Investigation and Design Studies of SOFC Electrode Performance at Elevated Pressure

Rolls-Royce

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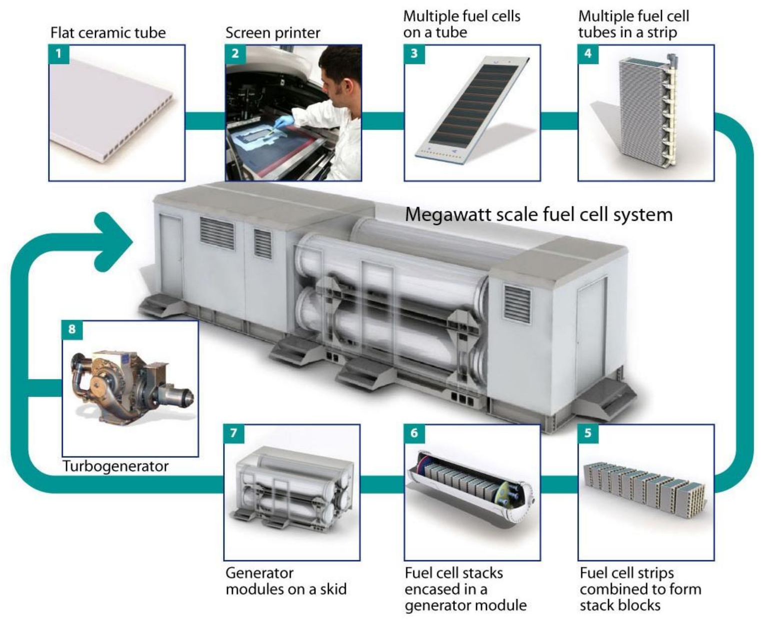
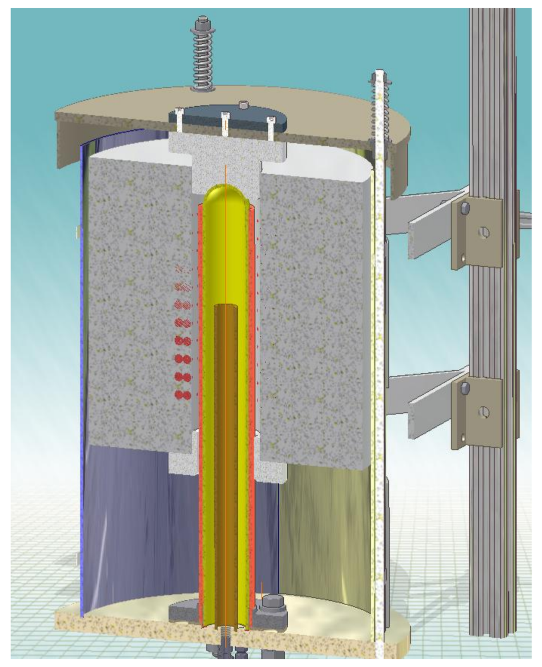
Background

The operation of the RRFCS solid oxide fuel cell (SOFC) system is at pressures up to 7 atmospheres. Further investigation of the performance of electrodes at high pressure, and under the system relevant gas compositions present in the RRFCS design is a critical research area for RRFCS in its development and commercialization of a 1MW distributed power plant, as well as for the US DOE in its emphasis on large combined cycle centralized power stations using SOFC technology.



Pressurized Testing Capability

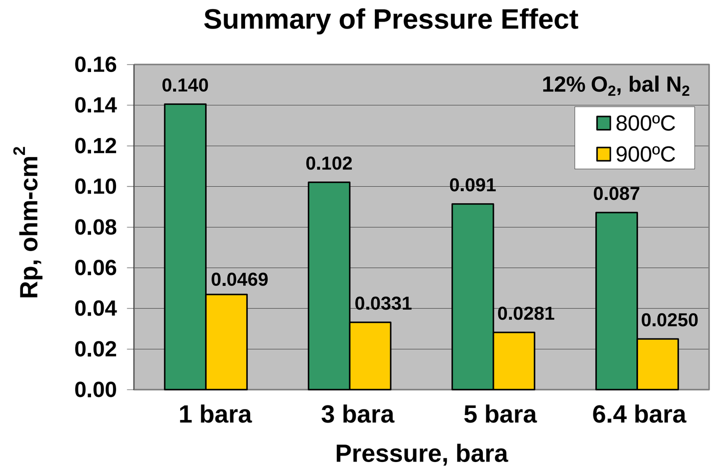


As part of this program, RRFCS has developed the capability to test cathode symmetric button cells at pressures up to 7 Bara and temperatures up to 1000ºC under various gas compositions consisting of O_2, N_2, CO_2, and steam. A Solartron EIS system is used to analyze electrode performance. RRFCS also has capabilities to test full fuel cells at system relevant conditions including pressure and the full range of anode compositions experienced in service. The combination of cathode button cell and full cell testing is used to deconvolve performance of the whole cell.

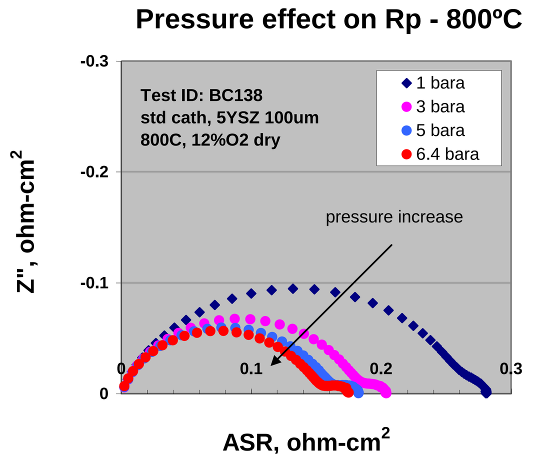
Cathode Testing

Testing of standard cathodes (LSM + YSZ) was conducted over a test matrix which included pressure, temperature, and concentration of O_2, CO_2, and H_2O. The chart to the right shows the impact of increasing pressure on total cathode polarization (Rp) with a 12% O_2 feed at two temperatures.

Summary of Pressure Effect

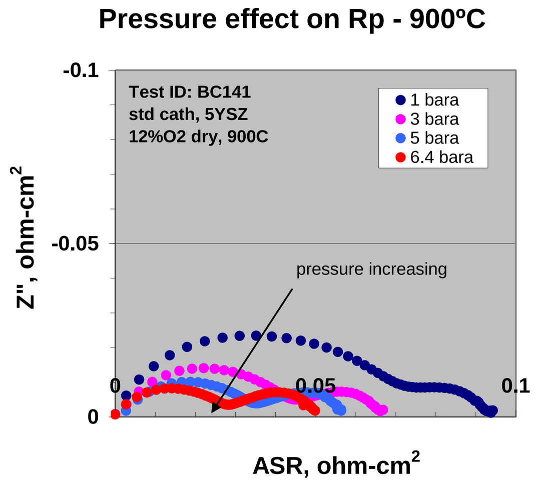


Pressure effect on Rp - 800ºC



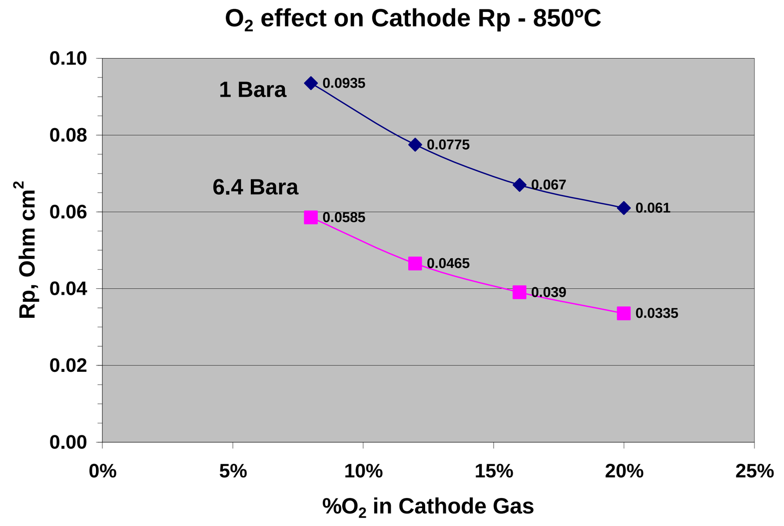
At 800ºC, the cathode polarization is dominated by the activation loss, which is the higher frequency arc to the left of the x-axis. There is an approximate 40% reduction in the polarization with the increase in pressure from 1 to 6.4 Bara, although the majority of that reduction takes place with the pressure increase from 1 to 3 Bara.

Pressure effect on Rp - 900ºC

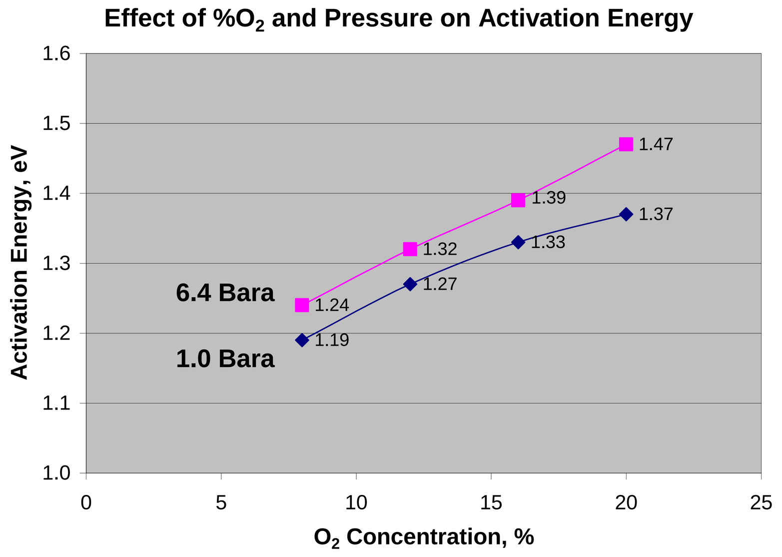


At 900ºC the activation polarization similarly shows an ~ 40% reduction in overall polarization going from 1 to 6.4 Bara. Of note is that the lower frequency part of the polarization (arc to the right of the x-axis) is now a significant part of the overall loss, and does not appear to be impacted by increased pressure. This is reflected clearly in the plot to the right, which shows that the polarization is a function of both O_2 concentration and pressure (P_{O2}) independently, indicating an activation process and a transport process. As mass diffusion of O_2 should be small for this arrangement, the effect may be a surface exchange phenomenon.

O_2 effect on Cathode Rp - 850ºC



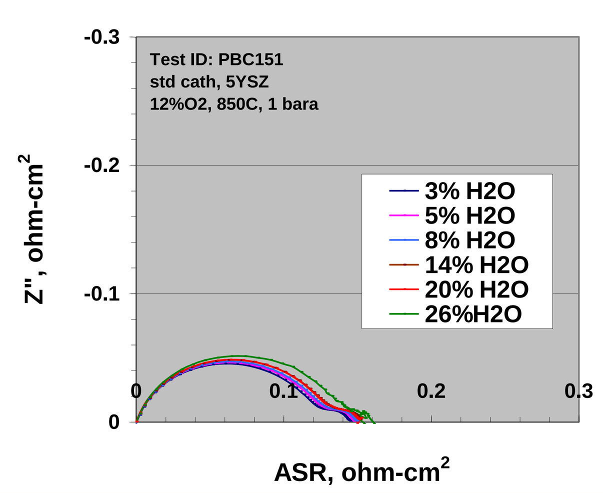
Effect of $\%O_2$ and Pressure on Activation Energy



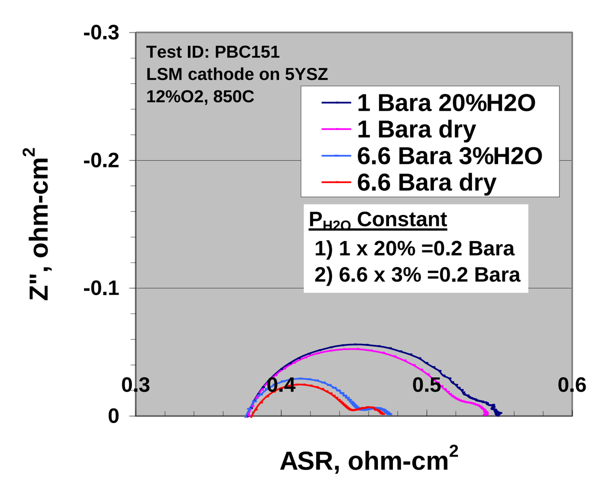
The cathode activation energy, shown at left, also shows a dependence upon $\%O_2$ and PO_2 independently, with $\%O_2$ being more dominant. This suggests that the simple dependence of current exchange density as a function of PO_2 alone is insufficient to describe the behavior.

The effect of steam on cathode performance, was found to be a long-term effect, but did not manifest itself in short-term (hour long) tests. The chart below left shows little change in polarization at steam levels from 3% to 26%. The chart below right shows the polarization at 1 and 6.4 Bara for the same PH_2O and dry conditions, which shows the steam addition has little impact on short-term performance.

Effect of Steam - Short Term



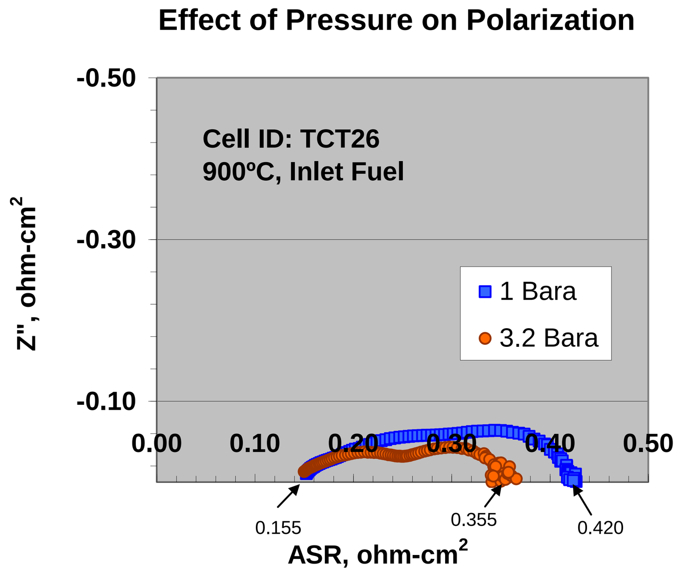
Effect of Steam and Pressure



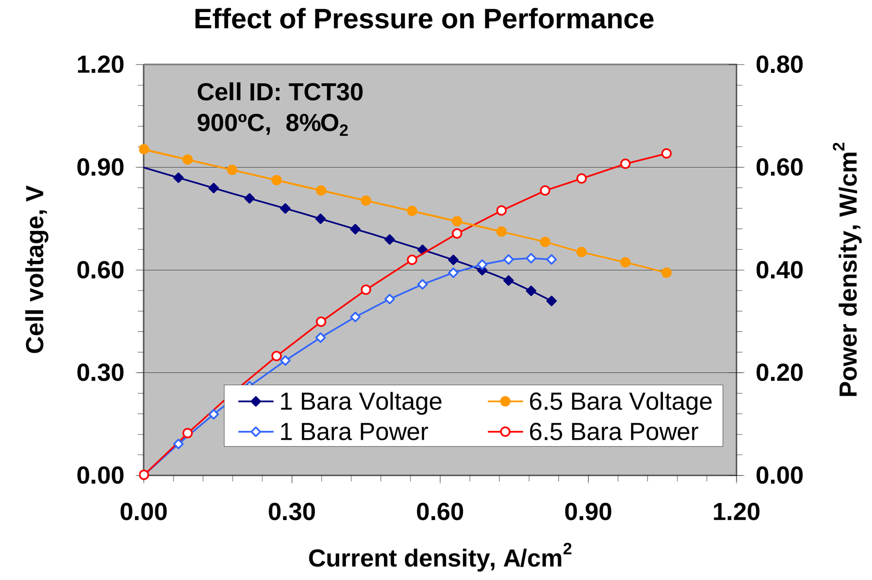
Fuel Cell Performance at Pressure

Testing was performed on three-cell samples under atmospheric and elevated pressures which were fully instrumented to give a breakdown of cell and interconnect components. Testing at various pressures showed total electrode polarization is reduced by about 0.09 ohm-cm^2 or 33% at 900ºC going from 1 to 6.5 Bara (up to 40% improvement was observed at other conditions). This is more than double the reduction observed for the cathode polarization alone. It is expected that pressure impacts not only the anode activation but also the concentration polarization because of the small pore size and thickness of the substrate. This improvement results in a decrease in total ASR of over 20%, and with increased Nernst potential yields a much higher power density.

Effect of Pressure on Polarization

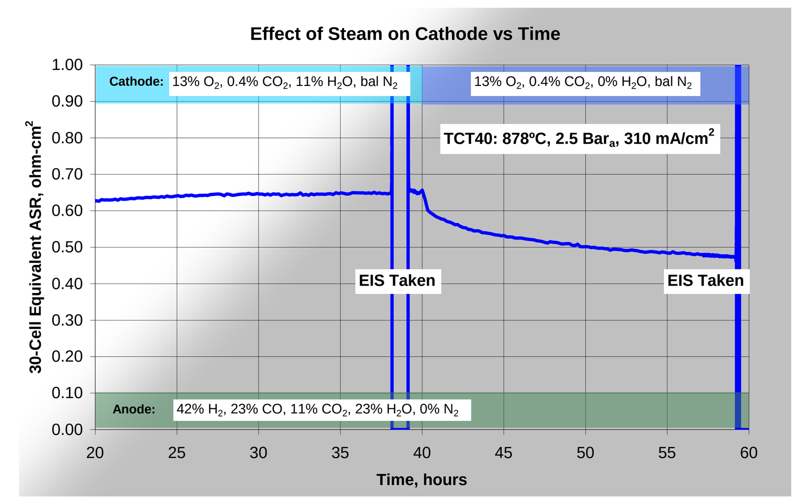


Effect of Pressure on Performance

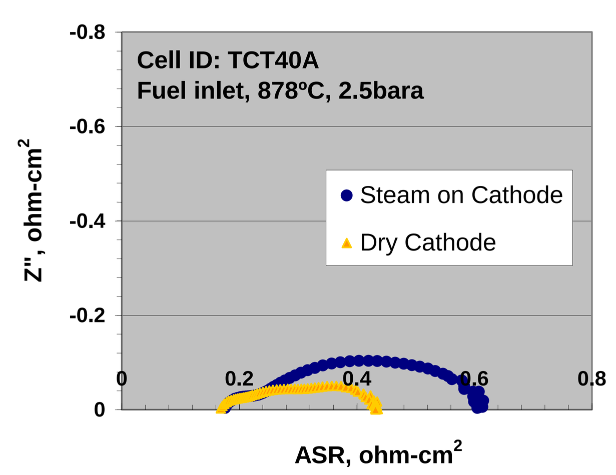


Effect of Cathode Steam

The original RRFCS system design used a direct combustion of the unused anode fuel to pre-heat the incoming cathode air. This was found to cause an unacceptable loss of performance and the system configuration has since been modified to eliminate this feature. The chart above shows the improvement in ASR on a three-cell sample after steam is removed from the cathode stream.

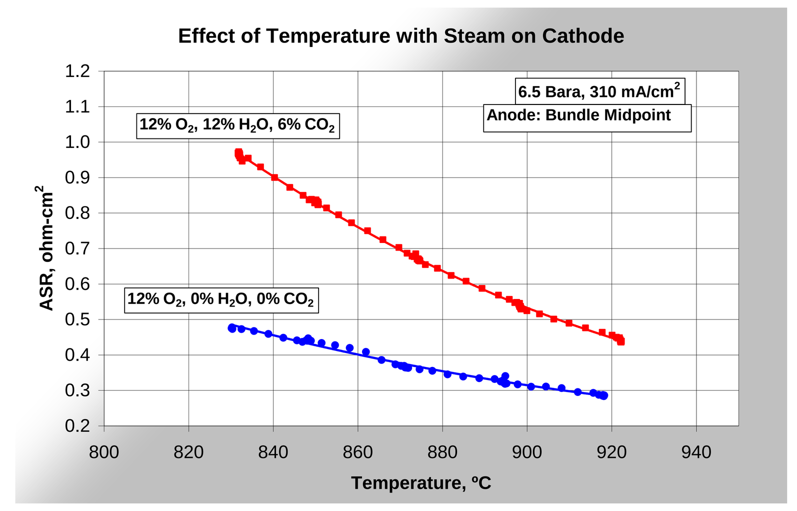


Steam Effect on Cathode Polarization



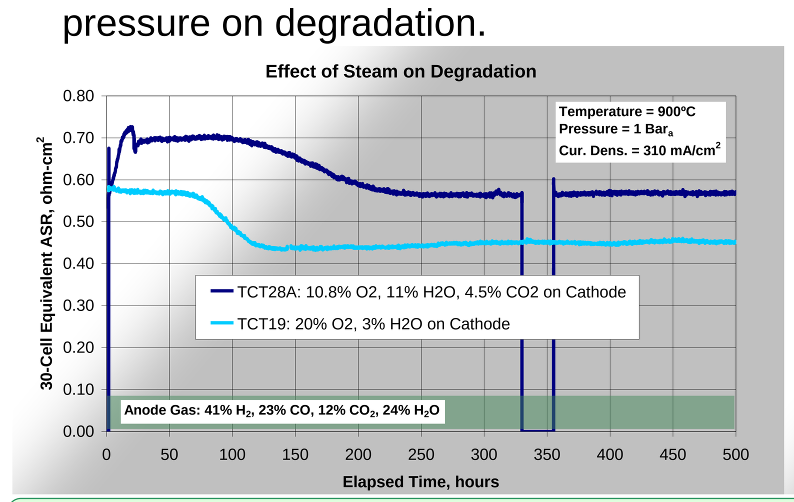
The chart to the left shows that the effect is a cathode polarization effect. Frequency analysis of impedance data showed that the increased polarization caused by steam is a slower process on the order of 10 Hz. This is similar to a mass transport process, and suggests a surface exchange phenomenon in the cathode.

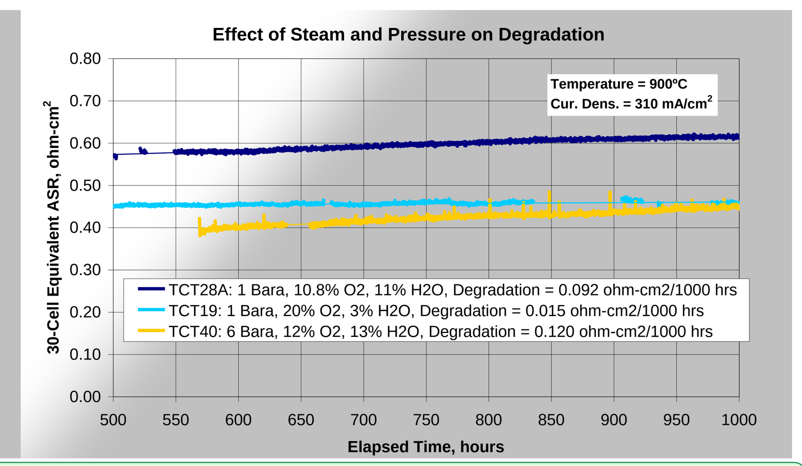
An important finding was that the effect of steam was highly temperature dependent. The loss of performance at temperatures below 850ºC was very large for the standard LSM + YSZ cathodes used at this time. Investigation of Mn valence changes have been carried out on a separate project along with Case Western Reserve University as a possible mechanism explaining this behavior.



Degradation Testing

Degradation testing was conducted on three-cell samples which were subjected to atmospheric and pressurized conditions, with high and low cathode steam concentration. The chart below to the left shows the "burn-in" behavior of an earlier generation of RRFCS fuel cells, and shows that the atmospheric test with steam has a higher ASR from the start. The chart below to the right shows that the effect of steam is a major factor in the degradation rate. The test at 6 Bara showed marginally higher degradation than at 1 Bara, but data was insufficient to substantiate the effect of pressure on degradation.





Conclusions

Improvement in anode and cathode electrode performance is on the order of 33-40% at pressures of 6.4 Bara compared to atmospheric pressure. Key cathode operational parameters are the concentration and partial pressure of O_2, and temperature. Anode performance also improves with pressure as both activation and mass transfer are aided. Steam on the cathode has been found to cause a longer-term loss of performance, especially at lower temperatures.

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