SUAV Main S&T results and foregrounds

Introduction
SUAV aims to design, optimise and build a 310W mSOFC stack, and to integrate it into a hybrid power system comprising the mSOFC stack and a battery. Additional components of the system are a CPOx processor to generate reformate gas from propane and other equipment for the electrical, mechanical and control balance of plant (BoP).
All these components are constituents of an entire fuel cell power generator which were first to be tested in the lab and, after further optimisation and miniaturisation, in a mini UAV (Unmanned Aerial Vehicle) platform. However, as a result of technical delays and risks in stack manufacturing, a second route was pursued in parallel comprising a commercial Fuel Cell sub-system.

System requirements
Electrically powered UAVs' primary limitation is the high levels of specific power that they require to sustain flight, and also the short power bursts that they require for activities such as take-off. The conventional lithium polymer (LiPo) batteries are well equipped to deal with high levels of specific power as can be seen in Figure 1. However, batteries do not offer the best performance in terms of energy storage. Fuel Cells offer a significant improvement in energy storage capacity compared to batteries, however as can be seen in Figure 1, a fuel cell's specific power is significantly lower than a battery's, which limits the rate that the energy that can be delivered.

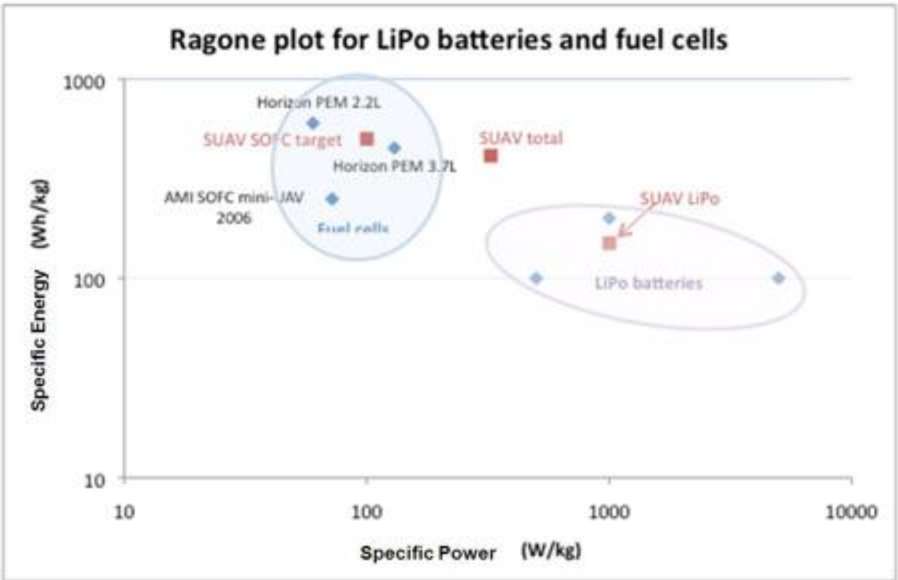


Figure 1. *Power densities per volume vs peak power of Lithium Polymer (LiPo) batteries and SUAV SOFC system.*

The UAV also has a highly variable load profile, with the average power of a mission being approximately 10-20% of the maximum power demand of the platform. For this reason a small buffer battery should be included in the fuel cell system, this battery will provide a high specific power for short durations, and recharge from the fuel cell when not needed.

As platform the DVF2000 UAV platform from SurveyCopter (France), see Figure 2, has been selected. .

Figure 2. *The chosen UAV platform of Survey Copter; the DVF2000.*

Propane was chosen as the fuel due to its superior energy density compared to hydrogen. Solid Oxide Fuel Cell (SOFC) technology was chosen since it can convert reformate (CO/H_2-mixtures) to electricity, as compared to other types of fuel cell that require pure hydrogen, which significantly reduces complexity and thus size and weight of fuel processing. The design of the mSOFC power generator is primarily driven by the weight and volume available in the mini-UAV. The application of a hybrid power supply should increase significantly the mission duration compared to use of state-of-the-art LithiumPolymer batteries.

The FC/LiPo generator is expected to replace the current LiPo-based power pack. As little as possible re-engineering of the UAV is desired for Survey Copter. This sets the overall outward dimensions, and thus the maximum volume, of the system to 3.32L. Deviations from the dimensions given, will negatively impact the aerodynamic resistance (drag) from the UAV, which results in an increase of power consumption of the UAV. To replace the currently used battery a total weight of 3.88kg is available. The overall weight requirement is split into the maximal weight of the major modules within the SRD. It is important to notice that next to the total weight, also the centre of gravity is important for UAV's. The centre of gravity needs to be the middle of the battery pack. During flight the centre should not change, so the placement of fuel canister needs to be placed correctly as during flight fuel will be used and the weight of the system will be reduced.

The telemetry recorded from a DVF2000 flight was analysed and different flight phases were determined with specific power requirements. This analysis was used to set the power requirements for the fuel cell/hybrid power generator.

An overview of the requirements of the hybrid Fuel Cell/Battery power generator is given below in Table 1. The demand of 250 W of nominal power requires a gross output of 310 W of the stack.

Table 2 and

Table 3 give the physical requirements for the total system and the requirements for the fuel cell stack in terms of operational capabilities.

Table 1. *Operating Requirements of mSOFC hybrid generator. The 250W is net output of the generator, so requires a gross output of the SOFC stack of 280W*.

System Energy Requirements	Current UAV	SOFC UAV	UNIT
Nominal Power	170	250*	W
Min. Power	30	30	W
Max. Power	2410	2410	W
Nominal Voltage	29.6	29.6**	V
Min Voltage	24	24**	V
Max Voltage	33.6	33.6**	V
Mass available for power system	3.88	3.88	kg
Volume available for power system	3.32***	3.32***	L

*Including overhead for electrical balance of plant charging and other parasitic loads introduced by the FC

**Output after electrical BoP and any voltage conditioning

Table 2. *Power supply physical requirements*.

Power supply Physical Requirements	Current UAV	SOFC UAV	UNIT
System Mass	3.88	3.88	kg
System Volume	3.32*	3.32*	L
Fuel Cell system Mass: *Fuel Cell Stack* *Chemical and Thermal BoP* *Electric BoP* *Packaging*	N/A	3 *1.5* *0.75* *0.5* *0.25*	kg
Fuel Mass (Including packaging)	N/A	0.88	kg
Mission duration	2	5	h
No. startups/shutdowns (thermal cycles only)	300	300	Cycles
Redox cycles	-	0	Cycles
Total life	600	600	h

Table 3. *Additional fuel cell requirements*.

Fuel Cell Requirements	Current UAV	SOFC UAV	UNIT
Startup time	5	20	min
Shutdown time	< 0.5	5	min
Cool down time	0	60	min
System degradation	300*	300*	Cycles
System max. skin temperature	30	50	°C

System design

A system Process Flow Diagram has been developed that fulfils the end-user requirements and has a safe operation control with the least possible parts to limit the volume and weight needed as much as possible. Different fuel processing options were analysed. Due to the stringent requirements on volume and weight, Catalytic Partial Oxidation (CPOx) was the technology of choice. Although CPOx has a little lower efficiency than steam reforming and autothermal reforming, the omission of needing water results in a higher power output per volume and weight and gives a better efficiency of the whole system as increased weight and drag of the UAV results in lower efficiencies.

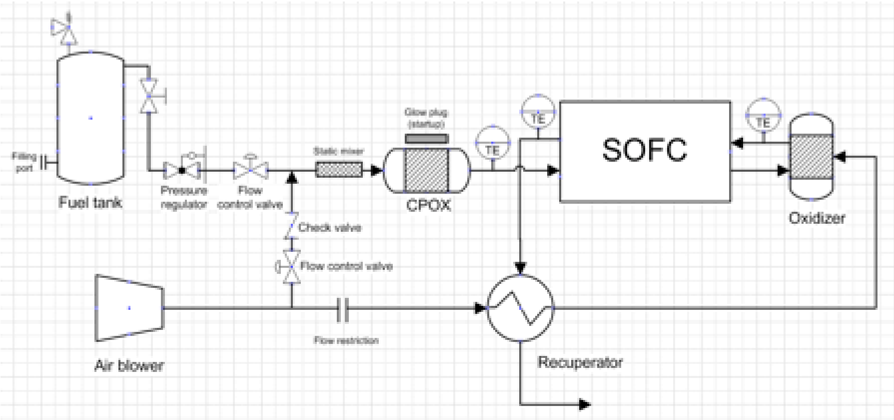


Figure 3. Process flow diagram of the fuel cell system.

System modelling

The fuel cell system was modelled to be able to optimize the system, calculating mass and energy balances, and heat fluxes. The modelling was done in three steps.

1. Models of the energy system and BoP modelling for:
   a. A simplified system fuelled by pure hydrogen - it allows for an initial assessment of the system design,
   b. A system with steam reforming of methane – recognition of modelling problems concerning the fuel reforming,
2. Further system models, where fuel reforming was simulated by using either steam reforming or catalytic partial oxidation (CPOX) of propane; the simplified SOFC model was used - in order to calculate of propane consumption for both reforming types. Lower fuel consumption was found for the steam reforming; however an additional water tank in that system is then required, which increases the weight of the whole power system
3. A system model including separate models for cathode and anode was investigated. Additional stack cooling by fresh air was included in the model at a later stage. Air flowrate to the cathode was slightly lowered and was equal to 120 slm, instead of 150 slm initially. Other modelling parameters and assumptions remained unchanged.

The simulation results for both initial and modified BoP models are presented in Table 4. The use of additional cooling resulted in a decrease the temperature at the cathode outlet from 700 °C to 666.7 °C. In addition, the calculated exchanger area in the recuperator was also about 50 % lower.

Table 4. *The simulation results for both previous and modified BoP models*.

air inlet to cathode [slm]	propane feed [g/h]	propane feed [m3/h]	H2 utilization [%]	CO utilization [%]	UA [W/K]; HX model	Heat duty [W]; HX model	Exchanger area [m^2]	Cathode-out temp. [°C]	Anode-out temp. [°C]
150 previous case	105.83	0.05672	50	20	4.297	1274.104	0.1432	700.0	934.97
120	105.83	0.05672	50	20	2.232	737.380	0.0744	666.7	934.97

additional cooling of stack,100W									

The system model was used to help optimise the system design. Fuel utilization has an impact on the fuel consumption and therefore on the fuel tank volume and weight of the mSOFC power system.

The CPOx simulation model was developed solving a family of ordinary differential equations considering the change of concentration through the residence time at which the fuel is exposed in the reactor, which is a wire mesh with specific catalytic sites. The characteristics or main assumptions were the following: The mass transport is only in the axial direction; stationary state; the convection transport is predominant; no interphase; non-isothermal - adiabatic operation.
The following reactions are the only ones that are taken into account and are most likely to take place:

Partial Oxidation $2\ C_3H_8 + 3\ O_2 \Rightarrow 6\ CO + 8\ H_2$

Total Oxidation $C_3H_8 + 5\ O_2 \Rightarrow 3\ CO_2 + 4\ H_2O$

Water Formation $2\ H_2 + O_2 \Rightarrow 2\ H_2O$

Dehydrogenation $C_3H_8 \Rightarrow C_3H_6 + H_2$

Figure 4 depicts the concentration of the reactants for a given temperature of 976 K depending on the residence time at the catalyst. It can be seen that propane and oxygen are consumed while notably hydrogen is generated.

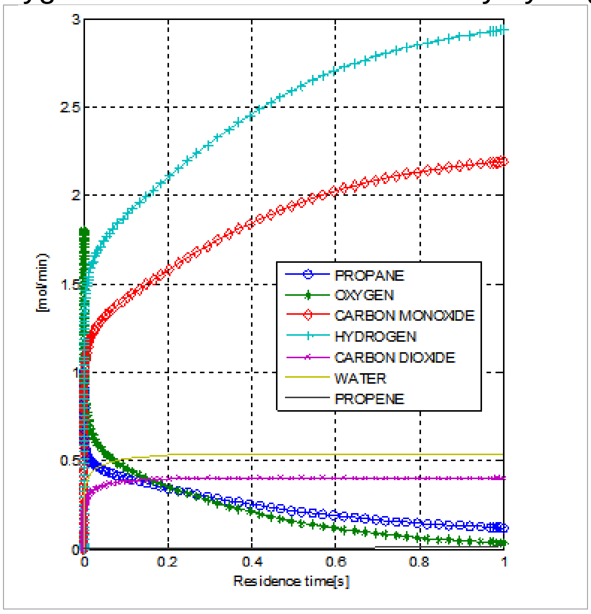


Figure 4. *Reactant Concentration.*

To model the Fuel Cell stack commercially available Aspen Plus process simulator was chosen. A system model including separate models for cathode and anode was investigated. Two cases concerning fuel utilization were analysed: I) utilizations are equal for both H_2 and CO, and II) H_2 utilization is 2.5 times higher than CO. That simplification allows for an initial assessment of the system design for assumed reformate temperature of 700 °C, temperature at the cathode outlet of 700°C and stack air flow of either 75 slm or 150 slm.

For each investigated case the influence of the airflow on system efficiency was studied and the fuel consumption was determined. The following general conclusions can be drawn:

- The fuel utilization has a significant impact on the fuel tank volume and weight of the mSOFC power system.
- The effect of the fuel utilization on the heat duty of the recuperator (HX model) was also determined. The UA value (specific heat duty) vs. fuel utilization in both studied cases (**Fout! Verwijzingsbron niet gevonden.**) was calculated. For air stream flow rate equal to 150 slm and for utilization of H_2/CO equal to 50% / 20% the fuel consumption was 106 [g/h] and the UA (specific heat duty) value was equal to 4.3 [W/K].
- In all studied cases the O_2/C ratio at the inlet to the CPOX reactor was close to 0.53. It resulted in the outlet temperature from the CPOX of 700 °C and allowed to avoid carbon formation, as thermodynamic calculations have shown.

A dynamic model was made using Aspen and it was validated by calculating the steady state and comparing it to the steady state model results. The dynamic system model developed in Aspen Dynamics allows to simulate time-dependent effects in whole system. This model is applied to help in optimisation of the system parameters, especially in both air and fuel inlet parameters adjustment.

In parallel a model for the complete system was created in Simulink. With this model it is possible to vary a number of inputs to the system and observe the behaviour of the system or single components.
The following statements could be drawn from the model calculations:

- There is a trade-off between maximum cell-power and high efficiency
- The pressurization of the system has only minor impact on both power and efficiency
- Slight temperature drops affect the power significantly
- Efficiency increases with fuel utilization
- Higher fuel-utilization leads to less power

The following recommendations were made for the system design:

- Fuel-utilization above 80% should be avoided as the power is then dropping rapidly
- A temperature of 800°C should be maintained as a temperature drop will affect the power
- There is a trade-off between power and efficiency. Power is impacting stack weight, because lower power results in more required cells. Efficiency is impacting fuel weight, because lower efficiency results in more fuel required by the system.

SOFC Stack Development

Originally it was anticipated that the UAV stack would be built from mSOFC tubes of diameter 2.3 mm and 5 6mm length. However at the start of the project, the supplier of the materials changed the specification of the tubes to 6.8 mm diameter x 149 mm length. One advantage of the new sizes were the expected ease of manifolding and current collection as with larger tubes, the amount of tubes can be significantly reduced. The new tubes could also be operated at lower temperatures. However, it was discovered that with the new SOFC-tubes, the formerly used electrode power collection method could not be applied to the new tubes. Alternative ways to do so had to be identified and tested. Furthermore, due to the absence of experimental data system modelling and design needed to be delayed.

With the change in tube specification, more cell development and materials selection were needed than anticipated. Several different components were tried and tested for interconnect wire, interconnect layer, sealant and manifolding.
A new cell design for contacting was developed and is given below.

Figure 5. *New Cell design on which advanced cell and stack testing was conducted.*

Arrival at this design saw single cell performance rise from initially 5 W reported in to excess of 8 W. The major change in cell design was the use of two types of silver ink, supplied from ESL and SPI, and using a single central collection with twisted silver wires. However when this design was tested for durability, it failed to meet the end of life criteria (6.5 W per cell) set for the mission. The key single cell results are given in the following figures.

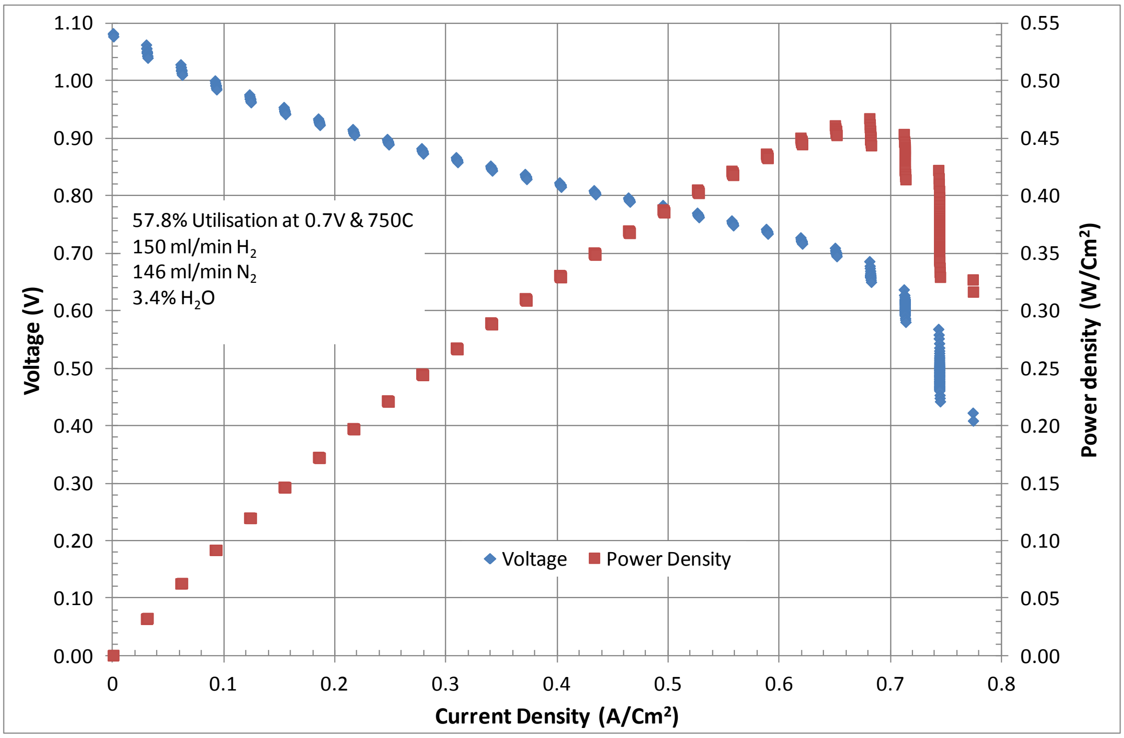


Figure 6. *Key single cell results, I-V curve; State of the Art (@0.70V @750C). Power: 8.84 W, Utilisation: 58%, ASR: 0.50, Gas: 150 H_2, 146 N_2, 3.4% H_2O*

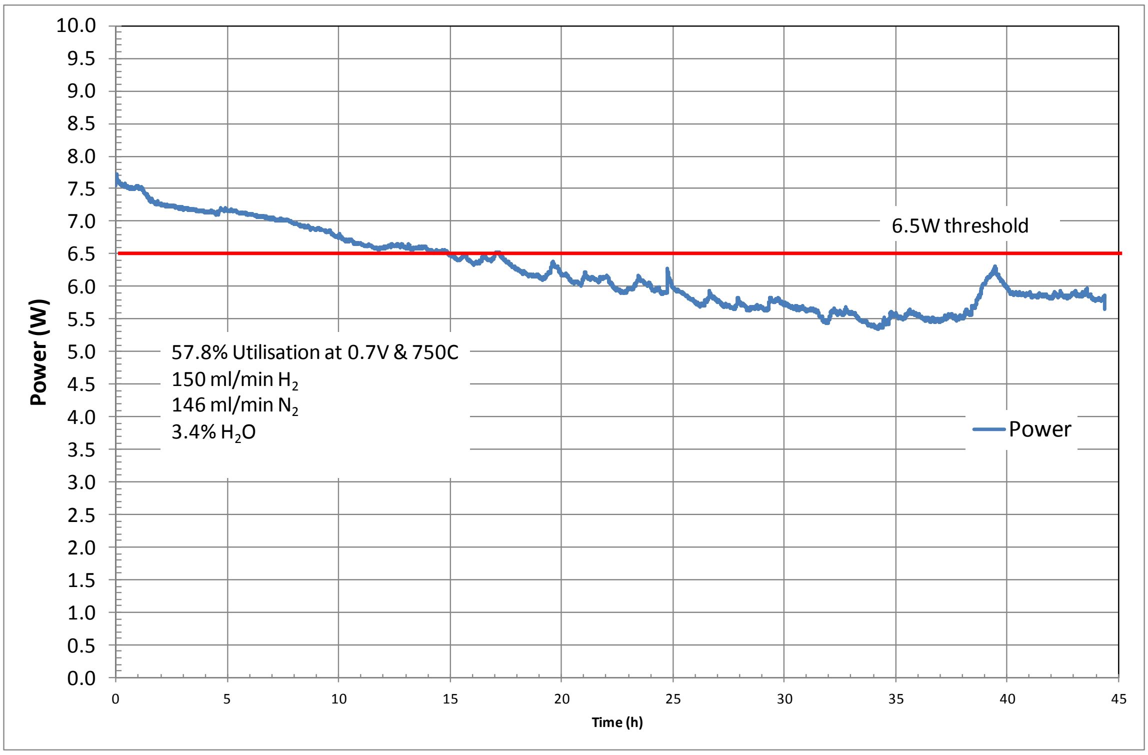


Figure 7. *Key single cell results; State of the Art durability 40 h, (@0.70V @750C); SoL Power: 7.65 W, EoL Power: 5.8 W, Average Power: 6.27 W.*

It can be seen that the cell performance drops to below 6.5W within 15 hours of operation. Top level requirements dictate that the cell must last 50 hours (10 x 5 hour cycles) for the flight missions. Post-mortem analysis of the micro tubes showed a significant degradation in the gas seals for the connections.

The following work was focused on improving the durability of the cells to meet the top level requirements. New formulations for sealants were constructed and trialled. As cells were improved, 4 cell stacks were tested with simulated real fuel, to give an idea of real performance.

Seal Testing

Seals from Ceramabond, Microtherm, Nyacol and St Gobain (proprietary glass formulations) were trialled. These were tested in several combinations of materials and temperatures. An example set is given below.

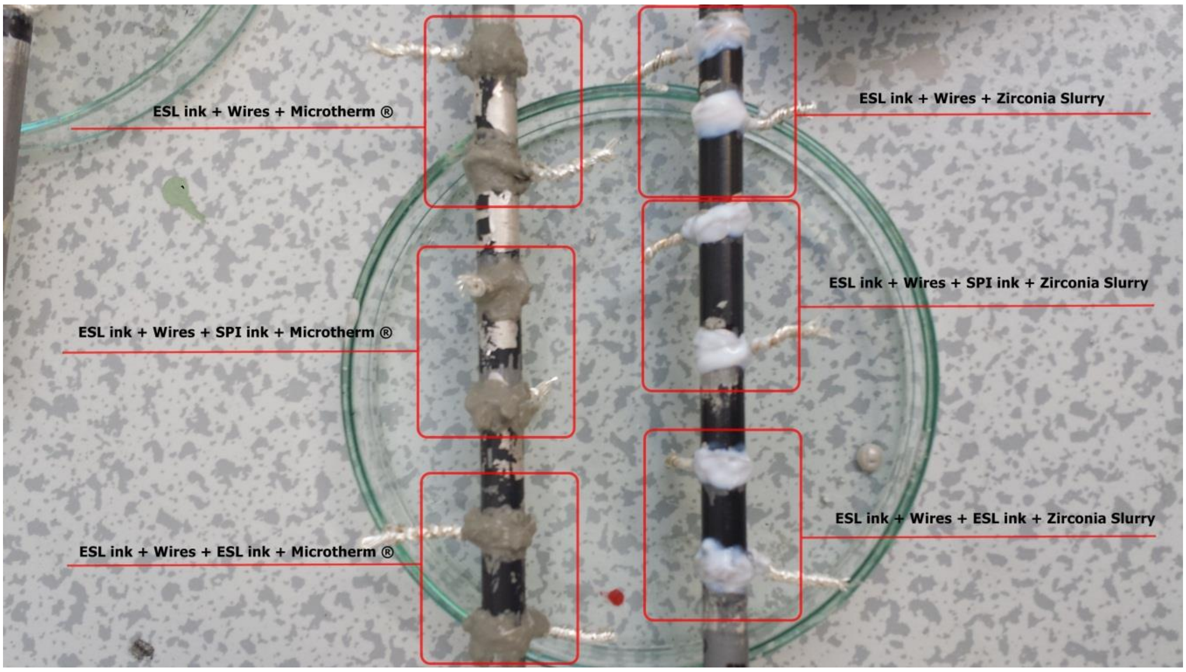
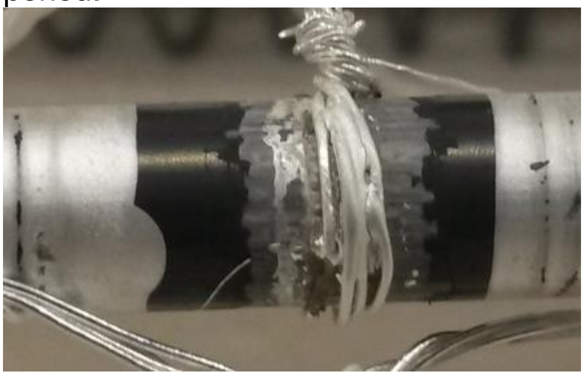


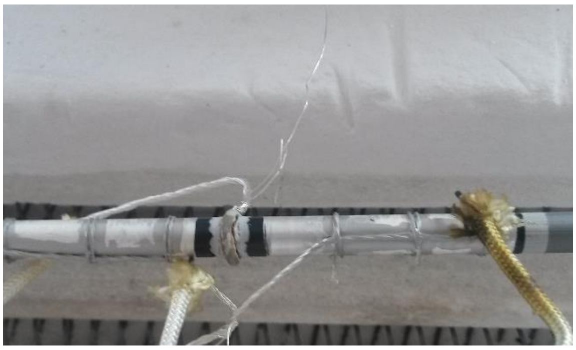
Figure 8. *Examples of different seals, and inks.*

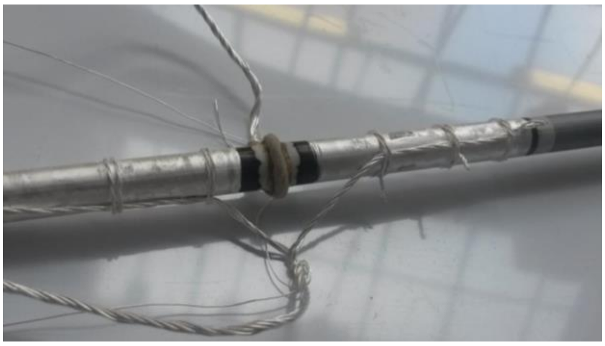
After thorough in situ and ex situ testing the results showed that the glass from Saint Gobain was the best for endurance and reliability; however a mixture of MicroTherm and Nyacol also produced good results. The following figures give a visual representation on how the seals changed in structure and colour during the test period.



Hot spot damage on Silver

Ny/MT sealant silver degradation, but still acceptable performance





Glass seal before (left) and after (right) a 55 hour/ 11 cycle test. Little change.

Figure 9. *Post-test views of seals.*

The new glass seal saw single cell performance stabilise and durability surpass the top level requirement of 50 hours. The results are given in the figures below.

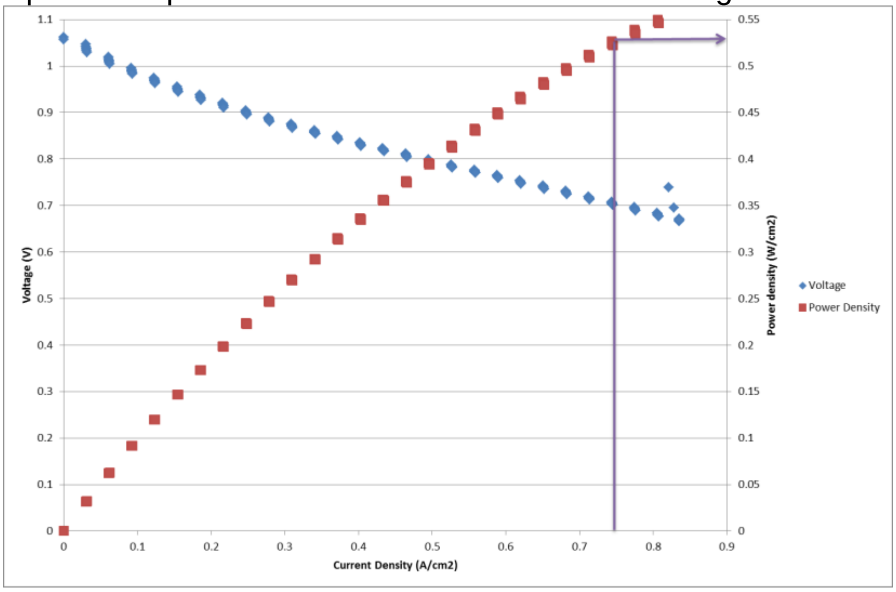


Figure 10. *Results of test with improved glass seal, I-V curve; State of the Art (@0.70V @750C). Power: 10.1 W, Utilisation: 66%, ASR: 0.40, Gas: 150 H_2, 146 N_2, 3.4% H_2O.*

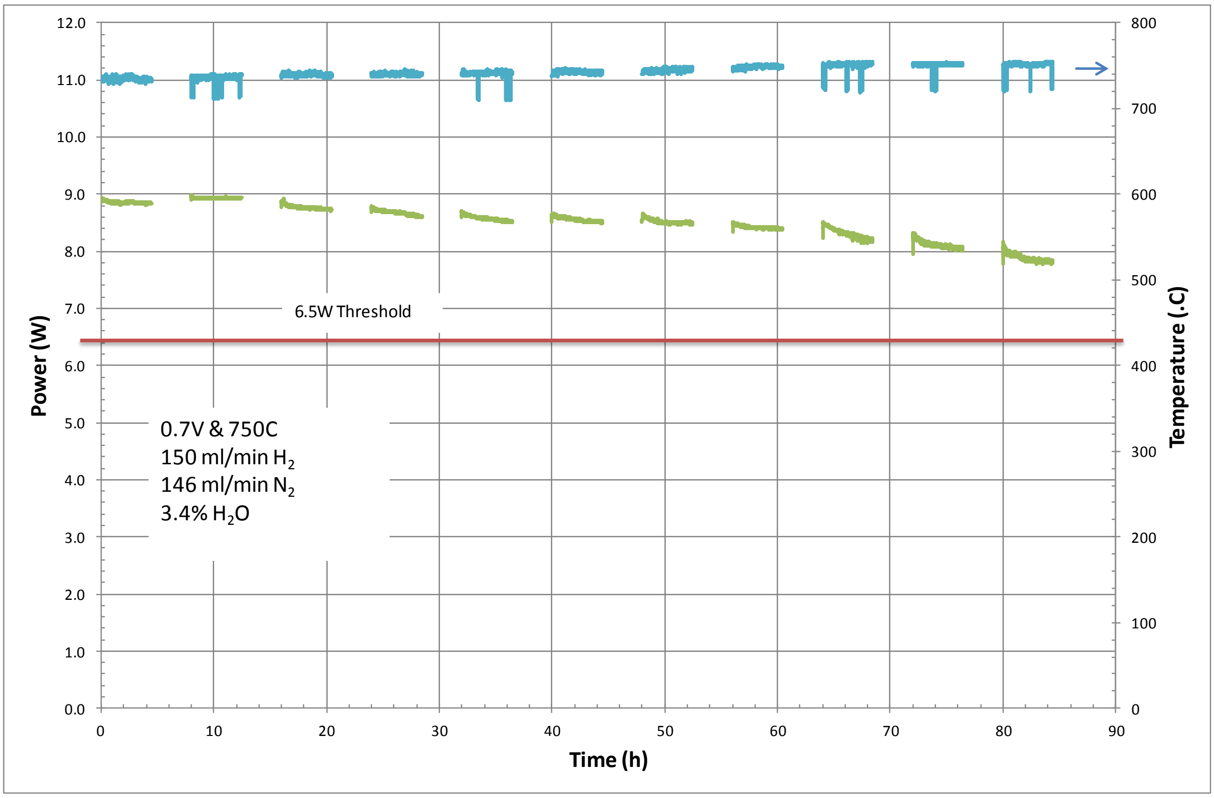


Figure 11. *Results of test with improved glass seal; SOTA Durability 85h (@0.70V @750C) (150 H2, 146 N2, 3.4% H2O)., SoL Power: 8.86 W, EoL Power: 7.8 W, Average Power: 8.51 W.*

In conclusion the top level target has been met at single cell level. A picture of the final acceptable cell design is given in the following figure.

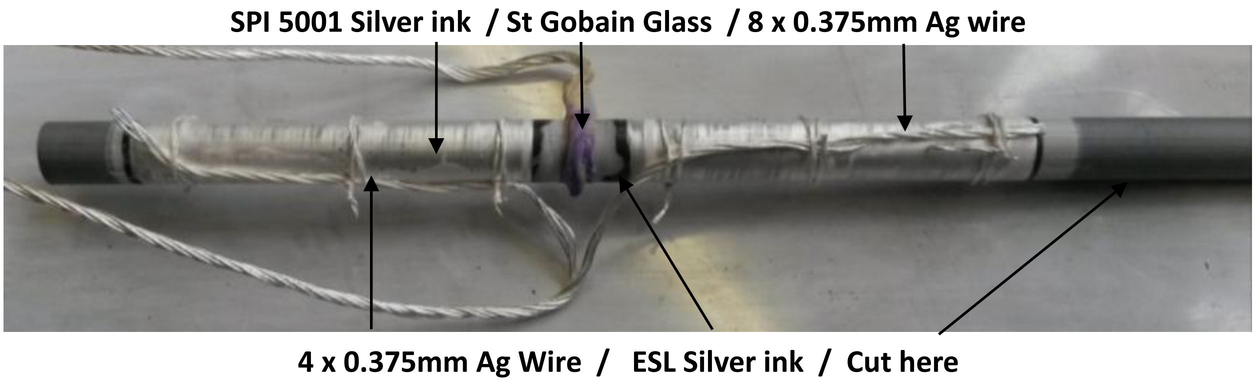


Figure 12. *Final Cell design.*

From this 4-cell stacks were constructed and analysed. It shows that a 4 cell bundle can be manufactured to give a power in the order of 32 W under load.

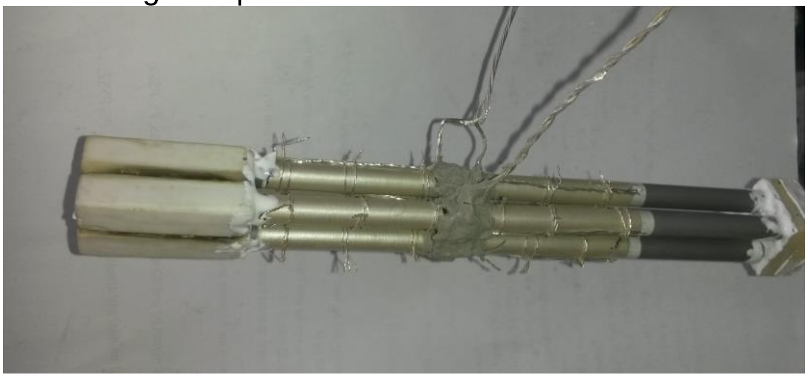


Figure 13. *Cell substack assembly (Microtherm/Nyacol seal).*

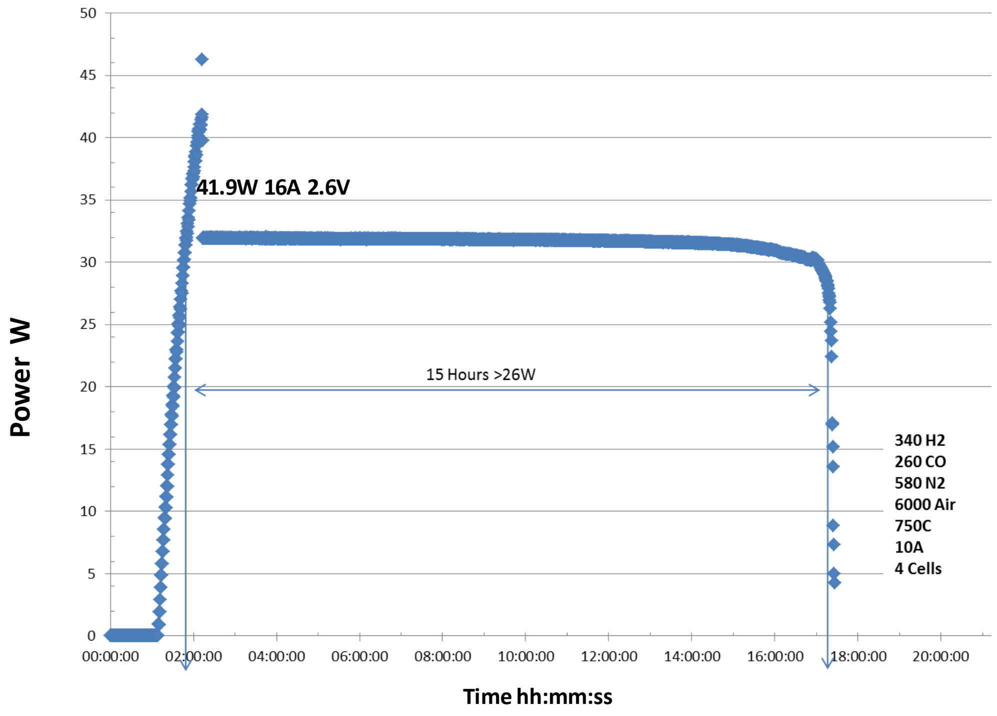


Figure 14. *Durability test of a 4-cell stack; SOTA Durability15h/1day (@10A @750C) (340 H2, 260 CO,580 N2, 3.4% H2O). SoL Power: 32 W, EoL Power: 30 W.*

Stack development
Several designs for the stack have been considered. Initially a 64-cell square stack design was considered, based on the 5W/cell performance. However, this design was too bulky and heavy for UAV-use.
Based on an improved performance of 7 W/cell a circular 48-cell stack design was made. The design was supported by CFD calculations to optimize the temperature and air flow distribution. Some results are shown in the figures below.

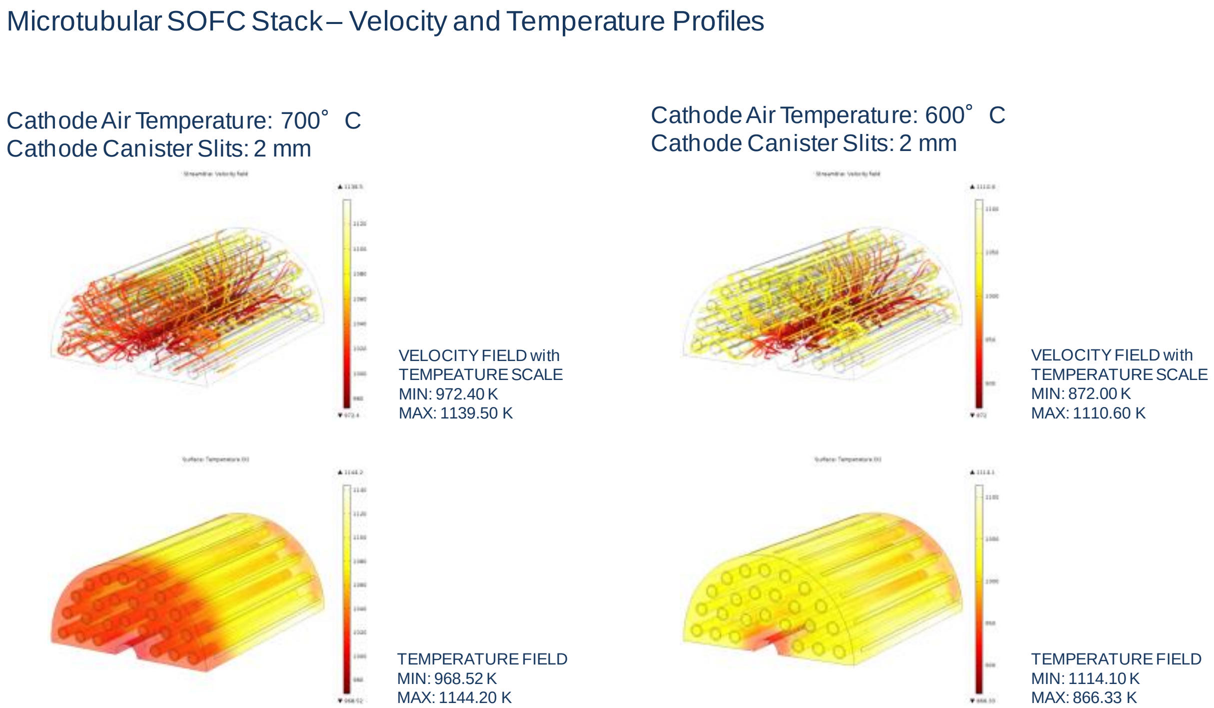


Figure 15. *Sample results of the CFD calculations.*

Finally after several iteration steps in conjunction with the system design a final design was made. According to this design two stacks were manufactured. A procedure containing 9 steps was followed to build the stacks. The stacks were produced in two half stacks of 24 cells, see Figure 16.

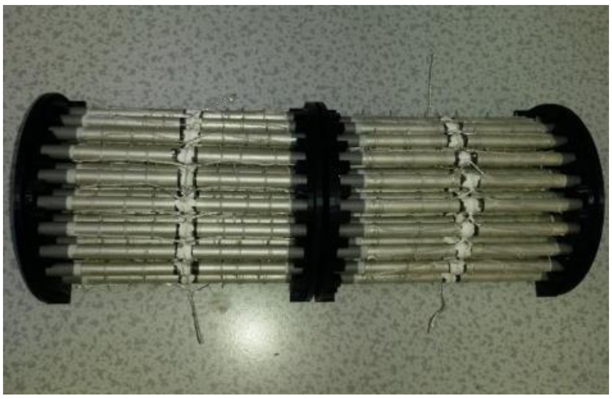


Figure 16. *Two halfs of the stack, 24 cells.*

Stack 1 failed unexpectedly, this was analysed through post mortem testing, before stack 2 was built. It was concluded that equipment (Furnace) was unsuitable for this test. As part of this analysis small modifications were made to the stack manifolds to aid in the building process. This essentially helped in locating the cells within the manifold. Stack 2 showed that 335W could be achieved at 0.7 V when fuelled with 6.07 L/min hydrogen, 68 L/min nitrogen, 0.46 L/min steam and 42 L/min cathode air, see Figure 17. This shows that the stack has a sufficiently high power density to be used in an UAV.

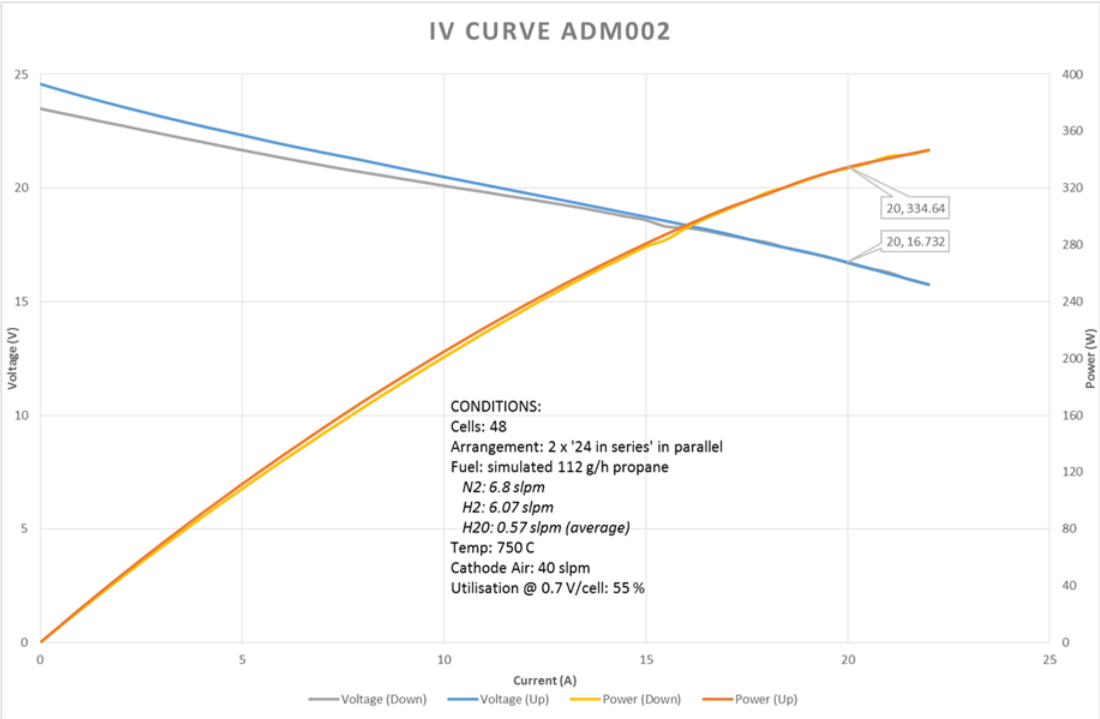


Figure 17. *IV Curve of stack 2. Voltage and power highlighted at 0.7V/Cell*.

Unfortunately this stack also suffered failure a short way in to the test, thus was not tested with the system.

Cell and stack modelling

The cell and stack developments were supported by electrochemical modelling, calculating the cell and stack voltages and the current distribution; CFD modelling, calculating the flow distribution and heat transfer; and FEM methods to calculate thermal stresses in a stack. The latter analyses showed that the stresses did not exceed the limits.

System design and manufacturing

As the pod of the UAV is cylindrical a system and stack design of a similar shape was pursued. A number of concepts were developed for such a system, differing in the way the air flows are guided through the system. Based on weight and volume considerations a final concept was selected. Using information from UoB concerning the stack dimensions, extensive CFD studies were performed to support the design

and determine the main dimensions of the system. The system comprises the following sections: reformer, burner, recuperator, and insulation. An important factor for dimensioning the system were the limits of the allowed pressure losses. In a detailed design technical issues, like hot sealing and expansion, were solved.
The system weight was minimized by limiting the number of annular spaces, keeping the length of each section to the minimum, and by using thin metal walls (in combination with the removal of metal in places where a high strength is not required). However the weight limit of 2300 g for use in the DVF2000 UAV could not be achieved, even if the system would be constructed from lightweight metal (titanium). The bare minimum weight that could be achieved amounted to 3000 g (including external BoP components). However, the power density of the system is better than commercially available systems. Either a smaller mSOFC system will need to be designed with less power and less weight, or the mSOFC system could be used in a bigger UAV.
To complete the system suitable lightweight Balance of Plant components were identified and purchased (blower, fuel valves) or, in case they turned out to be unavailable on the market, custom-designed (reformer air valve).
These components were first tested and characterized separately together with the reformer, before integration. For these tests a separate reformer was designed and constructed with the same geometry as the system reformer. The flows through the valves were determined prior to the tests as a function of the valve opening.
The performance of the reformer was tested at different propane flows. The outlet temperature is used for control. In general it can be concluded that the reformer temperatures were well controllable (i.e. within a band width of some 10 K or so) by varying the air valve opening. The reformate composition was measured by means of GC. In terms of H_2 content the reformate generally has a good quality with concentrations around 25%, as expected on the basis of equilibrium (depending on temperature and O_2C).

For the system a battery pack was selected having a storage capacity of 66Wh. Due to a voltage drop during a high power discharge at a chosen current the peak discharge power is not met, however, it is sufficient for a typical take off. For the development of the controller the electrical and mechanical BoP have been reviewed and the requirements for the sensors and effectors have been defined. Three thermocouples and the battery voltage are used as sensors. The blower, fuel valve, air valve and DC/DC output current limit are the effectors. Using the sensors and effectors control requirements and designs have been made.

Due to damage of the two built fuel cell stacks while testing at UoB a fuel cell was not available for testing within the prototype. In order to allow functional testing of the system and its components a dummy stack was designed and made. The dummy stack consists of 10 steel tubes positioned in a circle and welded to a steel inlet and outlet manifold. The sizing of the tubes is such that the pressure drop resembles the pressure drop of an actual stack.
After integration of BoP components with the system container, all different machine states for flight missions were tested;,start-up, partial load and full load simulation and a controlled shut-down and cool-down and a quick restart. The latter is shown in the figure below.

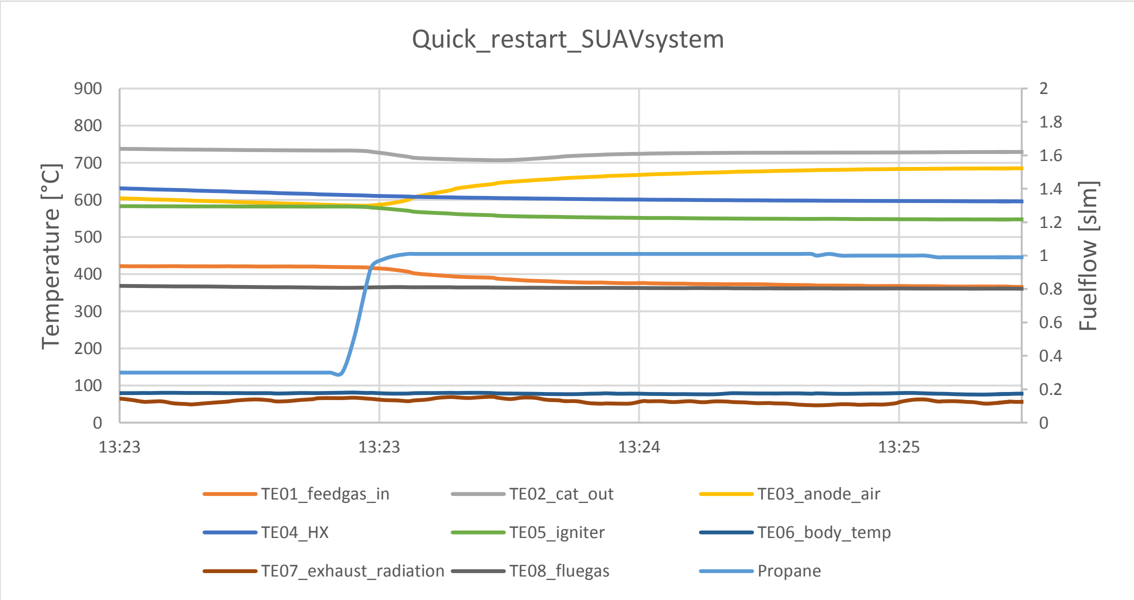


Figure 18. Effect of a quick restart. From a stand-by situation the fuel flow is ramped up in a short time.

The tests have shown that the system meets its design objectives: it is capable to provide the right environment for a solid oxide fuel cell to work properly. The system can be started up quickly, and a safe shut-down can be warranted, keeping the fuel cell reducing according to the requirements. The balance of plant components are well suited to do the job, and the system temperatures are well-controllable by variation on the blower and valve settings (as devised).
With the developed technology it is possible to build a small scale power-unit, powered by propane, if a suitable fuel cell is integrated. At this scale, it is possible to use the system as range extender for UAV's. More of these units together could provide backup-power in the kW electric range.

In conclusion, the system developed is capable to provide the right environment for a solid oxide fuel cell stack to work properly. It has been shown that a complete system is able to provide power for a UAV mission. Together with the SOFC-stack developed within SUAV it will have a sufficiently high power density to be used in an UAV.

Alternative system development route
For the SUAV-Alternative Core route the commercial SOFC system was integrated with battery pack for laboratory testing. First an acceptance test, see Figure 19 was done with the system checking some load settings and monitoring the electrical behaviour and the temperatures inside the system.
Following these tests a mission profile was applied to the system. From this experiment it was concluded that the integrated system is suitable for a UAV mission. Different mission profiles were simulated, see Figure 20, with the complete system in the lab. The system functions well.

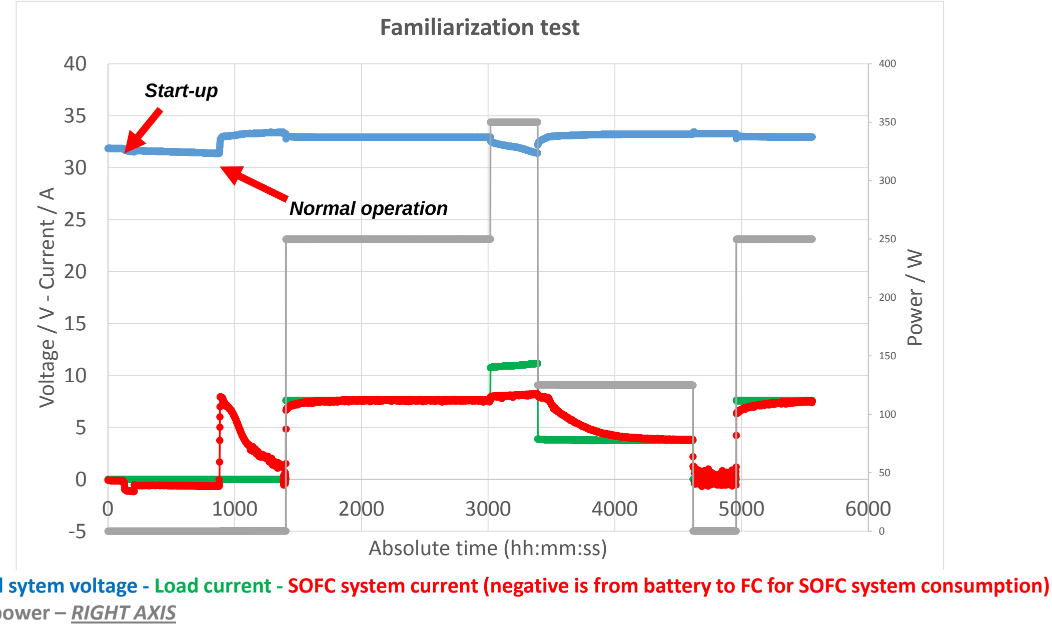


Figure 19. The electrical variable behaviour during the familiarization test (the system status is indicated).

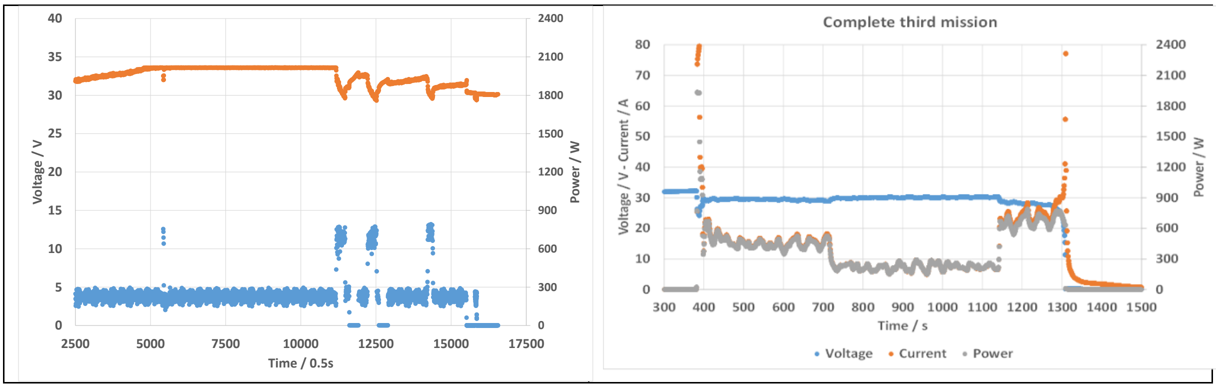


Figure 20. Two different mission profiles (based on the conventional UAV mission, as reference), used to test the suitability of the developed hybrid propulsion system.

The total system is intended to fit inside an enclosure that is a part of the fuselage of the UAV. There will be a short distance between the generator and the pod shell. Therefore, as a result of the high external surface temperature reached during the generator operation, unsuited values of internal temperature are expected. For this reason, it is important to ensure a proper ventilation of the air volume inside the pod to avoid malfunctioning of the electronic devices connected to the generator and high temperature spots that can affect the integrity of the pod shell. Therefore, tests in a confined environment that mimic the final application, have been set up.
From the experiments it is concluded that having an airflow between the system and the wall of the pod is sufficient to operate the system safely. However, at the exhaust of the generator temperatures over 200ºC can occur. At these locations proper thermal insulation needs to be present.
Using the experimental results a CFD model was set-up and validated to determine the temperature profile. Using the CFD model a design for a pod has been made.
Due to time limitations it was not possible to manufacture a new pod for an actual air mission.