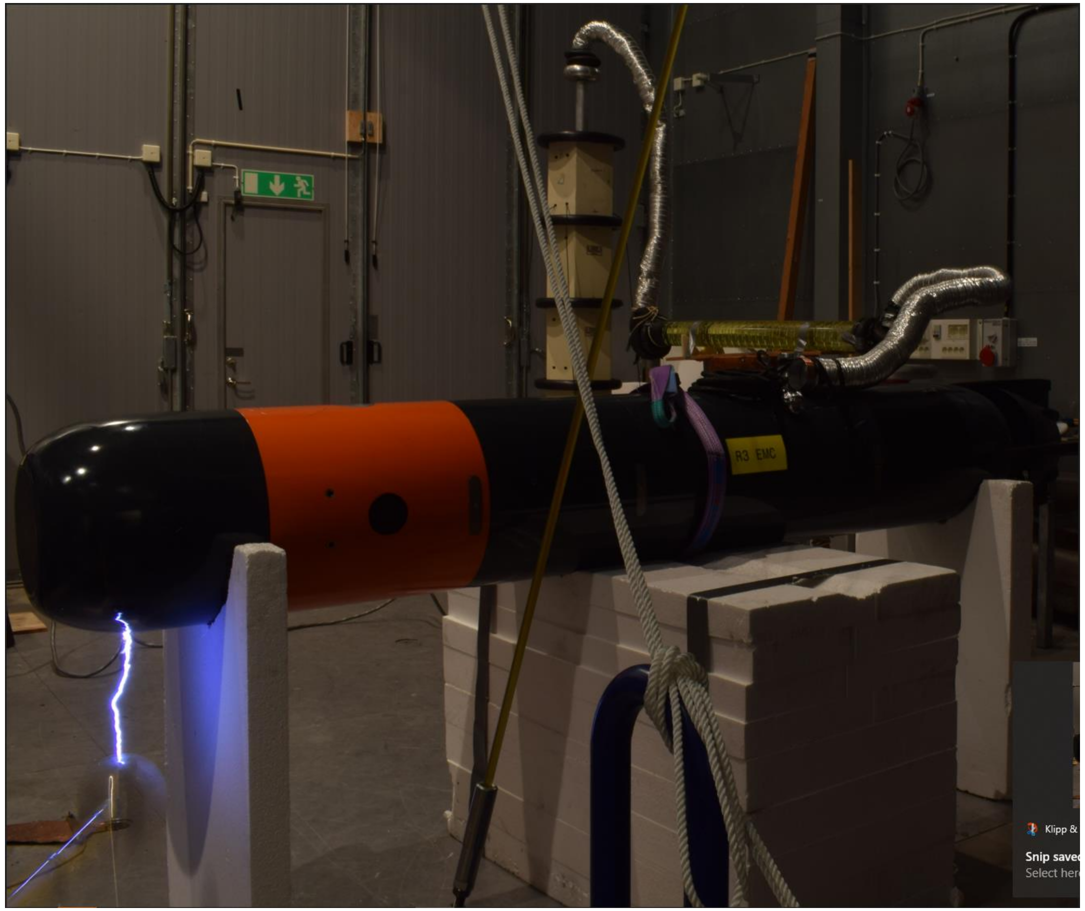




Testing of thermal batteries

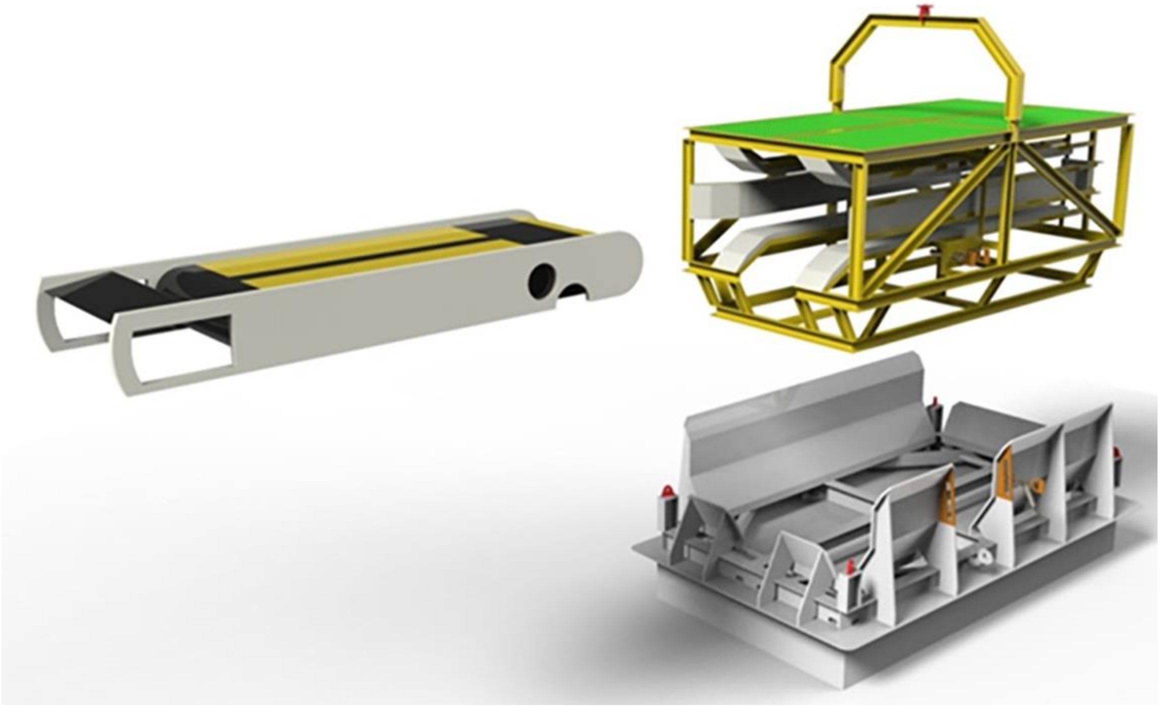
- Dangerous and challenging
- A thermal battery is a somewhat controlled exothermic thermal runaway...
- Thermal runaway as a terminology for a thermal battery means a heat within that melts the internal layers and perhaps even breaking the hull, starting an ejection of hot material.
- A break-through the casing can be seen as a hot plasma cutting of anything in the vicinity.
- A good thermal battery design makes sure it is a hermetically sealed envorinment, if that fails the chemical exposure to the surrounding and the heat released is troublesome to handle in a test lab.
- To start such a battery an igniter is used, meaning the item is regarded as an explosive. The battery itself is an pyrotechnical system. This in itself poses a safety problem during all testing, including EMC.
- Normally these batteries are tested separately and exchanged with dummies in systems when the system is tested.

Various products, land, air, sea, underwater...



Endurance

- Endurance... 107 years of search for Sir Ernest Shackletons ship Endurance was ended this year.
- Saab Dynamics ROV Sabertooth was used to find the wreck.
- A depth of 3000 meters, 15 km fiber optic tether and self contained battery power. 40km endurance.
- The Sabertooth is a hybrid AUV/ROV capable of working in deep water either as an autonomous vehicle, or via a tether. 700 kg 3,8x0,5x0,7m.
- 3x380-480VAC or 690VDC. 10kWh



ROVs

- Some tethered ROVs uses 2kVDC
- Ships mostly deliver power as unearthed 3phase IT-system.
- A stand alone diesel generator on deck may deliver 3phase as a TN-S system, a TN-C or TN-C-S system, with or without bonding/earthing to the ship.
- The vehicle may or may not have touchable parts earthed.
- The potential of a vehicle may drift relative to surrounding where an operator is positioned.
- There are multiple power issues during testing of ROVs, and electrical safety depends on a combination of many factors.
- Even though products are to be used under water, service, preparation and some equipment (power and control) are above water, hence both civilian and military EMC rules apply, as well as all specific issues for sea worthiness of ships.
- This is similar to airborne products where airworthiness, safety and both civilian and military rules may apply.

Electrical safety

1. Start the work with **both** hands in your pockets. Use your brain.
2. When your work in point 1 is done, start working with **one** hand in your pocket.
3. Only if measurements have been performed and inspections made, can you start to work with both hands.
4. Read number 1 again.

It is the current that kills, but it is the voltage that drives the current. Without voltage, a potential difference, there will be no current flow. The amount of current depends on the loop impedance.

Two types of electrical accidents:

1. Electric shock, physiological phenomenon by current through the human body.
   - Muscle cramps, let go, heart, lungs
   - Interference on neurological pathways
   - External and internal burns
2. Arc flash, current through air creating a plasma
   - Extreme sounds 140-170 dB’
   - Extreme light, eye damages
   - Extreme radiation, burn
   - Extreme heat 10-20 000°C
   - Vaporizes anything and everything
   - Sputtering of metal and other materials

Earth? To stand on or plant crops in?

- Grounding, earthing, bonding – the number one misconception all engineers have a delusion of understanding.
- There is no concept more fundamentally misinterpreted.
- What is protective earth protecting?
- Is PE really in itself protecting anything?
- If you "earth" a metallic object, is that then safe?
- Or is it that any and all earth connections add another current pathway?
- Different power systems are in use worldwide, ships, airplanes, AC/DC etc.

- The current loop source-fuse-fault-return path has some impedance and results in some fault current.
- If the fault current is 10x the fuse rating the time until break up of the circuit is reasonable short, about a second or shorter.
- In most cases everything done has an implication of using fuses as primary protection and earthing/grounding/bonding as a tool to increase the likelihood of a fuse to actually break.

Vagabond in the system...stray currents

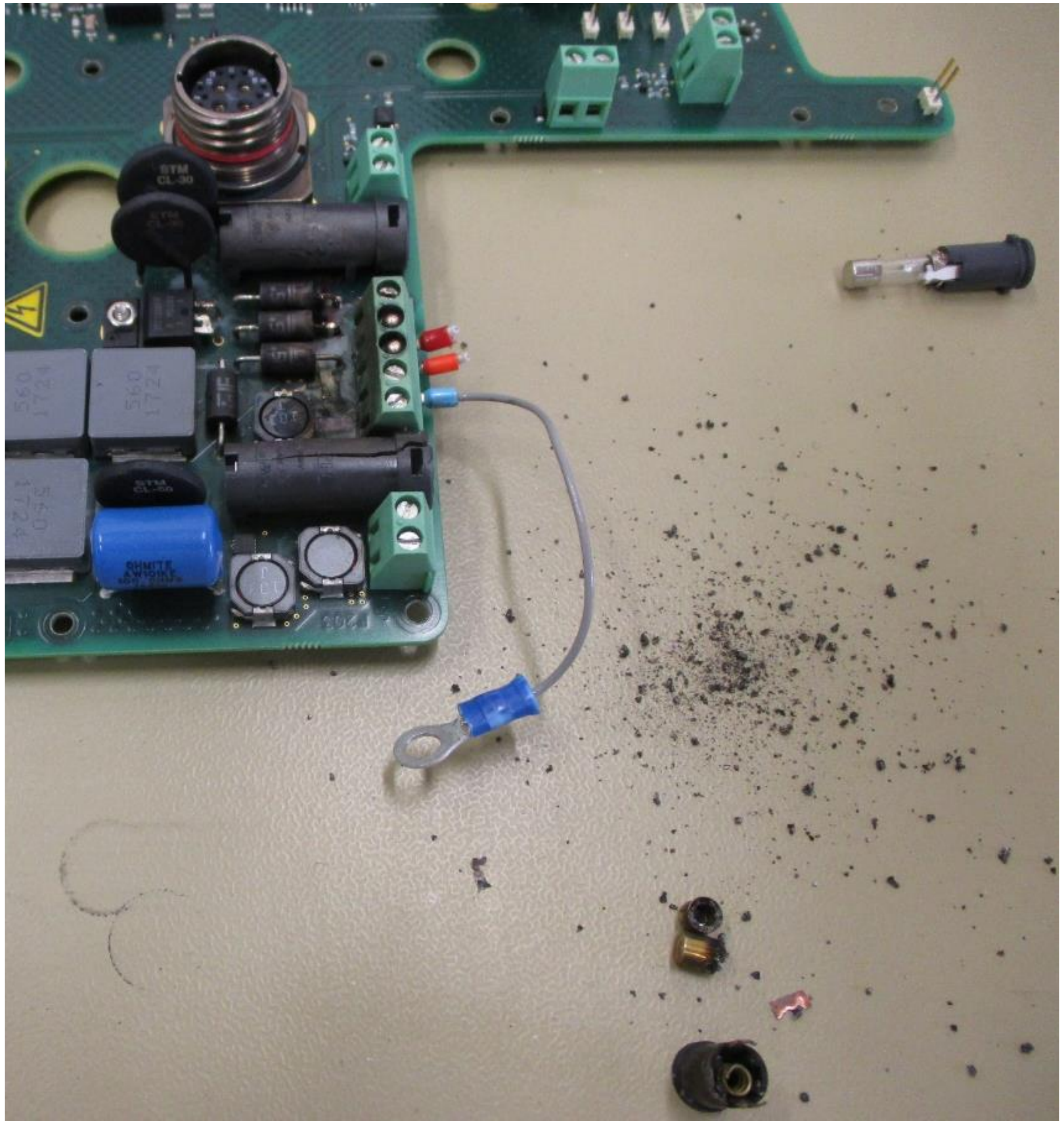
- Anything conductive can conduct current if there is a driving force, a potential difference.
- Earthing and equpotential bonding creates low impedance paths where current can flow. The potential is kept low BECAUSE it enables large currents to flow.
- The drawback is that any potential from whatever source, will give stray currents in whatever interconnected structures.
- A vibrator table is connected to PE as well as, in most cases, structure of the building, but also to the test object and test equipment.
- There is a risk connecting any test object to different power sources and systems. Battery packs is such a possible problem.
- If the battery pack is “grounded” in its chassis there is a possible problem of a current pathway of DC through the AC power network in the building as well as the structures, test equipment etc. Even without isolation faults or even a fault at all.

Fuses – to break or not to break, that is the question

- Fuses are the second most misunderstood concept of engineers.
- A fuse has a fuse rating, for which it shall never ever break.
- This is often interpreted as a binary threshold, above which it breaks.
- In reality it is a function of time and current (energy deposition into the material of the fuse), a never-break curve.
- Above the fuse rating there is a gray zone, undetermined and statistical.
- Over a large enough current (pulse) the energy is sufficient to melt and vaporize the fuse bridge (wire).
- For any fuse there exist a function curve for an always-break condition.
- Thus the “fuse rating” is in reality two sets of curves. This complete characterization of fuses are almost never published by manufacturers, at best a “typical” break-curve and perhaps some statement of statistical spread.

Example of fuse problem

- During environmental testing of a product a short circuit occurred.
- The fuse did not work as intended, it created a short circuit.
- PCB traces were melted until the process stopped.
- The battery fuse did NOT break.
- Solutions:
  - New fuse type
  - New fuse length
  - New fuse holder
  - Smaller main battery fuse amperage
  - or redesign with current limiting instead.



Fuse?

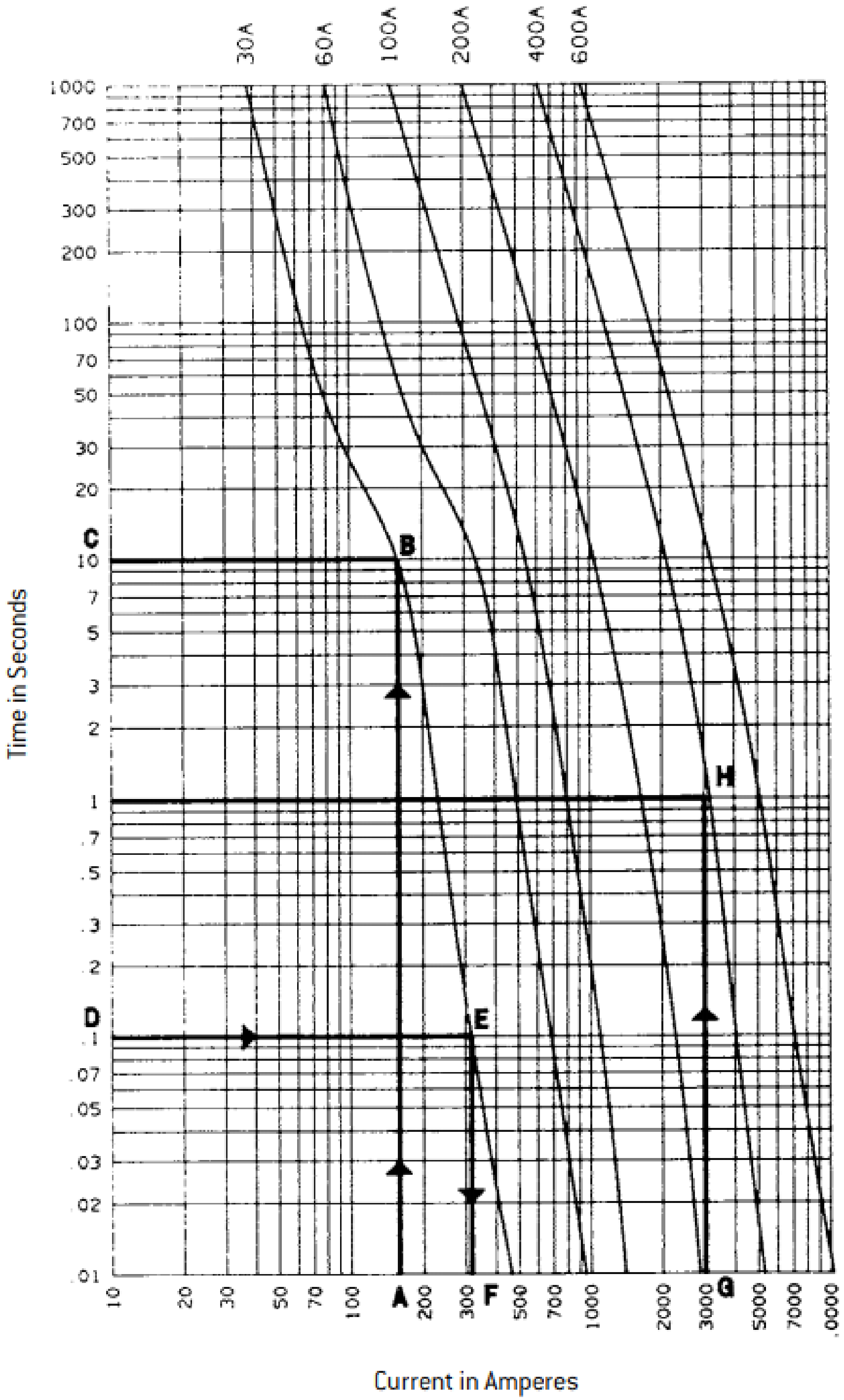
- Fuses protect cables feeding a short circuit or overload fault as well as prior distribution network including the battery cells themselves.
- Fuses only break quickly for large overcurrents, which demands low impedence return pathways.
- Fuses imply system wide design choices for isolation versus return pathways (“grounding”).
- Fuses contradict reliability while improving safety.

There are many alternative fault coping mechanisms apart from the brute force use of a fuse, disconnect, re-route, circumwent, ignore, detect, restrict, accept...

A current limitation can be designed in many ways, a fuse is a simplistic solution.

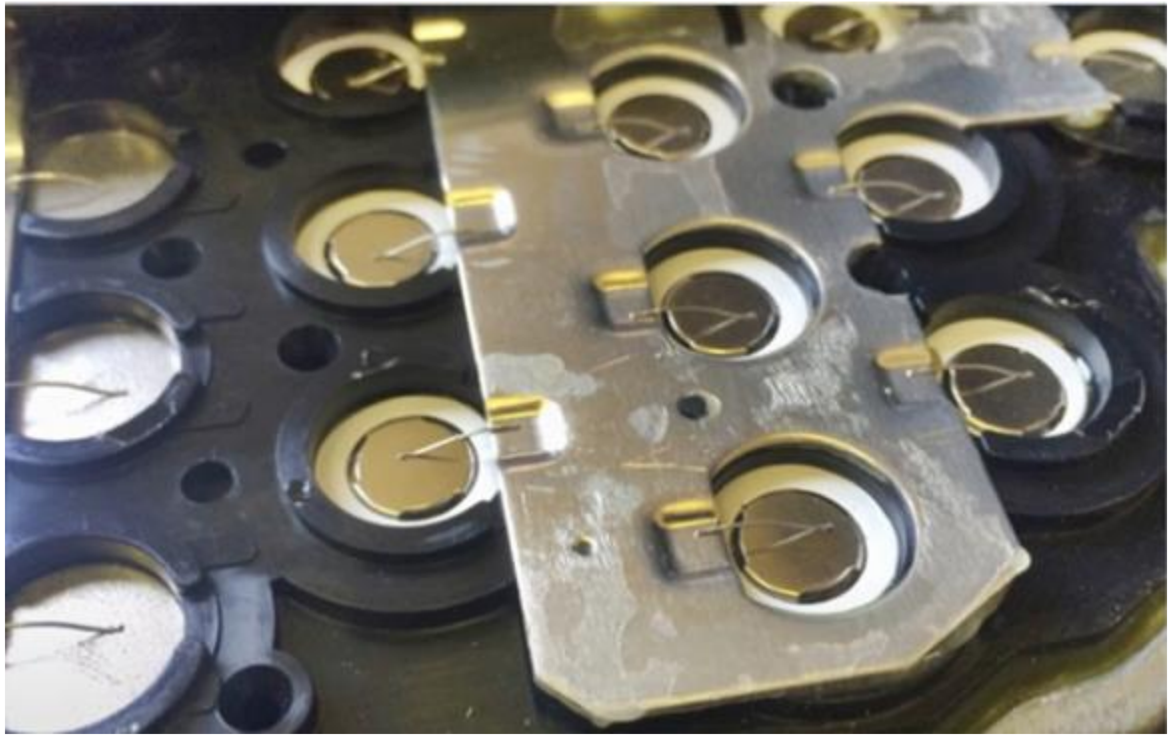
Fuse? Will it break?

- Fuses protect cables leading to a short circuit or overload fault as well as prior distribution network including the battery cells themselves.
- Fuses only break quickly for large overcurrents, which demands low impedance return pathways.
- Fuses imply system wide design choices for isolation versus return pathways (“grounding”).
- Grounding only creates more return paths and relies on the fuse to break.
- Fuses contradict reliability while improving safety.



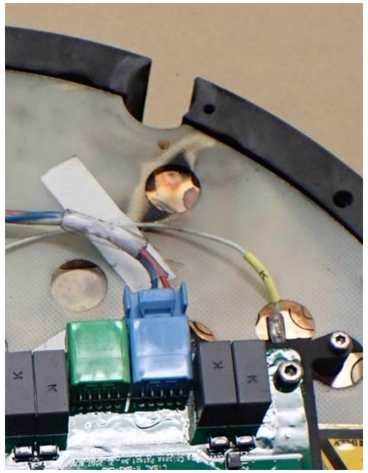
Batteries and short circuits

- Wires from cells may be used as wire fuses.
- Busbars may carry current from many cells in parallel.
- Busbars may come into contact with other parts, possibly creating short circuits



Example of flash over due to movements

- During environmental testing movements was enough to ignite a flash over between copper bus bar and structure. It melted the copper foil and when the distance was large enough it stopped.
- The main battery fuse did not break – of course!



Short circuits, cause and effect

- Short circuit = serious overcurrent due to low loop impedance
- Kirchoff's current law
- If you "earth" you also open a new pathway. A batterypack with its minus (or plus) connected to the frame, chassi grounding, any isolation faults relative to chassis will create a short circuit. Within the battery pack or anywhere external to it, even in test equipment in the lab.
- Without a solid grounding in the battery it floats and a single isolation fault is not immediately dangerous.
- Floating potentials has to have secure galvanic isolations, otherwise there may be hidden current pathways. This includes all equipment surrounding a test object, including test instruments etc.
- Short circuits do not care about designed return paths, every possible path will be utilized, even on pipes, bolts, reinforcements bars in walls, air ducts etc.
- In a typical lab almost everything is "earthed" by intention, laziness or happenstance.

Short circuits, cause and effect

- Causes of short circuits are commonly isolation faults of some kind.
- Loose wires, movement or bus bars, damaged insulation, moisture and fobs initiating arcing etc.
- The symptom is large currents, more than intended or designed for.
- The effect is heat at spots and/or cables, connections and connectors, sparks and arcing, potentially leading to fire and damages.
- It drains batteries ...

Arcs, isolation and air pressure

- Arcs are created when a gas no longer can withstand the electric field intensity, a break-down occurs.
- A flash-over, an arc, is a plasma and electrically conductive.
- The heat is very intense and creates an expansion, a shock-wave, a sound level that can exceed 140 dB up to about 170 dB.
- The light radiation emission is very intense, it can ignite and/or burn surface materials nearby, including clothes and severely burn human skin.
- The radiation is broadband, including IR, visual and UV light.
- It is intense enough to give temporary or permanent visual impairments.
- The plasma is HOT, over 10 000°C
- The plasma will consume and vaporize any material including metals.
- The arc will distinguish if
  - the circuit is discontinued (intentionally or unintentionally)
  - the distance has increased such that the available voltage no longer can withhold the arcing.

DC arcs versus AC arcs

- Arcing is very dangerous! For the installation, equipment and for humans nearby.
- The arc will continue as long as there is a voltage driving it.
- For AC the voltage will pass zero 2x the frequency of the power supply. During that zero voltage passage the arcing may distinguish.
- If the conditions for starting the arcing is no longer there, the arcing will not start again when the voltage starts to increase.
- AC will create arcing for as long as the distance and top voltage of the waveform is enough to start arcing.
- DC is another beast altogether. The start condition is the same, but the stop condition is much more severe.
- Since there is no zero voltage until the circuit is distcontinued, the arcing continues until the distance has grown to a point where the arcing stops. This distance is MUCH longer than the distance needed to start the arcing for a given voltage!
- The distance is often increased by the arcing itself by consuming all materials within reach...

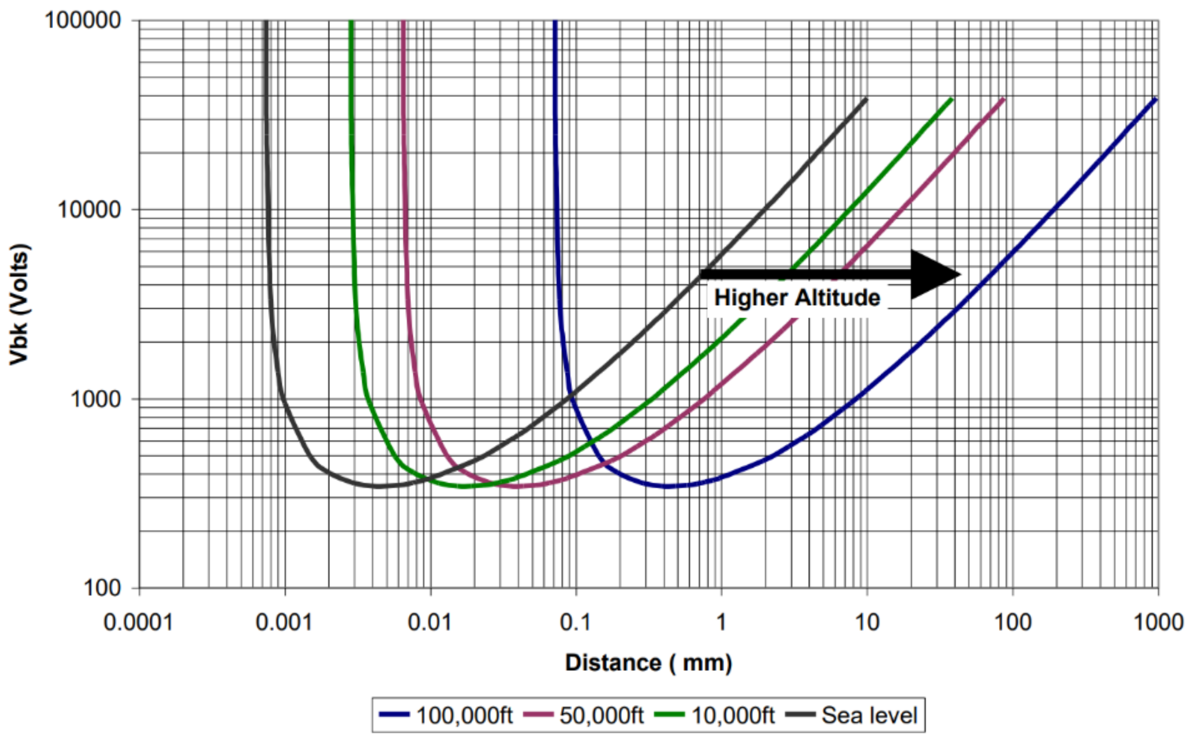
Example of serious short circuit...

- During environmental testing of a COTS product a component pin created a short circuit. The flash melted a several millimeter thick aluminium bus bar. A triangle of 100x50x3 mm disappeared, as well as all PCB:s...
- The amount of energy to not only melt but vapourize metal is large, but a battery of a few hundred volts can deliver tens of kilowatts, a second is enough to deliver 10-100 kWs
- The main battery fuze did not break.

Paschen’s law

- By plotting the spark distance versus voltage for various air pressures we get a diagram often called Paschen’s law.
- For a spark gap of 1mm only 400V is needed for discharge to occur at 100kft (blue), while on sea level (black) 1mm of air withstands 6000V.
- This can be used to upscale a voltage at some height to a test voltage at ground giving the same spark distance.
- If the design can tolerate some voltage at some altitude it can tolerate a higher voltage at sea level.
- 500V at 10kft can be tested at ground level with 1000V, representating the same spark distance of 0.1mm.
- 19kPa is about 40kft or 12km.

- **Paschen’s law is valid ONLY for AIR!**
- Any other insulating material needs to be evaluated by other means. Most have no dependency of air pressure at all.
- 301500719



The leftmost part of the curves which tend to infinity is an extrapolation that is ***not*** physically relevant. For really short distances, under 0.01mm other properties start to be important. For distances tending to zero the voltage needed also tends to zero.
Apart from the above observation, Paschen’s law is experimentally proven, and correlates to theoretical calculations for any reasonably large spark gap.