Development and testing of the fuel cell power module for 3-ton electric forklift

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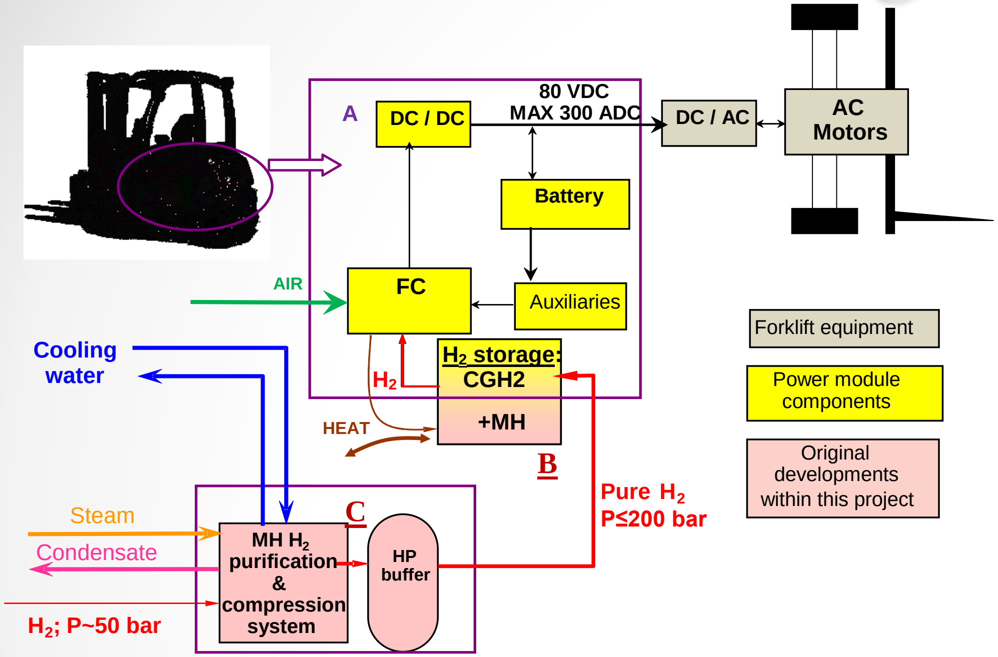
Background



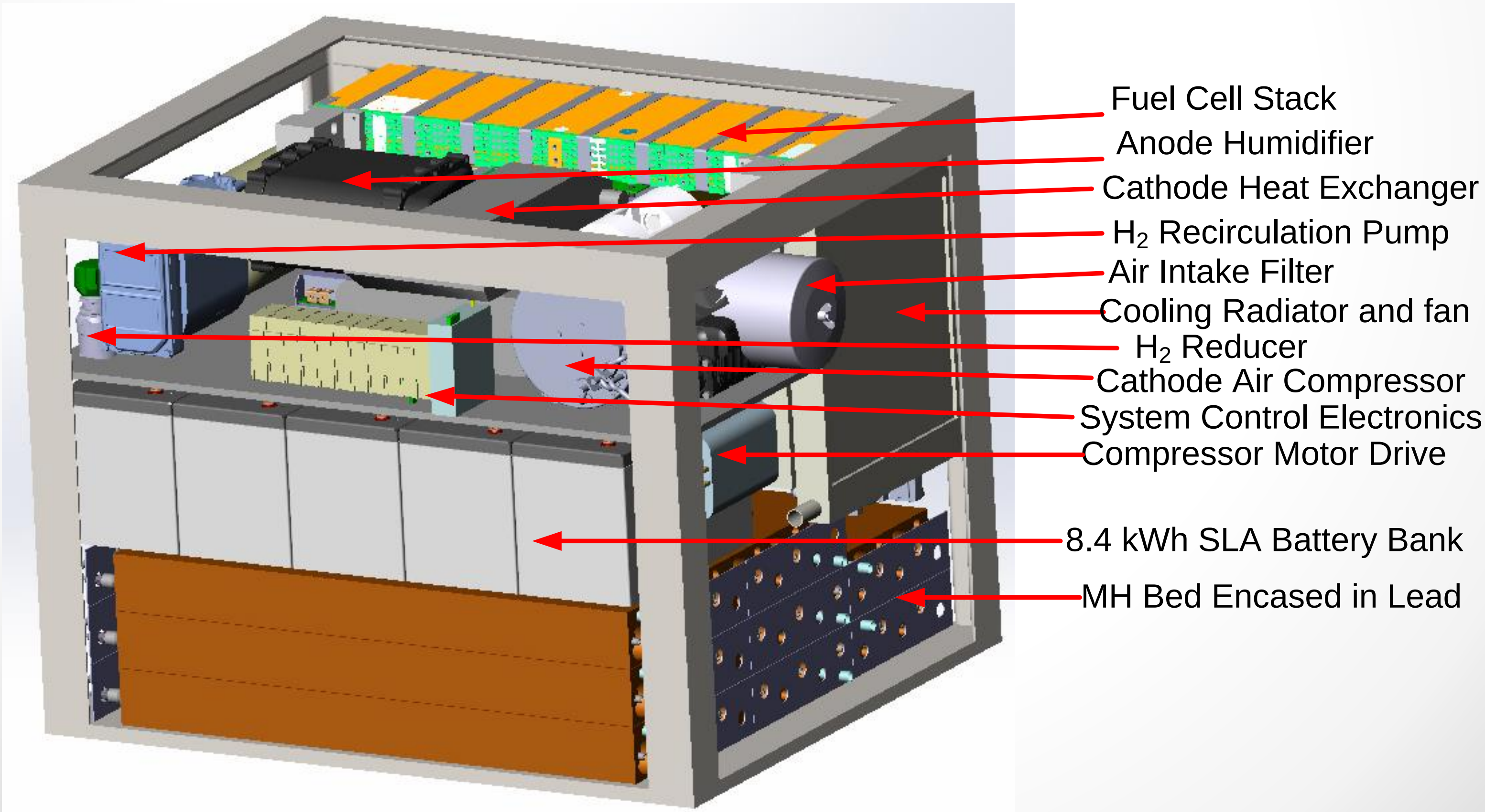
- In 2012-2015, HySA Systems integrated a metal hydride (MH) H_2 storage extension tank in a commercial GenDrive 1600-80CEA fuel cell power module (Plug Power Inc.) which was installed in a 3 tonne STILL electric forklift.
- Main performances (VDI-60):
  - Energy consumption 11.15 kWh/h.
  - H_2 fuel consumption 689 NL/kWh (CGH2 31%, MH 69%).
- The prototype is in operation at Impala Platinum refineries in Springs, South Africa, since September 2015.
- Main malfunctions identified were mainly related to Li-ion battery.

[1] Lototskyy, M.V. et al., Metal hydride hydrogen storage and supply systems for electric forklift with low-temperature proton exchange membrane fuel cell power module Int. J. Hydrogen Energy, 41 (2016) 13831-13842.
[2] Lototskyy, M.V. et al., Performance of electric forklift with low-temperature polymer exchange membrane fuel cell power module and metal hydride hydrogen storage extension tank J. Power Sources, 316 (2016) 239-250

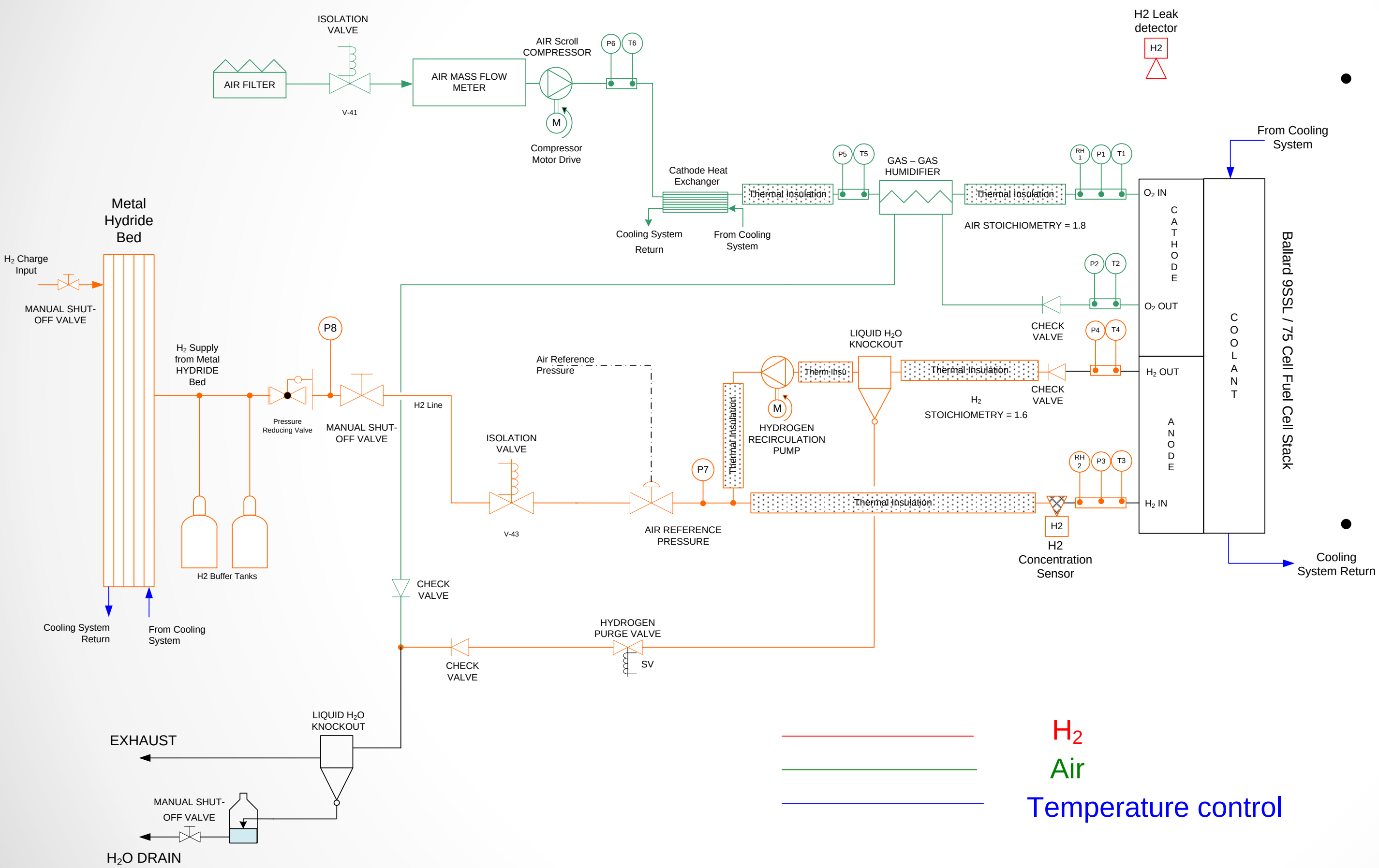
Specification and concept design

- Donor vehicle: STILL RX60-30L;
- Bus voltage (VDC): 80;
- Output power (kW): ~15 (average), up to 30 (peak);
- Dimensions (mm): 840 (L) x 1010 (W) x 777 (H);
- Weight (kg): 1800…1900

- Stack: closed cathode FC;
- H_2 storage: integrated MH storage unit, 20 Nm^3;
- Battery bank: deep cycle lead-acid, 8…10 kWh.



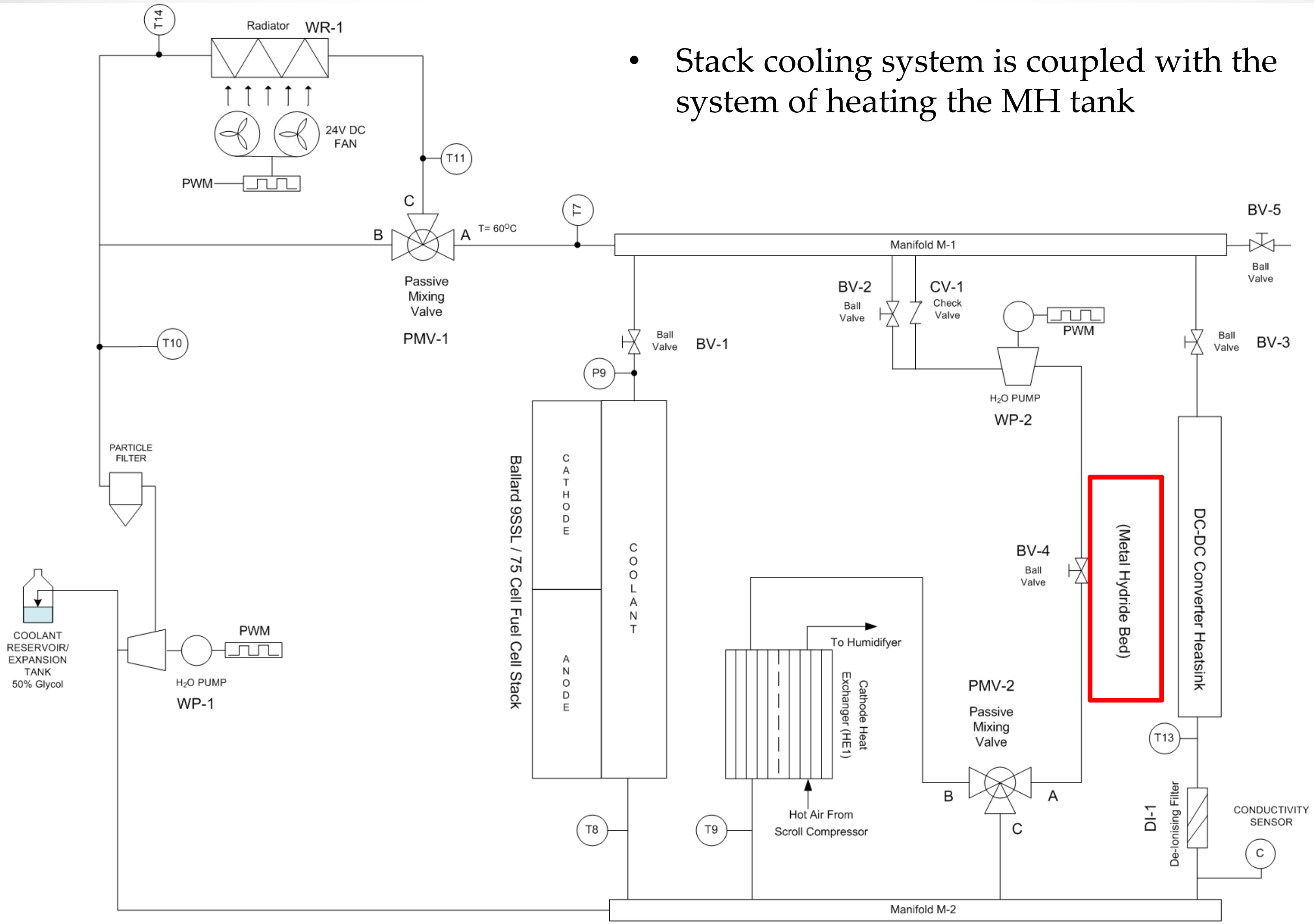
BoP design



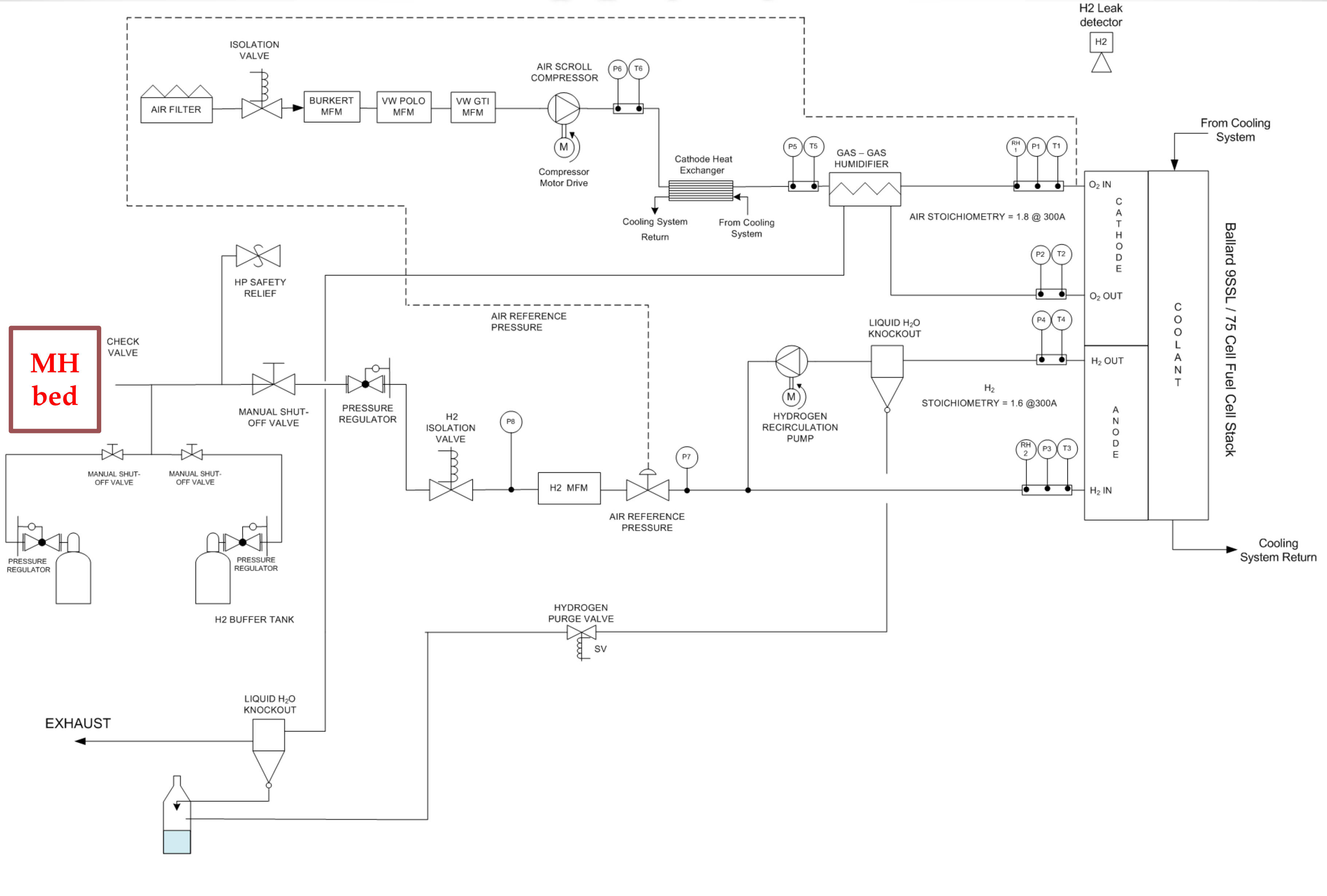
- The BoP designed around Ballard 9SSL / 75 Cell FC Stack.
- Main subsystems include:
  - The Cathode, Air Subsystem;
  - The Anode, H_2 Subsystem;
  - The Closed Circuit Water cooling (stack) / heating (MH) subsystem.
- Challenges:
  - Component selection constraints (availability, functionality & performance, size);
  - Insufficient weight (ballast required);
  - Alignment of the communication protocols

Stack cooling / MH heating system

- Stack cooling system is coupled with the system of heating the MH tank



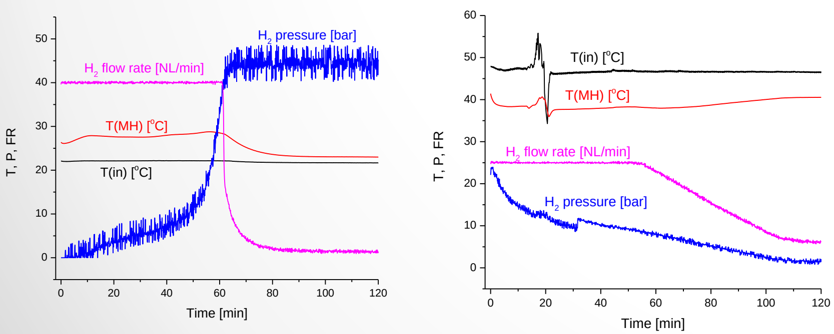
Gas supply systems



MH hydrogen storage

Lead encasing

Left: two ready-to-use MH cassettes. Right: MH tank for forklift power module comprising 8 MH cassettes



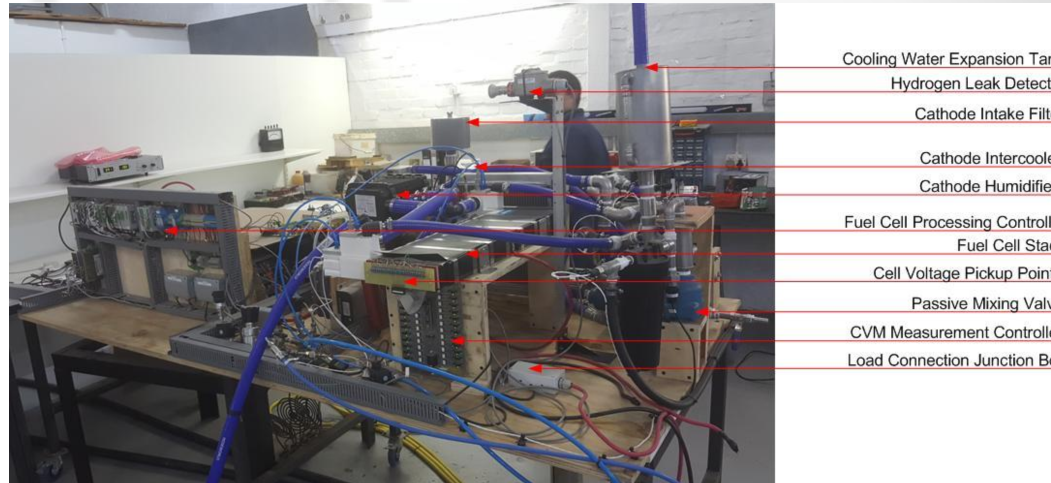
H_2 charge (left) and discharge (right) performance of the MH cassette; water flow ~4 L/min

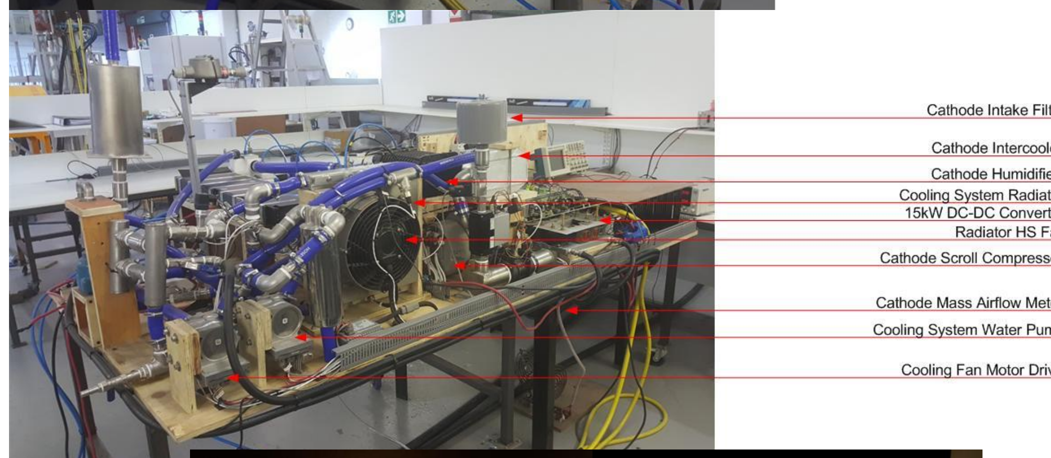
- Main challenge of conventional solution (MH containers in a water tank) is insufficient system weight. **<u>Suggested approach</u>: assembly of cassettes each comprising several MH containers encased in lead.**
- Special procedure of lead encasing which allows to simultaneously activate the MH material in the MH cassette has been developed.
- When heated with running water to T=40–50 °C, the cassette releases more than 60% of its full capacity (~2.5 Nm^3) at the H_2 flow rate of 25 NL/min.
- 8 MH cassettes have been manufactured and installed in the frame of forklift power module to form, together with 9L buffer cylinder, a hydrogen storage tank.
- The tank is characterised by H_2 storage capacity above 20 Nm^3 (1.8 kg) and has a weight ~1.2 tonnes that allows to provide counterbalancing weight (1850 kg for the whole power module within the space constrains) necessary for the safe operation of 3 tonne forklift.
- The tank can provide >2 hour long H_2 supply to the FC stack operated at 11 kWe (H_2 flow rate of 120 NL/min).
- The refuelling time of the MH tank (T=15–20 °C, P(H_2)=150–180 bar) is about 15–20 minutes.

✓ ***Patent application filed: UK1806840.3; 26.04.2018***

System prototyping

- All BoP components have been identified, procured and assembled off-board;
- Most of the components are standard, from automotive industry;
- Main challenge – the communication interface link between the various components;
- The PLC supplier has developed special firmware for the control system to enable it to communicate with the components via CAN2.0 protocol;
- The CAN implementation has been completed, and all of the BoP components requiring CAN bus communication have been integrated into a network controlled by an industrial PLC system;
- Original cell voltage monitoring system has been developed;
- The switching Load Bank Resistors have been introduced to emulate various operating conditions.

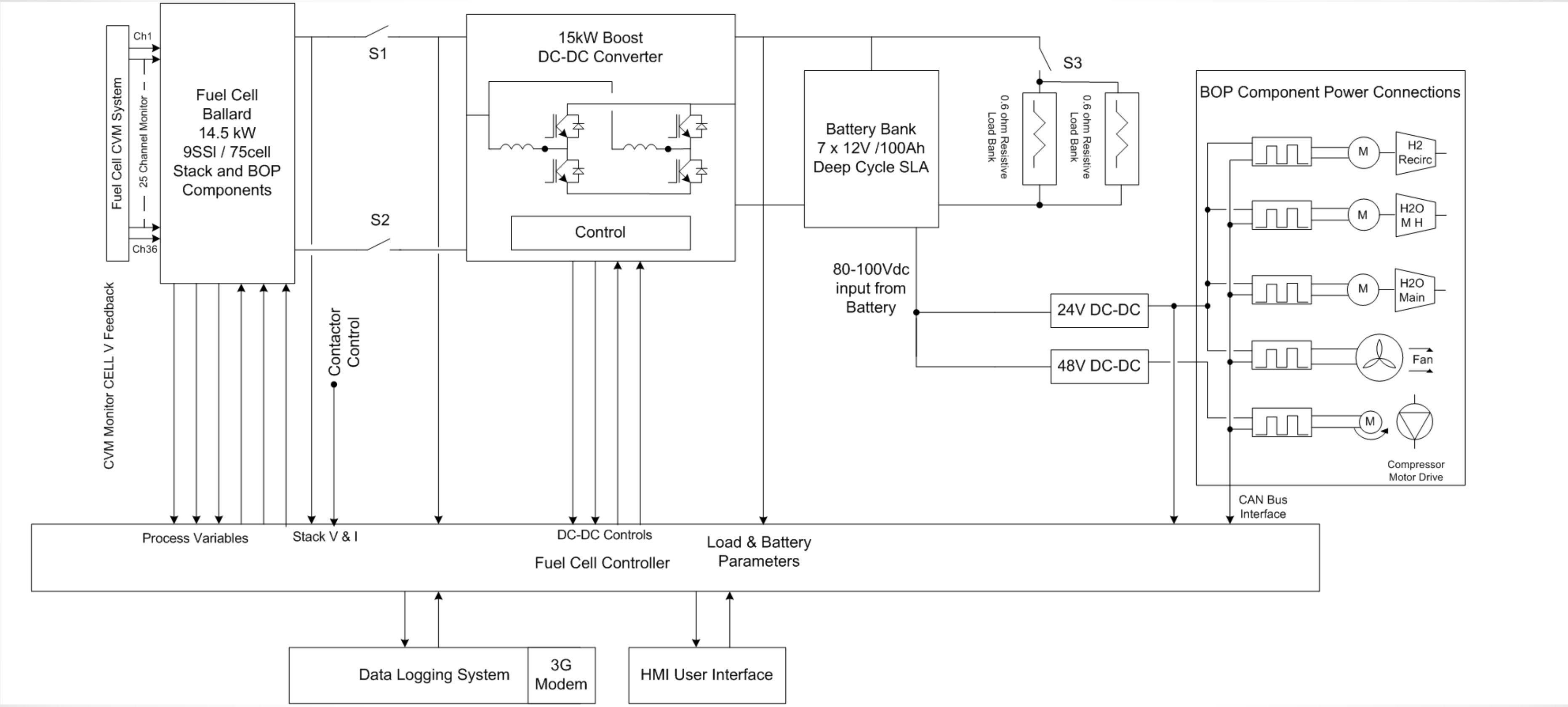




➢ **The off-board test results will be presented below.**

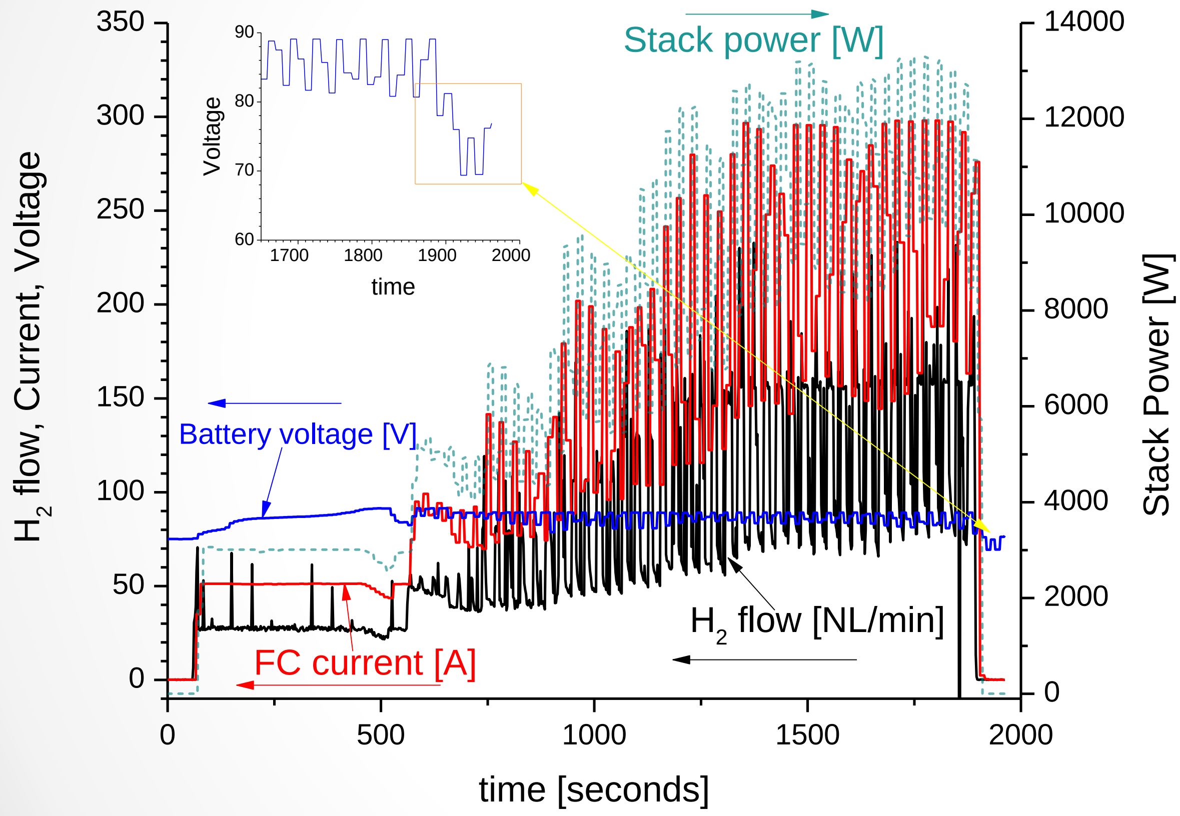
HMI screenshots

Electrical layout (1)



- <u>Initial configuration</u>: auxiliary DC/DC converters are connected to 84 (7 x 12) V battery terminals

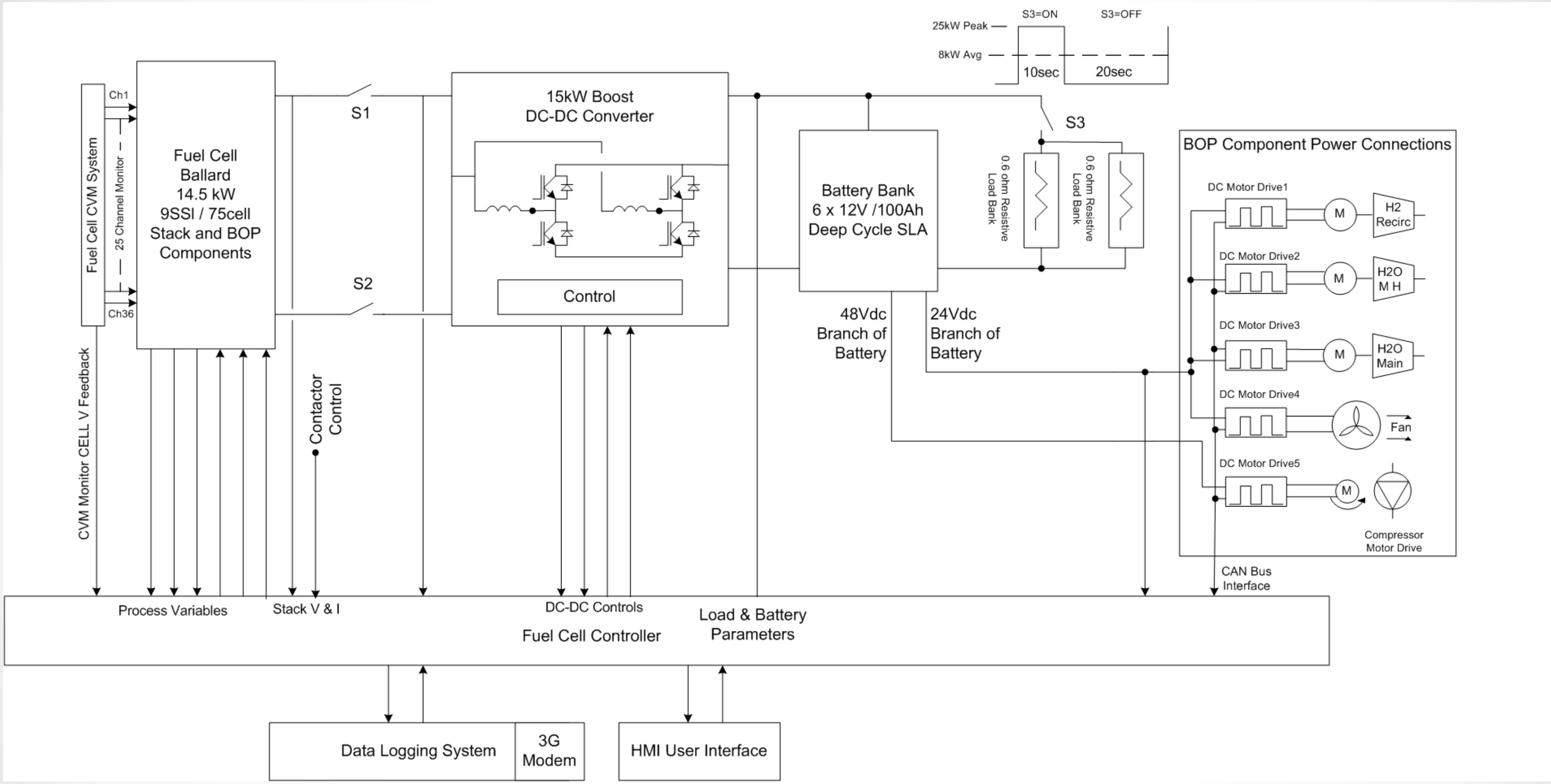
Electrical layout (1): test results



- At maximum stack power, the battery voltage drops below the minimum voltage required for the operation of the auxiliary DC/DC's resulting in the stack shut-down.
- Origin – too high internal resistance of the lead-acid battery.

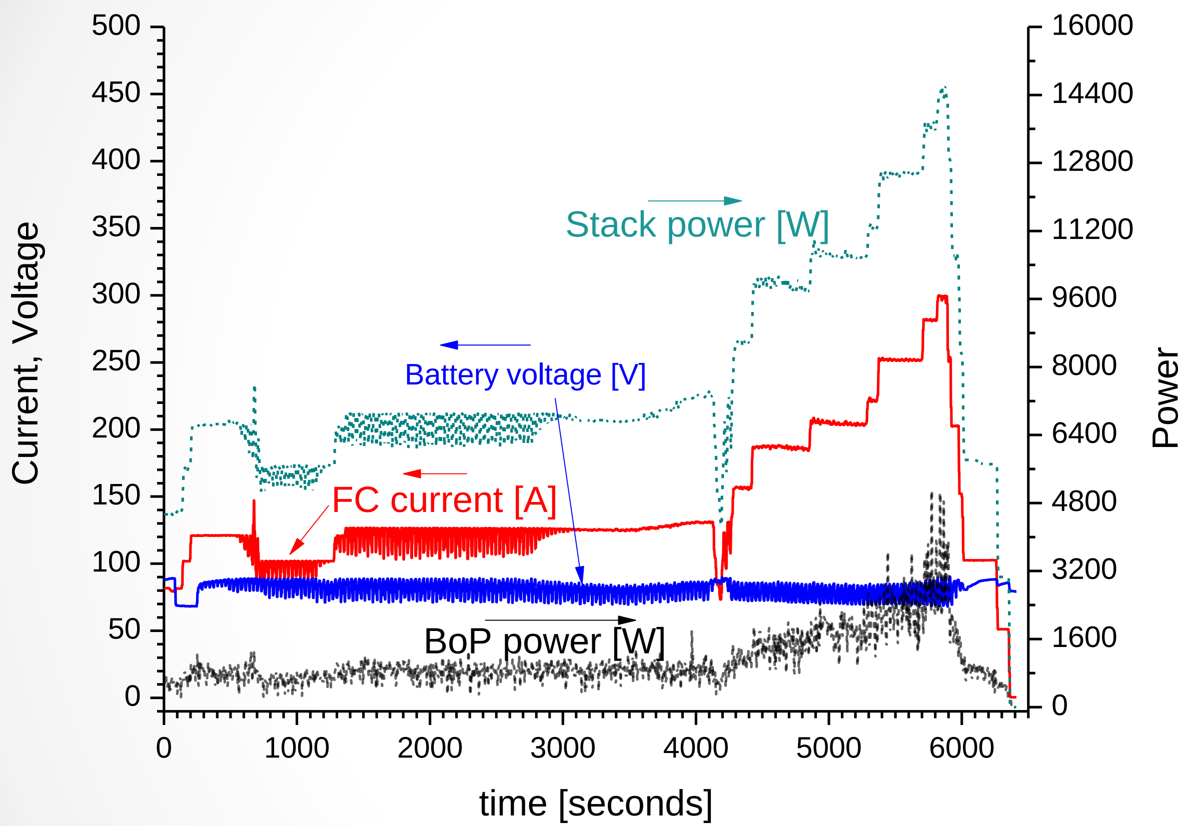
➢ **Electrical layout should be modified.**

Electrical layout (2)



- Revised configuration: auxiliary DC/DC converters were removed (auxiliaries connected directly to 24 V and 48 V branches of the battery bank); one battery was removed from the bank.

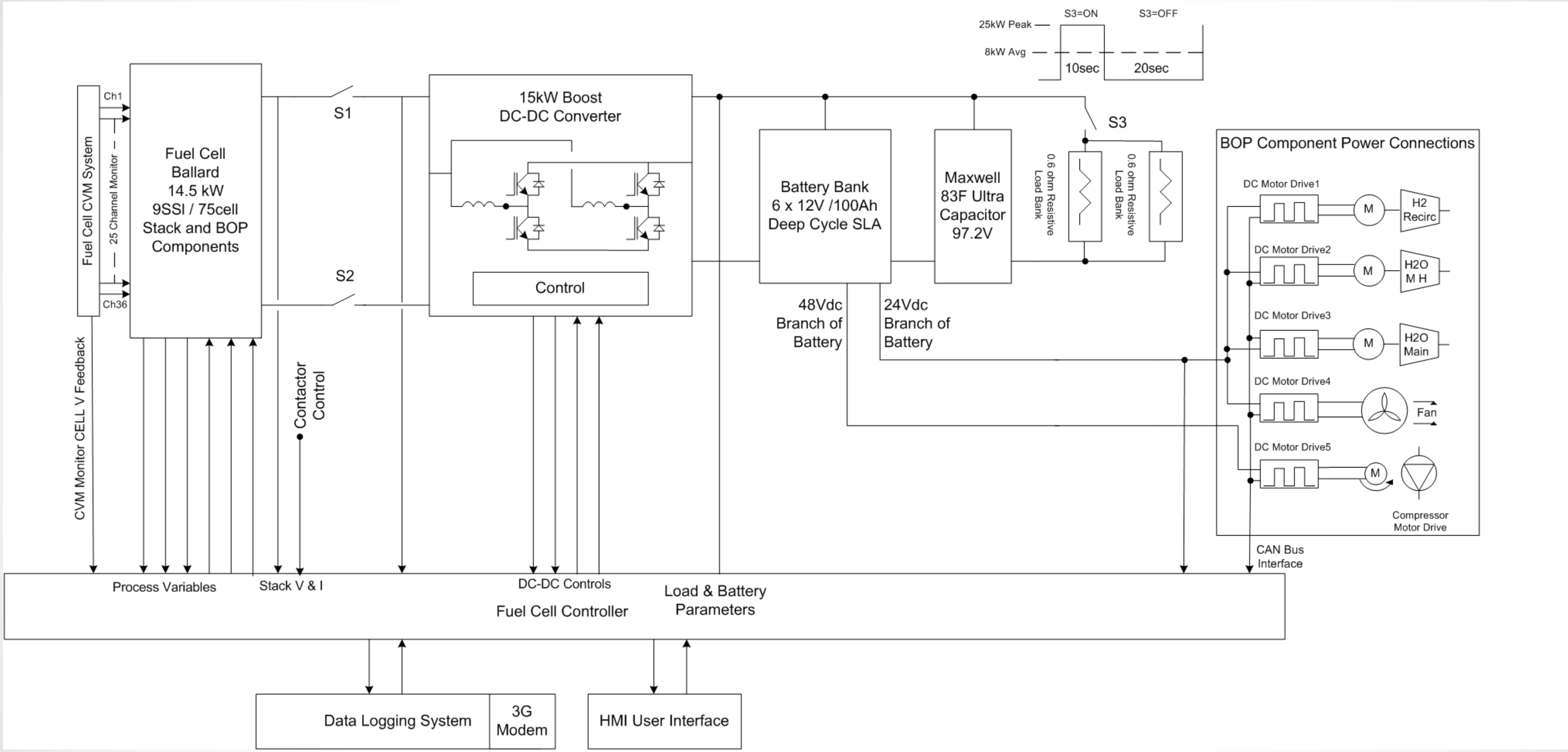
Electrical layout (2): test results



- No battery voltage drop was observed.
- Unstable operation when the load power (peaks) exceeds MAX stack power.
- Heating-up the battery during the operation at high load power (incl. peak load).

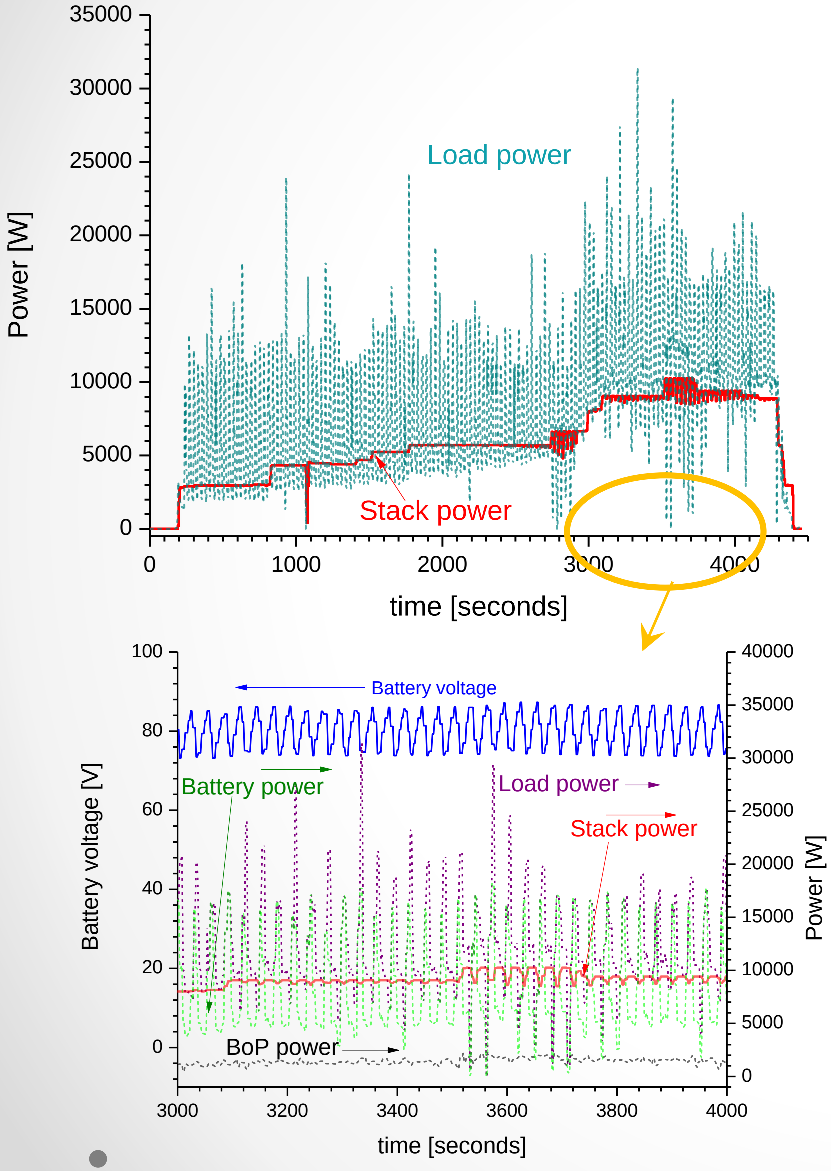
➢ **Electrical layout should be further modified**

Electrical layout (3)



- Revised configuration: To compensate for the peak power draw of the load, an ultra capacitor was added to the system in parallel with the Lead Acid battery

Electrical layout (3): test results



- Stable operation at peak power up to 30 kW.
- The battery contribution to the load power during the peaks decreases in ~2 times due to the contribution of ultra capacitor.
- The battery is not heated-up.
- The battery depth of discharge is also significantly lower than for the layout (2).
- Average fuel cell power required is ~8 kW.

✓ **Average energy consumption ~ 9.0 kWh/h**

✓ **Average load power ~ 8.1 kW**

✓ **Average BoP power ~ 900 W**

✓ **Average H_2 consumption ~ 900 NL/kWh**

✓ **Estimated system efficiency ~30% (related to HHV)**

Assembling on-board prototype

- Based on the test results presented above, the BoP configuration has been updated.
- All BoP parts for the on-board prototype have been procured.
- Assembling of the prototype power module is in progress.
- The control algorithm is being finalised towards:
  - Automatic switch of the stack to a) Standby, b) Run and c) Shutdown modes depending on the system status;
  - Optimisation of the fuel supply and purging strategy to reduce H_2 consumption and increase efficiency.

Conclusions

- General layout of fuel cell power module for 3 tonne electric forklift with integrated MH hydrogen storage system has been elaborated.
- The module fits in the space and weight constrains of the application and comprises the following components:
  - 14.5 kW closed cathode PEMFC stack (Ballard);
  - Lead-acid battery bank;
  - Advanced metal hydride hydrogen storage tank (20 Nm^3 H_2).
- Test bench prototype of the power module has been built and tested in various hardware configurations.
- The optimal electrical system layout providing it stable operation at presence of peak loads (up to 30 kW) has been identified including:
  - Powering of auxiliary system components directly from the sections of the battery bank;
  - Sizing of the battery bank;
  - Introducing ultra-capacitors.
- Further increase of the overall system efficiency by the optimisation of purging strategy, together with the assembling of the on-board prototype, is underway.

Acknowledgements

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