Safety aspects of hydrogen / oxygen fuel cells for autonomous under water vehicles

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Outline

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- Generic fuel cell system designs for COTS stacks
- Basic risk assessment
- Introduction in to the Failure Mode Effect Analysis (FMEA)
- Exemplary discussions
- Conclusions

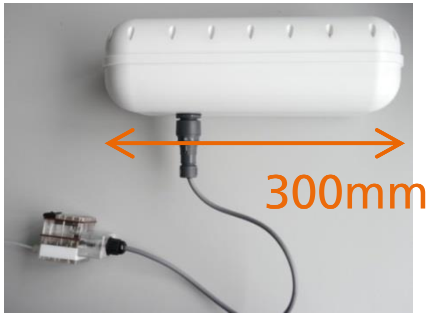
Motivation

- Autonomous Underwater Vehicles (AUV) can be used in different scenarios in future naval warfare e.g.
    - Autonomous screening of larger sea areas for mine detection
    - Patrolling of harbour entrances for harbour protection.
- For many of this applications a long autonomy of the vehicle without recharging would be helpful
- Here fuel cells can offer
    - High energy density exceeding those of most batteries
    - Fast recharging by refuelling

Motivation: Example of innovative pay loads electrochemical sensor payload

trace detection for explosives

- autonomous operation:
  - uses own power and neural network
- remotely operated:
  - power and communication linked to vehicle
- successfully tested with TNT, PETN in North Sea and Baltic Sea



Motivation

- With fuel cell cars being on the verge of commercialisation hydrogen air fuel cell technology can be considered technically mature.
- Also the use of hydrogen / oxygen fuel cell systems has been established
  - For space applications
  - On board of some submarines like German U212A
- Here specifically developed systems for this application are employed
- One goal of the introduction of AUV is the reduction of costs for certain mission.
- Therefore the price for a specific solution could exceed the cost limits for AUV
- It is therefore the intention to base the system on commercial hydrogen air fuel cell stacks or modules
- Here some consideration needs to take if the safety measures designed into theses parts with land use in mind are adequate for use in underwater vehicles

Generic operational phases

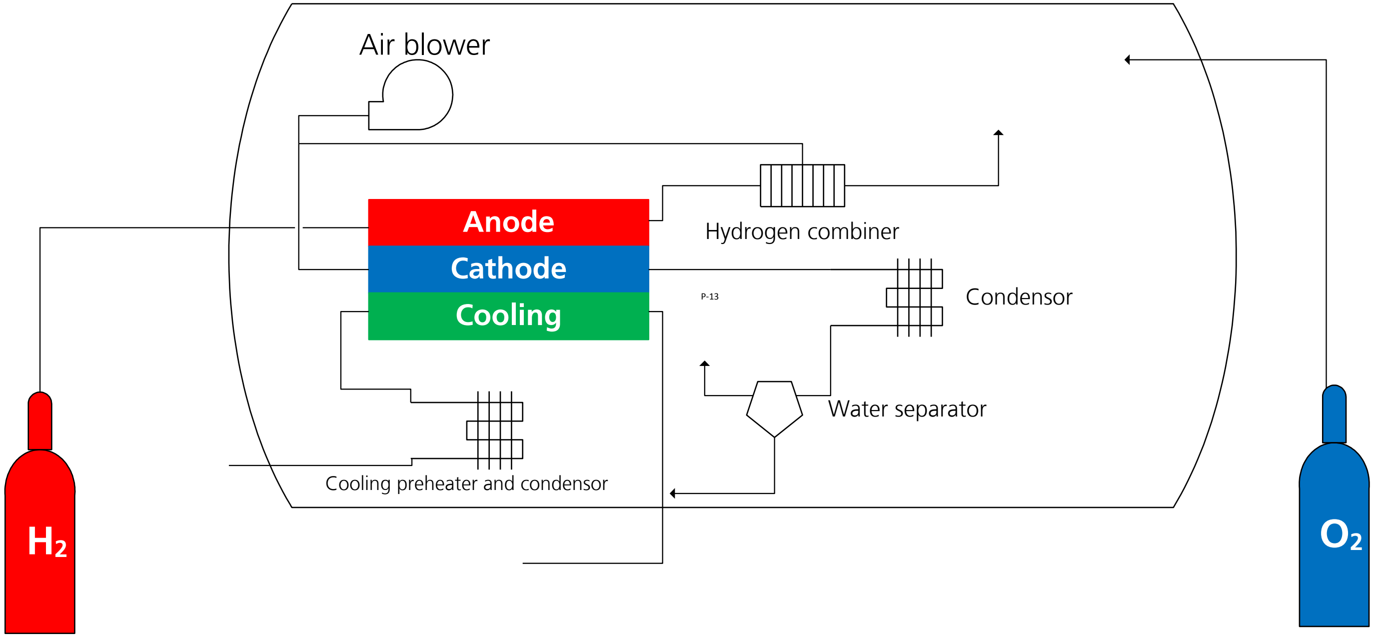
- For the safety analysis three different operational phases will be taken into account
- In the preparatory phase
  - the vehicle will be out of the sea on board of the deploying vessel or on land.
  - The fuel cell system will be in its "off-state" (VG 97010-1)
  - the valves of the hydrogen and oxygen will be closed.
  - Personnel can be close to the vessel

Generic operational phases

- In the operation phase
  - the vehicle will be in the sea and mostly submerged
  - The fuel cell will be in its “stand-by” mode or is “operating” mode (VG 97010-1)
  - Calves of the hydrogen and oxygen tanks will be open
  - No personnel should be close to the vessel
- In the recovery phase
  - The vessel will be above sea or out of sea on
  - The fuel cell should be in the “off-state” but might also be in “stand-by state”
  - Valves of both tanks will still be open
  - Personnel needs to approach the vessel

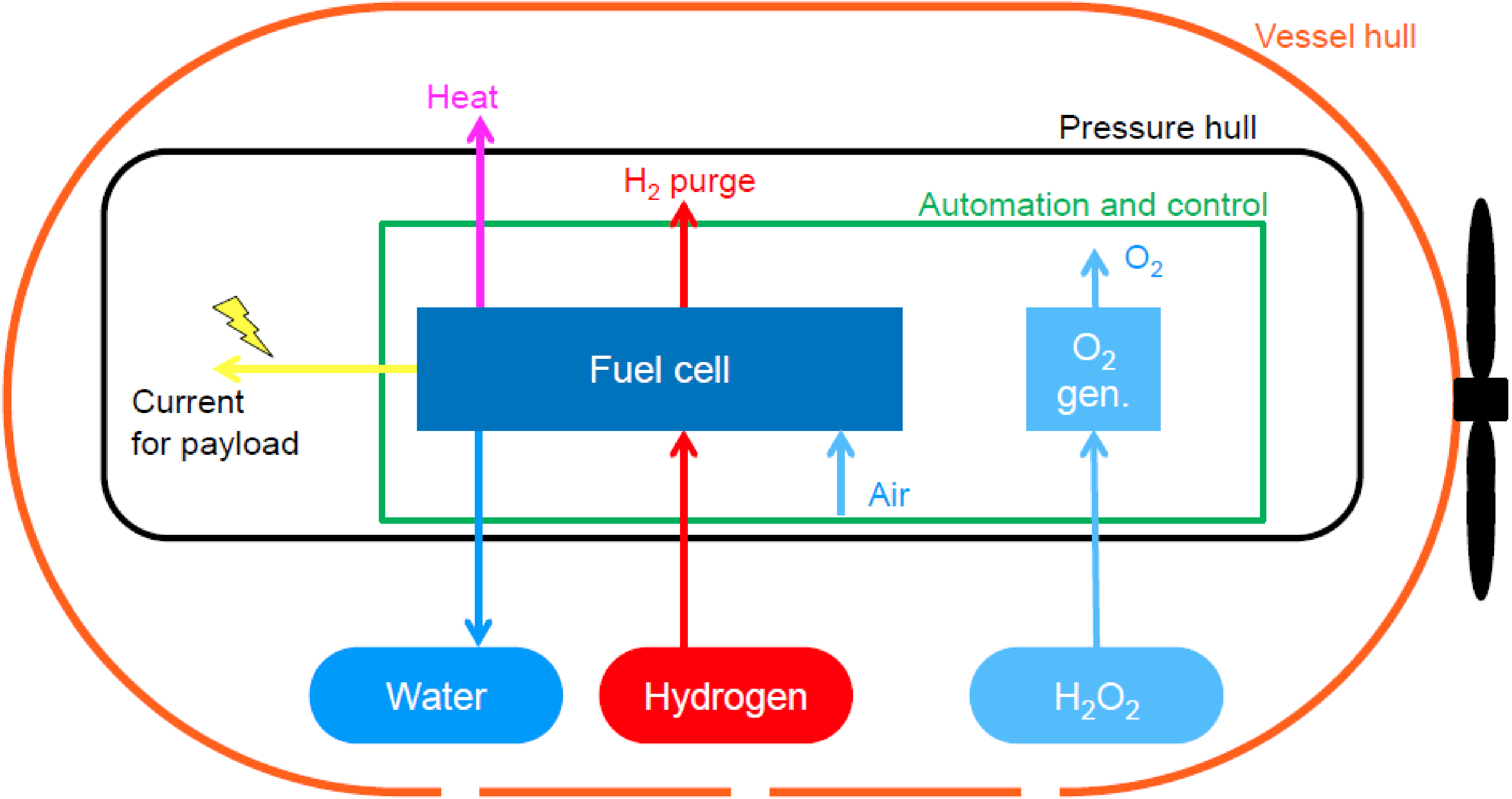
Generic fuel cell system designs for COTS stacks

- Two principle system designs have evolved that allow for using COTS PEMFC stacks on-board of AUV
  - Use the pressure hull as simulated air environment
  - Pure oxygen operation with strict avoidance of flow stagnancies



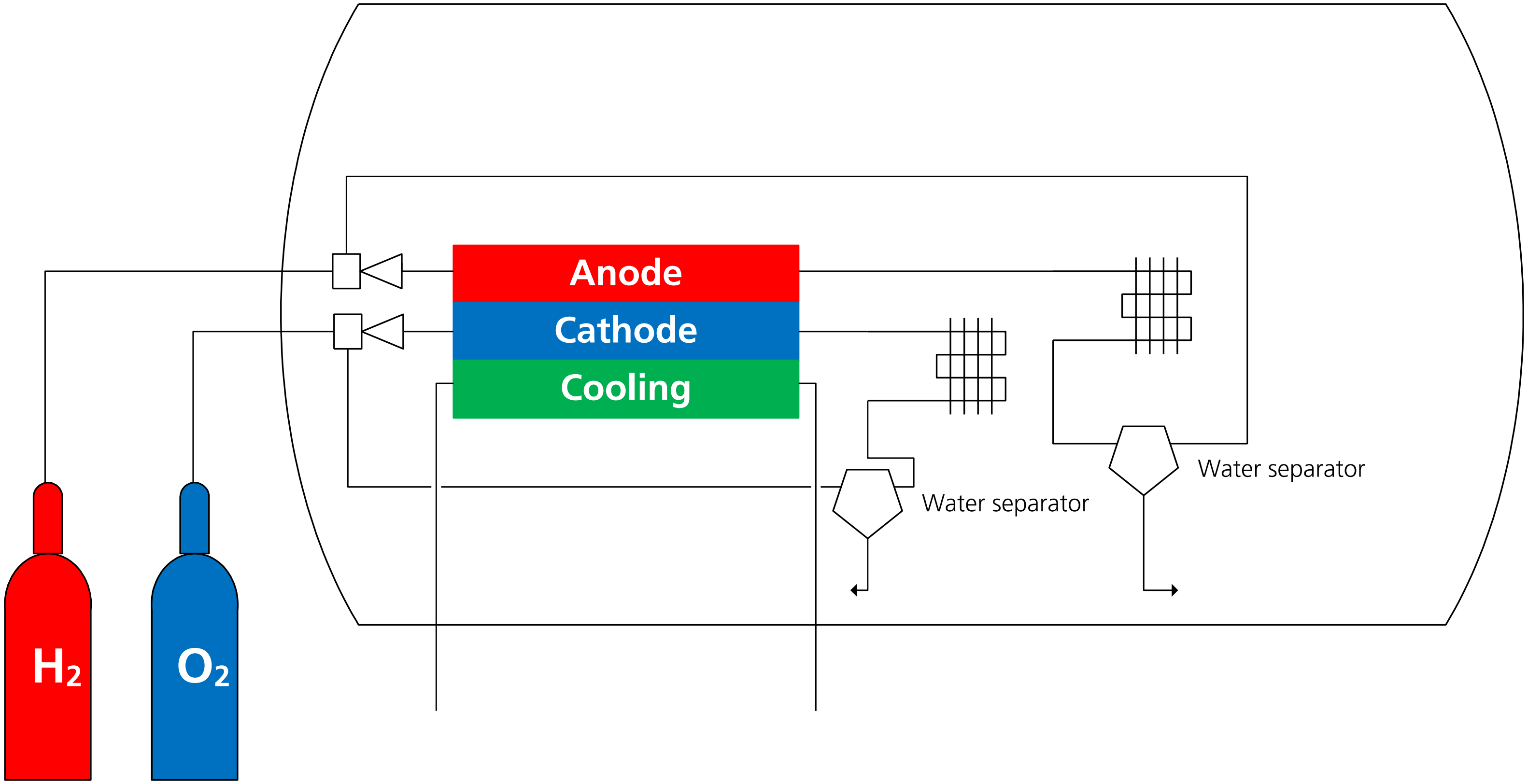
Basic scheme of a system using the pressure hull to provide a simulated air environment

Generic fuel cell system designs for COTS stacks



More detailed scheme of the fuel cell system design used developed by the FFI; Source H. Weydahl, M. Gilljam, T. Lian, T.C. Johannesen, S. Forseth, Ø. Hasvold, Presentation "A fuel cell system for autonomous underwater vehicles" presented at "Nordic hydrogen and fuel cells conference 2013" 31st October – 1st November 2013, Oslo, Norway

Generic fuel cell system designs for COTS stacks



Basic scheme of a system with closed cathode and anode loops

Basic risks assessment

- The operation of a hydrogen/oxygen fuel cell systems bears a number of potential risks
- Some important can be found in
    - High pressure of the gases
    - Flammability of hydrogen
    - Oxidising properties of pure oxygen
    - High electrical voltage
    - Hot liquid coolant
- The systems will be built in most part out of commercial components designed for that purpose
- Theses should operate safely in normal operation
- It needs to be evaluated if their designed way to react to failures is appropriate

Introduction Failure Mode Effect Analysis (FMEA)

- Failure Mode Effect Analysis (FMEA) is the required way of risk analysis for fuel cell modules according to IEC 62282-2:2012
- FMEA analysis each component of the system with respect to possible failures and their consequence with regards to three criteria
  - The severity (S) of the consequence of a failure
  - The estimated likelihood of their occurrence (O)
  - The probability of detection (D) of the failure
- For each parameter a value in the range of 1 to 10 is rated with 1 being a negligible risk and 10 a very high risk
- Single values above a threshold value often 6 or 7 require additional measures
- Optionally the three values can be multiplied to yield the so called risk priority number (RPN)
- Here additional measures should first be take for issues with highest RPN

Exemplary discussions

Risk of ignitable atmosphere, case FC system in air pressure hall

- In the case of a fuel cell system using the pressure hull as artificial air atmosphere hydrogen release into the hull can quickly lead to an ignitable atmosphere.
- Relevant components which fault can lead to such a situation are e.g.
  - The catalytic hydrogen reactor
  - The stack itself
  - The tubing
- The severity in particular in recuperation phase would be high (S = 8)
- The likelihood for the failure to occur can be regarded as:
  - Low for a properly mounted tubing O = 2
  - Low for an automotive stack (O = 3)
  - Medium for the catalytic reactor (O = 6)
- Chances to detect a failure without additional measures are very low (D = 9)
- Total RPN 144 - 432

Exemplary discussion

- The analysis reveals the low probability to detect errors is a major contribution to the over all risk
- A hydrogen sensor in the pressure hull is therefore mandatory
- As the atmosphere in the pressure hull should equal ambient air, in principle commercial automotive sensors can be used
- It needs however to be taken into account, that the atmosphere will exhibit a high level of humidity after some time of operation
- For sensors using thermal conduction this will influence the accuracy.
- Also electrochemical sensors can be influenced if water condenses on the gas diffusion electrode.
- So best option seems to be a heated electrochemical sensor
- Detected critical levels of hydrogen should lead to
  - Shut-down of the system including shut-off of the hydrogen supply
  - An external indication

Exemplary discussion

<u>Risk of ignitable atmosphere, case closed loop reactant supply</u>

- The risk can be extremely reduced if in the preparation phase the pressure hull is flooded with an inert atmosphere such as hydrogen
- In that case hydrogen leakage alone cannot cause the formation of an ignitable atmosphere inside the hull
- Only a leakage of the stack itself can cause the simultaneous release of hydrogen an oxygen due to a single failure
- So FMEA assessment
  - Severity S = 8
  - Likelihood of occurrence O = 5
  - Chance to detect D = 9
  - RPN 360

Exemplary discussion

- Again difficulty in detecting an error inside the system contributes majorly
- A sensor is required
- Selection criteria for the sensor are however quite different.
- An electrochemical sensor requires the presence of oxygen in order to operate
- Hydrogen release alone thus would not be detected!
- A sensor signal would than, however, be a clear indication of a dangerous atmosphere caused by release oh hydrogen <u>and</u> oxygen
- As no gases a regularly released into the hull humidity levels should be low.
- An thermal conduction sensor is thus applicable
- It can however only detect hydrogen as heat conductivity of nitrogen and oxygen are similar

Exemplary discussion

- Viable options
- Mount only a thermal conduction sensor
  - In that case shut down is always required when hydrogen is detected
- Alternatively an additional electrochemical sensor can be mounted
  - In that case for situation where only the thermal conduction sensor reacts shut-down can possibly be avoided
  - External indication of the presence of hydrogen is however required
  - Precondition for that scenario is a very careful calibration and regular recalibration of the electrochemical sensor for the gas mixture hydrogen, oxygen, nitrogen

Exemplary discussion

Risk of pressure built-up in the pressure hull

- The fuel cell will be operated with pressurised gases.
- Depending of the kind of gas storage pressure can range from 5 bar to 700 bar
- A leak in the gas supply within the hull can cause fast pressure built up
- This can cause rupture of the hull during recovery and subsequent opening of the system
- For land systems pressure release to the environment is part of the safety strategy
- Different tools exists
  - Rupture discs for fast pressure release
  - Overflow valves for controlled but slower pressure release
  - Excess flow valves to stop rapid release of gas supply into environment

Exemplary discussion

- Pressure built up is a relevant risk during operation and recovery phase of operation
- During the operation phase, pressure release to the environment is hindered by the outside pressure of the underwater environment.
- Standard excess flow valves are therefore barely useable as the required high flow will not be reached
- Over-flow valves for pressure release will operate on differential pressure.
- So in operational phase they cannot prevent inside hull pressure built up to the external pressure plus a given set-off
- This is acceptable as long as the exit orifice is selected large enough to allow for fast pressure release during surfacing.
- Internal parts must allow for that over pressure

Exemplary discussion

- To reduce the impact further recommended measures are
  - Reduction of the pressure entering the hull to minimum level
  - Over pressure protection at the entrance of the gas supply into the hull
  - Use of tubing with minimum diameter
- Further to protect the user for opening bulkhead <u>long bolds</u> should be employed so that in case that the hull is opened with still some remaining overpressure inside, the bulkhead can move slightly outwards releasing the pressure without endangering the user.
- Finally an external indicator for the inside pressure is recommended.

Exemplary discussion

Risk of electrical hazards

- The fuel cell will connect to the board grid so that user safety should be covered by he existing measures.
- In case that the fuel cell is used as range-extender for an existing battery the charging of the battery by the fuel cell needs to be controlled to avoid risk from battery overcharging over over-discharging
- Risk of over-discharging can occur in case of a unrecognised failure of the fuel cell system
- An active signal e.g. TTL high for the indicating of the proper functioning of the fuel cell is therefore recommended

Exemplary discussion

- Overcharging is the more likely risk
- Charging of the battery is usually performed in two stages (CC-CV)
    - Constant current (CC) charging to about 80% of the rated capacity
    - Constant voltage (CV) charging for the balance.
- A safe approach is therefore to select the DC/DC converter which connects the fuel cell to the vessel so that the maximum output voltage is <u>below the cut-off value</u> for CC charging
- Safety can further be enhanced if charging must be requested by the battery management system via an active signal e.g. TTL high

Exemplary discussion

- Frequent start-stop cycling is detrimental for PEMFC
- For systems with closed loop supply operating on pure oxygen a shut-down is particularly harmful.
- In order to avoid it a signal from the BMS indicating approaching end of charging phase is helpful.
- In response to such a signal the fuel cell system can be turned down to a reduced charging load below typical duty load of the vessel so that charging to the end of charging point can be avoided

Fuel Cell o.k	Accept Charge	Charging close to end	System effect
low	high or low	high or low	Vessel can move on remaining battery capacity
high	low	low	Fuel cell in stand-by, no charging
high	high	low	Fuel cell charges at rated power
high	high	high	Fuel cell charges at reduced power

Conclusions

- Hydrogen and fuel cell technology has become quite mature so that the basic safety of commercial modules is rather high
- Because of the use in an underwater environment some of the safety measures in particular such mitigating pressure built up need to be adapted.
- It is important that critical conditions insight of the fuel cell system pressure hull as presence of an ignitable atmosphere or over pressure are externally indicated.
- Fuel cells provide electrical power only if fuelled so that electrical risks are lower than for batteries
- If the fuel cell is used as range-extender for a battery the communication between fuel cell controller and BMS needs to be carefully designed.

Thank You for Your attention

Questions?

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