

# The effect of coal syngas containing HCl on the performance of solid oxide fuel cells: Investigations into the effect of operational temperature and HCl concentration

J.P. Trembly<sup>a,\*</sup>, R.S. Gemmen<sup>a</sup>, D.J. Bayless<sup>b</sup>

<sup>a</sup> National Energy Technology Laboratory, 3610 Collins Ferry Rd., Morgantown, WV 26507, USA

<sup>b</sup> 248 Stocker Center, Mechanical Engineering Department, Ohio University, Athens, OH 45701, USA

Received 16 February 2007; received in revised form 9 March 2007; accepted 12 March 2007

Available online 16 March 2007

## Abstract

The performance of solid oxide fuel cells (SOFCs) using simulated coal-derived syngas, with and without hydrogen chloride (HCl), was studied. Electrolyte-supported SOFCs were tested potentiostatically at 0.7 V at 800 and 900 °C with simulated coal syngas containing 0, 20, and 160 ppm HCl. The results from the tests without HCl show good performance with little degradation over 100 h of operation. Both 20 and 160 ppm HCl were shown to cause performance losses in the SOFCs after injection into the system. Although the tests presented in this paper show that HCl does cause degradation to SOFC performance, the cell performance was recoverable upon the removal of HCl from the fuel. Also recent results from anticipated Integrated Gasification Combined Cycle IGCC warm/hot-gas-cleanup technologies suggest that HCl will be removed to levels that will not cause any significant performance losses in SOFCs.

Published by Elsevier B.V.

**Keywords:** Solid oxide fuel cell; Coal syngas; Experimental performance; Hydrogen chloride

## 1. Introduction

Coal is one of the lowest-priced fuels in terms of cost-per-unit energy. Given the vast resources of coal within the U.S., it will be used in power generation for years to come. With ever-increasing scrutiny of coal-fired-power-plant emissions, more efficient and cleaner power production processes are being sought. Gasification technology, along with new cleanup and sequestration technologies, allows for the environmentally benign use of coal for power production. The U.S. Department of Energy is currently investing in the development of both fuel cell and coal-gasification technologies for use in projects such as FutureGen [1], which will test such systems' abilities to generate clean power and clean fuels, such as hydrogen.

Incorporation of solid oxide fuel cell technology into future power-plant systems may help reduce plant costs due to the high efficiency of electrochemical systems, resulting in a smaller

physical plant size for a given electric-power output. Many studies have been completed to determine the feasibility of operating solid oxide fuel cells on carbon-based fuels such as natural gas, however very few studies have concentrated on the use of gasified coal [2]. Recent studies have demonstrated that planar solid oxide fuel cells (PSOFCs) were able to operate on simulated coal syngas, as well as coal syngas produced by the Power Systems Development Facility's advanced fluidized bed reactor cleaned of trace species [3,4]. Finally, at least one earlier fuel cell study showed that 1 ppm HCl in a simulated coal syngas caused no degradations to a tubular SOFC operating at 0.35 A cm<sup>-2</sup> [5,6]. However, this study was completed at 1000 °C, which does not directly apply to existing technology now operating at much lower temperatures.

While these tests were encouraging, it is well known that syngas contains many residual trace species that are expected to affect the performance of fuel cells. For example, hydrogen sulfide (H<sub>2</sub>S) in coal syngas detrimentally affects a solid oxide fuel cell's performance [3,7]. In order to identify the level of residual trace specie removal that will be required of future cleanup technologies, the effect of trace coal-syngas species on

\* Corresponding author. Tel.: +1 304 285 1332; fax: +1 304 285 0903.  
E-mail address: [jason.trembly@NETL.DOE.GOV](mailto:jason.trembly@NETL.DOE.GOV) (J.P. Trembly).

the performance of SOFCs must be measured. Presently, the U.S. DOE's National Energy Technology Laboratory (NETL) is investigating the effect of several trace coal syngas species (HCl, AsH<sub>3</sub>, PH<sub>3</sub>, H<sub>2</sub>Se, Pb, Cd, Hg, and Sb) [8] on the performance of PSOFCs to help identify the levels of cleanup that will be required for gasification systems coupled with SOFCs and to help develop anodes better suited for coal-syngas applications [8].

One difficulty in studying contaminate effects on SOFC technology is knowing which contaminants will be present at significant levels within the syngas. Available information shows that existing water-scrubber-cleanup technology is successful in removing large amounts of H<sub>2</sub>S from coal syngas [9,10]. However, other contaminants may not be significantly captured and can be expected to pass to the fuel cell. Because cleanup technology continues to advance in its ability to remove syngas contaminants, it remains unclear what the optimal cleanup strategy will be for coal-based fuel cell plants. Therefore, the final concentrations of contaminate loadings remains unclear. For the present work being conducted, we will assume that a "worse case" scenario for fuel cells will be trace elements at existing cleanup technology levels.

Hydrochloric acid (HCl) is of particular interest because of the high levels of chlorine present in most U.S. coals, especially eastern bituminous coals. HCl has previously been shown to decrease the activity of various metal catalysts. The poisoning effect of HCl on methanol synthesis catalyst is well documented. The presence of HCl in coal syngas causes an immediate decrease in the activity of the LPMEOH<sup>TM</sup> catalyst that continues after the HCl source is removed. Chlorine poisoning may increase sintering of the catalyst due to the low melting temperature of CuCl [11–16]. HCl has also been shown to decrease the activity of a Pd/Al<sub>2</sub>O<sub>3</sub> catalyst used for the oxidation of methane. HCl is theorized to compete with reactants for active metal sites and thereby decrease the activity of the catalyst [16].

Chlorine is readily found in U.S. coals as sodium and potassium chlorides ranging from 0.01 to 0.5% in weight. Nearly all chlorine in coal is converted to HCl in the reducing environment of the gasification process. HCl concentrations as high as 500 ppm have been reported in coal syngas from gasifier effluents [10]. Although water scrubbing has been demonstrated to remove a significant portion of the chlorides present in coal syngas, up to one third may still pass through the scrubber system, allowing the anode of a potential fuel cell to be exposed to HCl [9]. This paper reports on the results obtained from recent research investigating the effect of a simulated coal syngas containing HCl on the performance of a SOFC.

## 2. Experimental

### 2.1. Button cell description

Electrolyte-supported SOFCs manufactured by Nextech Materials were used in this study. Each button SOFC consisted of a 1.27-cm-diameter cathode composed of a 25- $\mu$ m-thick La<sub>0.8</sub>Sm<sub>0.2</sub>MnO<sub>3</sub>(LSM)–Ce<sub>0.9</sub>Gd<sub>0.1</sub>O<sub>1.95</sub>(GDC) interlayer and

a 25- $\mu$ m-thick current-collection layer made of LSM. The 3.00-cm-diameter electrolyte was made of 110- $\mu$ m-thick scandia stabilized zirconia (ScSZ). The 1.27-cm-diameter anode was composed of a 25- $\mu$ m-thick Ni-GDC interlayer and a 25- $\mu$ m-thick Ni–8YSZ current-collection layer.

### 2.2. Button cell test setup

Platinum current collection meshes were attached to each electrode using Pt paint. Silver current cables and voltage taps were spot welded onto opposite sides of each current collection mesh. The button SOFCs were mounted between two alumina flanges and ceramic *o*-rings using mica as the sealing material.

For all tests, the button cell assembly was mounted in a split tube furnace operated at 800 or 900 °C. Alicat<sup>TM</sup> mass flow controllers (MFCs) were used to control the fuel and air stream flow rates and compositions. Separate MFCs were used to control the flow rates of H<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>/HCl to the anode and air to the cathode. A temperature controlled humidifier was used to control the water content of the simulated coal syngas provided to the anode. The total fuel flow rate was kept at approximately 550 ± 12.5 sccm and the air flow rate was kept at approximately 2000 ± 10 sccm. The anode flow lines were heat traced to ensure no condensation would take place between the humidifier and split tube furnace. HCl was injected downstream of the water bubbler to help ensure all species injected into the stream reached the anode of the SOFC.

### 2.3. Experimental testing

The SOFCs were heated from room temperature to 800 °C over 12 h. During the heating period the anode was provided 100 sccm of N<sub>2</sub> and the cathode was provided 500 sccm of air. Once the PSOFC reached its operational temperature, the anode of the button cell was reduced by slowly increasing the H<sub>2</sub> flow by 10 sccm every 10 min while keeping the total flow rate to the button cell at 100 sccm. Upon reduction of the anode, which was indicated by a steady-open-circuit potential typically within 5% of the theoretical open-cell potential, the cathode-air-flow rate was increased to 2000 sccm, and the open cell voltage (OCV) of the cell was monitored for its expected Nernst value to ensure negligible leakage around the cell. The anode was then provided 400 sccm of H<sub>2</sub> and an area specific resistance (ASR) measurement was completed. If the ASR of the button cell was found to be within 10% of its design value (0.5  $\Omega$  cm<sup>2</sup>), the cell was determined to be acceptable for testing. For testing at 900 °C the cell was subsequently heated to operational temperature over an additional 2-h period.

After the button cell was deemed acceptable for testing, it was operated potentiostatically at 0.7 V while the water bubbler was brought to its operational temperature. Water-bubbler temperatures of 75 and 64 °C were used for the 160-ppm and 20-ppm trials, respectively. Two different water-bubbler temperatures were used in the testing to ensure a fuel gas with a constant composition was supplied to the fuel cell with HCl concentration as the only variable. The HCl was provided using a certified gas mixture of H<sub>2</sub> containing 557 ppm HCl, thereby providing a total

Table 1  
Simulated coal-derived syngas compositions used in testing

Component	160 ppm HCl trials (vol%)	20 ppm HCl trials (vol%)
H <sub>2</sub>	29.1 ± 0.7	29.1 ± 0.8
CO	28.6 ± 0.7	28.6 ± 0.8
CO <sub>2</sub>	12.0 ± 0.3	12.0 ± 0.3
N <sub>2</sub>	3.2 ± 0.1	3.2 ± 0.1
H <sub>2</sub> O	27.1 ± 0.6	27.1 ± 0.7
HCl	160 ± 3 ppm	20 ± 1 ppm

fuel-flow rate of 550 sccm. Because less H<sub>2</sub>/HCl gas mixture was needed to achieve 20 ppm HCl, more gas was humidified through the water bubbler, resulting in a lower operating temperature to achieve the same water content as in the 160 ppm HCl trial. None of the H<sub>2</sub>/HCl gas was passed through the water bubbler because water acts as a scrubbing agent. Once the water bubbler stabilized at its operational temperature, the button cell was provided a simulated coal syngas based on an entrained-flow gasifier [17]. Table 1 presents the simulated coal-syngas compositions that were used for both HCl investigations.

Although typical entrained-flow coal-gasification compositions only contain 15–17 vol% H<sub>2</sub>O, additional water was added to the system to ensure that coking did not take place at the anode. (Note: specific strategies for dealing with potential coking of the anode under coal-syngas operation remain to be identified). Fig. 1 presents the ternary (C–H–O) diagram for the system and the location of the compositions used in the testing.

The button cell was operated potentiostatically for at least 24 h with the simulated-coal-syngas mixtures before HCl was introduced. Based on the flow rates presented in Table 1 and the certified gas mixture, approximately 160 ± 3 ppm and 20 ± 3 ppm of HCl were provided to the anode of the PSOFC during testing. ASR and electrochemical-impedance-

spectroscopy measurements were made using an Agilent electronic load (N3301A), a Solartron impedance analyzer (SI 1260), and Solartron electrochemical interface (1287). The voltage and current of the SOFC were also monitored over time. After the trials, SEM and EDS analyses were completed using a JEOL JSM 6300FV SEM and Thermo Electron Noran System Six EDS. XRD analyses were also completed using an X-pert Pro PANalytical XRD.

### 3. Results and discussion

#### 3.1. 800 °C tests

Button cell tests were completed at 800 °C containing 0, 20, and 160 ppm HCl. The tests were completed as described in Section 2. Fig. 2 presents the power density–time history-profiles of the SOFCs under various HCl loadings operating at 800 °C and 0.7 V.

From Fig. 2 it may be seen that HCl concentrations of 20 ppm and 160 ppm had a measurable effect on the performance of the fuel cell over time. However, it must be noted that the SOFC showed stable operation over time while operating on a coal syngas mixture without HCl. At the beginning of the trial the fuel cells started with an approximate operational-current density range of 0.32–0.34 A cm<sup>-2</sup>. After 100 h of operation the cells operating with 20 ppm and 160 ppm HCl had operational current densities of approximately 0.28 A cm<sup>-2</sup> and 0.24 A cm<sup>-2</sup>, equating to 17.4 and 26.1% degradation, respectively. The SOFC was shown to sustain stable operation with 20 ppm HCl after approximately 50 h of operation, while the fuel cell operating with 160 ppm HCl tended to stabilize toward the end of the trial. Although the HCl has shown an effect on the operation of the SOFCs, it must be noted that this effect is far less detrimental than the effect of H<sub>2</sub>S that has previously been shown [18].

Fig. 3 presents AC-impedance plots for the three trials, which approximately match the trends shown in Fig. 2. All three plots show approximately the same ohmic-resistance across the cell, which is found at the high-frequency *x*-intercept, and charge-

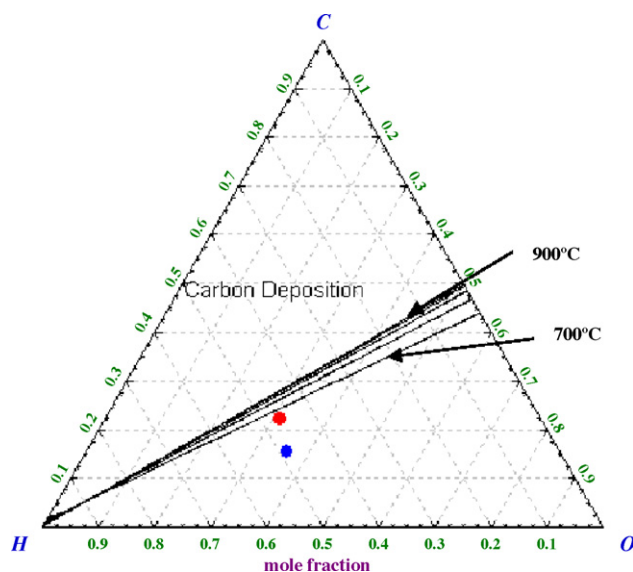


Fig. 1. C–H–O ternary diagram with a typical entrained-flow syngas composition (red) and the composition used in the investigations (blue). Constant-temperature lines demarcate the regions with carbon deposition and without carbon deposition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

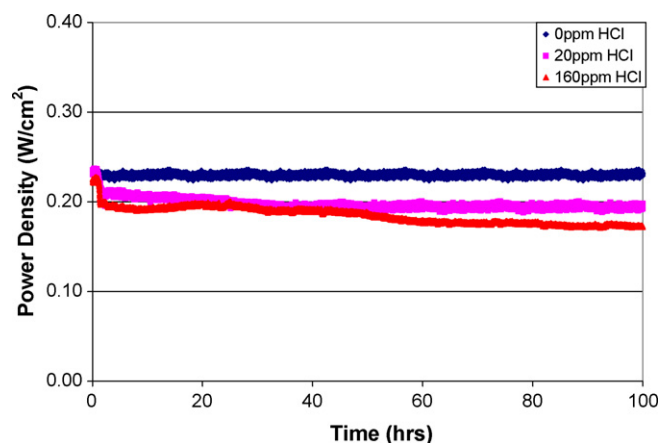


Fig. 2. SOFC power density operating at 800 °C and 0.7 V over time with HCl concentrations of 0 ppm, 20 ppm, and 160 ppm.

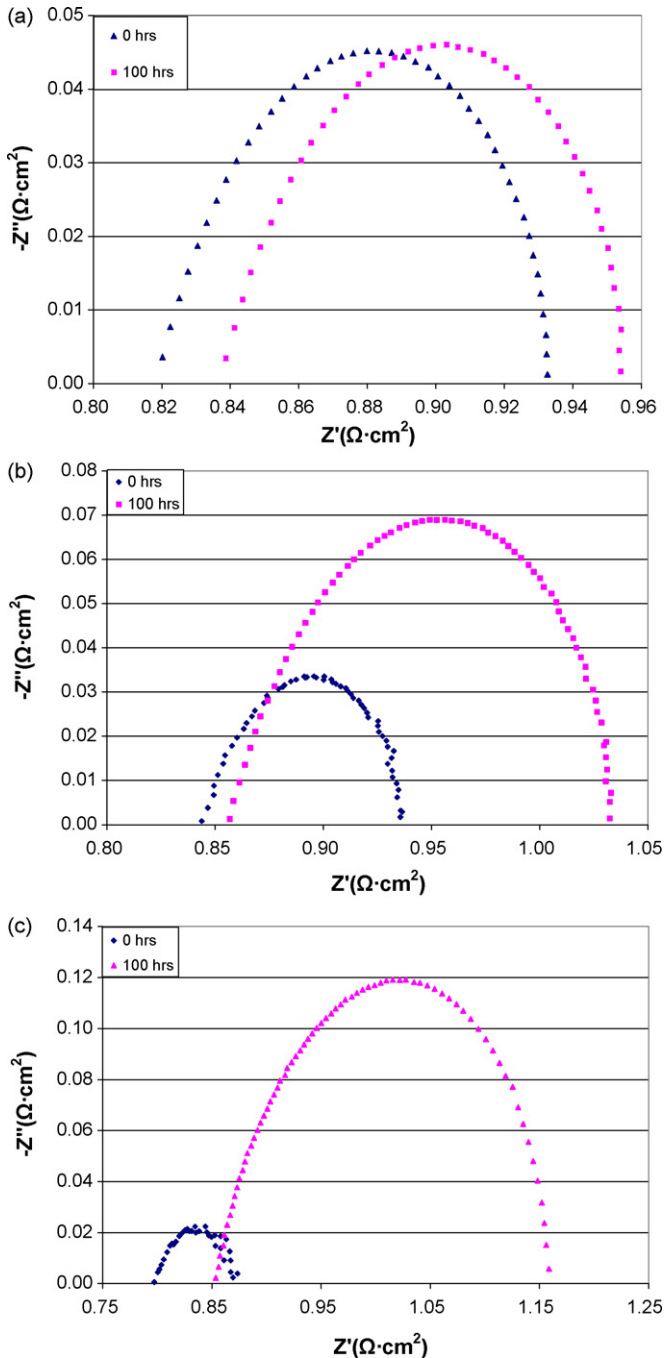


Fig. 3. AC-impedance plots for SOFCs operating with CSG as fuel at 800 °C, 0.7 V, and 0 ppm HCl (a), 20 ppm HCl (b), and 160 ppm HCl (c).

transfer resistance across the fuel cell for all three trials before the injection of HCl. However, major differences between the three plots can be seen when comparing the AC-impedance after 100 h of operation. The SOFC operated without HCl showed an ohmic-resistance increase of approximately 2.0% over the 100-h-time period and a charge-transfer resistance increase of only 4.2%. When 20 ppm of HCl was injected it may be seen from Fig. 3b that there was only a slight increase in the ohmic-resistance across the fuel cell, approximately 1.8%; however, the charge-transfer resistance associated with the system showed a very large increase, 84.4%. Although the charge-

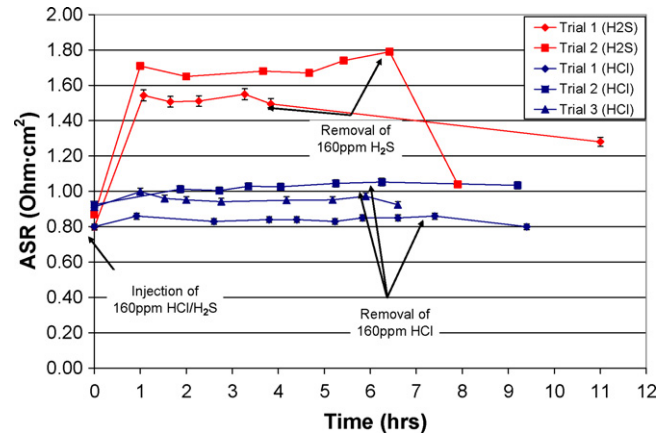


Fig. 4. SOFC ASR data over time for SOFCs operating 800 °C with CSG containing 160 ppm of HCl and H<sub>2</sub>S, respectively. Overall, the effect of H<sub>2</sub>S was irreversible, while the effect HCl was reversible.

transfer resistance contains the impedance of both the anode- and cathode-electrochemical systems, it may be assumed that the changes that were shown to take place were associated with the addition of HCl to the anode, because all other parameters remained constant. As expected, the fuel cell exposed to a fuel containing approximately 160 ppm sustained higher performance losses than the fuel cell exposed to 20 ppm HCl. This cell showed an ohmic-resistance increase of 7.2%, a charge-transfer resistance increase of 300%.

The tests completed at 800 °C show that worst-case levels (that may be found from present cold-gas-cleanup systems) would be a problem for present SOFC systems. Although these levels were shown to cause a great amount of degradation, the performance of the fuel cells did tend to stabilize over time. Although these levels were shown to be quite large, the effect of HCl was not nearly as detrimental as that of H<sub>2</sub>S [18]. Fig. 4 presents area specific resistance data for the same SOFCs operated on coal syngas containing approximately 160 ppm of HCl and H<sub>2</sub>S, respectively [18].

From Fig. 4 it may be seen that at equivalent loadings H<sub>2</sub>S causes far greater performance losses as the ASR of the SOFCs increased by up to 112% while the same loading of HCl caused an ASR increase of approximately 20% after 6 h of operation. Also from Fig. 4 it should be noted that upon the removal of HCl from the simulated coal syngas, the SOFC performance was shown to recover back towards the original operating state of the fuel cell before the injection of HCl. This data shows that the poisoning effect of HCl on the SOFC anode tends to be reversible with HCl concentrations as high as 160 ppm. Similar results have been shown previously in literature with lower concentrations of H<sub>2</sub>S [7].

### 3.2. 900 °C tests

Button cell tests were completed at 900 °C using 0, 20, and 160 ppm HCl. The tests were completed as described in Section 2. Fig. 5 presents the power density–time-history profiles of the SOFCs under various HCl loadings operating at 0.7 V.

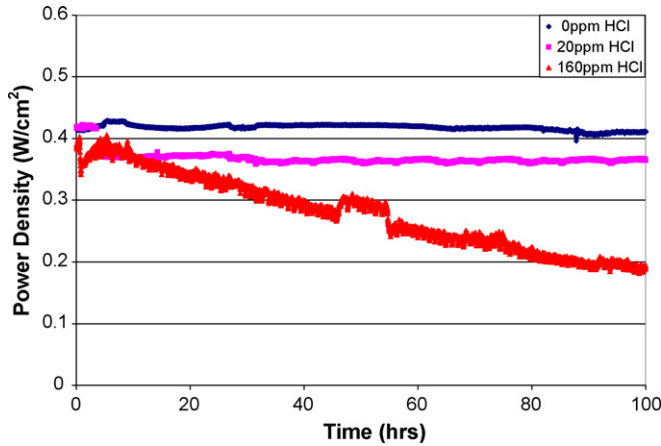


Fig. 5. SOFC power density curves at 900 °C and 0.7 V over time with HCl concentration of 0 ppm, 20 ppm, and 160 ppm.

The data in Fig. 5 indicate that HCl concentrations of 20 ppm and 160 ppm had an effect on the performance of the fuel cell. However, it must also be noticed that the fuel cell showed stable operation over time while operating on a coal-syngas mixture without HCl at 900 °C. The cells operated at a higher initial current density, 0.56–0.60 A cm<sup>-2</sup>, at 900 °C than the cells operated at 800 °C. This was expected due to the lowering of the ohmic-resistance associated with the electrolyte. After 100 h of operation the SOFCs operating with 20 ppm and 160 ppm HCl had operational-current densities of approximately 0.52 A cm<sup>-2</sup> and 0.27 A cm<sup>-2</sup>, respectively, causing 13.3% and 51.8% degradation. The SOFC was shown to sustain stable operation with 20 ppm HCl after approximately 30 h of operation while the fuel cell operating with 160 ppm HCl did not reach steady operation. However, the rate of degradation for the 160-ppm test was tending to slow (slightly) at approximately 75 h of operation.

AC-impedance plots for the three trials completed at 900 °C are shown in Fig. 6. These data indicate that the AC-impedance plot trends correspond to the data shown in Fig. 5. All three plots show approximately the same initial ohmic-resistance and charge-transfer resistance across the fuel cell before injection of HCl. Fig. 6a shows an ohmic-resistance increase of 4.2%, a charge-transfer resistance increase of 22.7%, with no HCl injected. However, major differences between the three plots can be seen when comparing the AC-impedance after 100 h of operation. When 20 ppm of HCl was injected it may be seen from Fig. 6b that there was an increase in both the ohmic- and charge-transfer resistance of the cell, 7.2 and 53.1%, respectively. As shown in Figs. 3b and 6b the cell exposed to 160 ppm HCl sustained higher losses than the fuel cell exposed to lower levels of HCl. However, unlike the SOFC exposed to 160 ppm HCl at 800 °C, the fuel cell incurred higher ohmic-resistance degradation, 9.2%, over the 100 h trial period at 900 °C. Examining Fig. 6c, it may be seen that a much larger portion of the performance loss was attributed to the increase in the ohmic-resistance across the fuel cell rather than the increase in charger-transfer resistance, which was also shown to take place.

This same phenomenon may be seen in the results presented in Fig. 6b when compared with Fig. 3b. It is believed that this

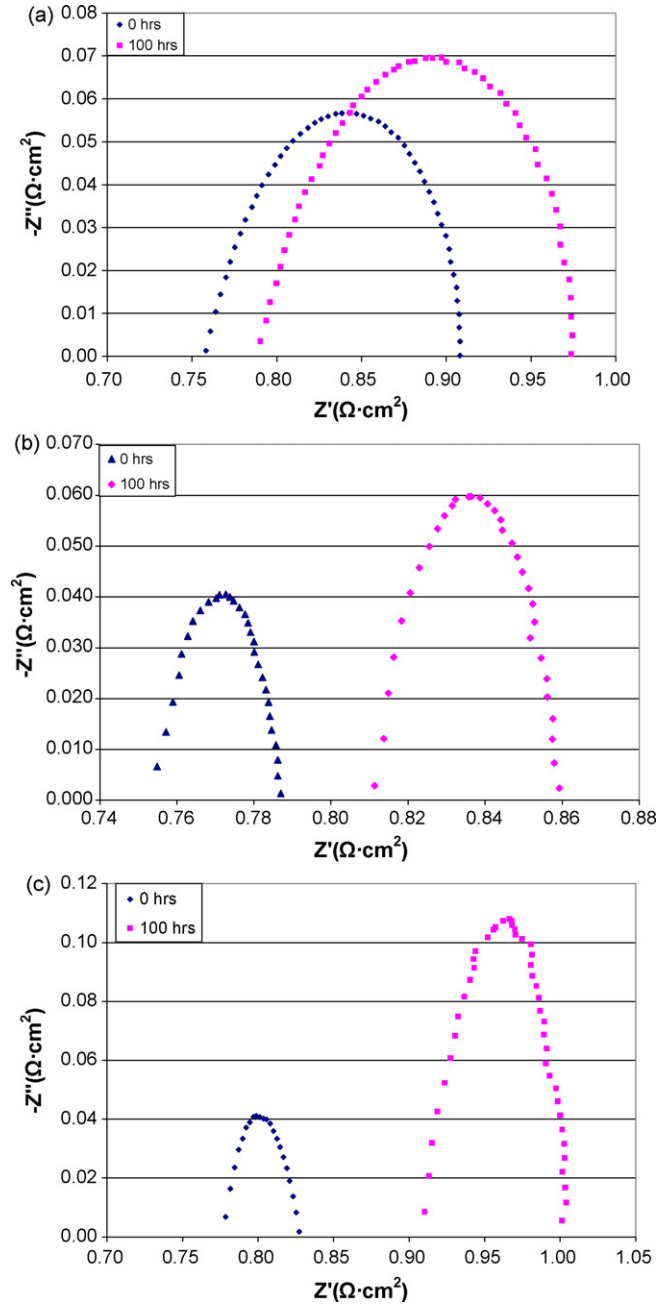


Fig. 6. AC-impedance plots for SOFCs operating with CSG as fuel at 900 °C, 0.7 V, and 0 ppm HCl (a), 20 ppm HCl (b), and 160 ppm HCl (c).

increase in ohmic-resistance was caused by the effect of the higher temperature on the Pt contact paint, not by the effect of HCl on the anodic system. Upon completion of the trials at 900 °C it was found that the Pt current-collection mesh was partially pulled away from the anode of the SOFC. A decrease in the contact between the anode of the SOFC and the current-collection mesh over time could explain the higher ohmic-resistance degradation rates seen in the 900 °C trials.

### 3.3. Post-trial material analyses

In order to determine if any secondary chloride phases were formed during operation with simulated coal syngas with HCl,

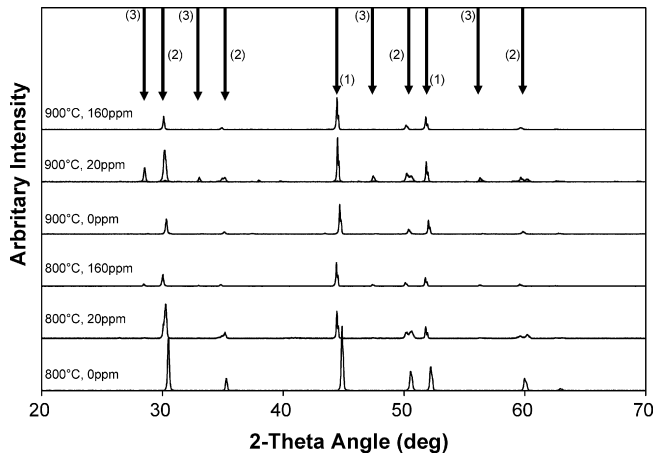


Fig. 7. SOFC anode XRD profiles after operation with CSG containing HCl. Phases identified are Ni (1), YSZ (2), and GDC (3).

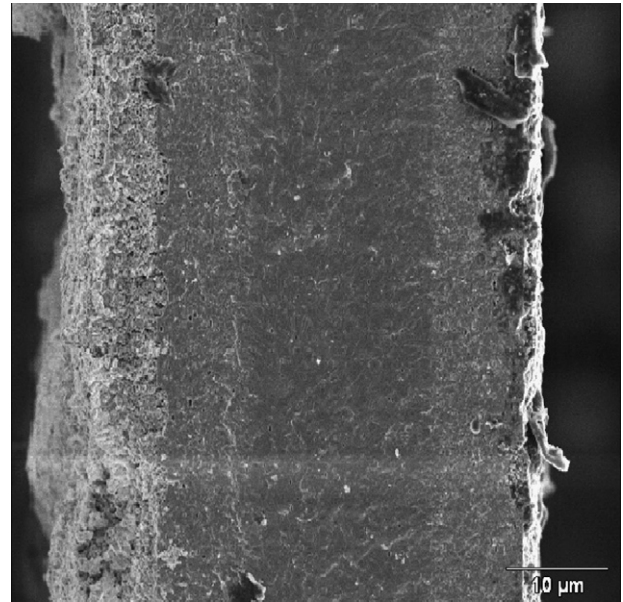


Fig. 8. Representative SOFC cross-section at 2000 $\times$ .

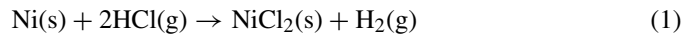
several post-trial analyses were performed using XRD, SEM, and EDS. Fig. 7 presents the XRD profiles of the SOFCs operated under the various coal syngas conditions and temperatures. The data in Fig. 7 show the three main components of the anode system: Ni, YSZ, and GDC. The results from the XRD show no signs of secondary chloride phases forming in the anode of the SOFC and no effects on the anode materials.

SEM and EDS analyses were also completed on all of the SOFCs used in this study. Fig. 8 presents a typical cross section of one of the SOFCs after testing. In Fig. 8 the porous cathode material may be seen on the left of the cell, the SSZ electrolyte in the middle, and anode on the right. To better determine if any secondary nickel chloride phases formed across the anode, EDS line scans were completed across the SOFCs after testing. Fig. 9 presents a typical SEM image and line scan across the anode of the SOFC operated at 900 °C with 160 ppm HCl.

The results in Fig. 9 correspond well to the original construction of the SOFC anode. The left portion of the scan shows a large zirconium signal, corresponding to the electrolyte. In the middle of the scan, the signal dissipates dramatically, corresponding to the anode interlayer, which is composed of nickel and GDC. At the right of the scan, the zirconium peaks once again, corresponding to the current-collection layer of the SOFC, which

contains nickel and YSZ. Most importantly, no chlorine signal was found in any of the anodes tested.

To examine mechanisms of degradation, it was necessary to rule out the possibility of secondary nickel chloride formation. While the material analyses did not indicate the presence of nickel chloride, thermodynamic calculations were also used to determine the possibility of a secondary nickel chloride formation in the anode based on Eq. (1). The results from these calculations are presented in Fig. 10.



From Fig. 10 it may be seen that there is a positive change in the Gibbs free energy for this reaction over the operational-temperature range of typical SOFCs, showing that the formation of the secondary nickel phase, NiCl<sub>2</sub>(s), is not feasible. Therefore, combining these results, the material analyses, and the previous electrochemical data showing degradation when HCl was added to the coal syngas fuel, it can be concluded that HCl affects the electrochemical processes of the SOFC anode

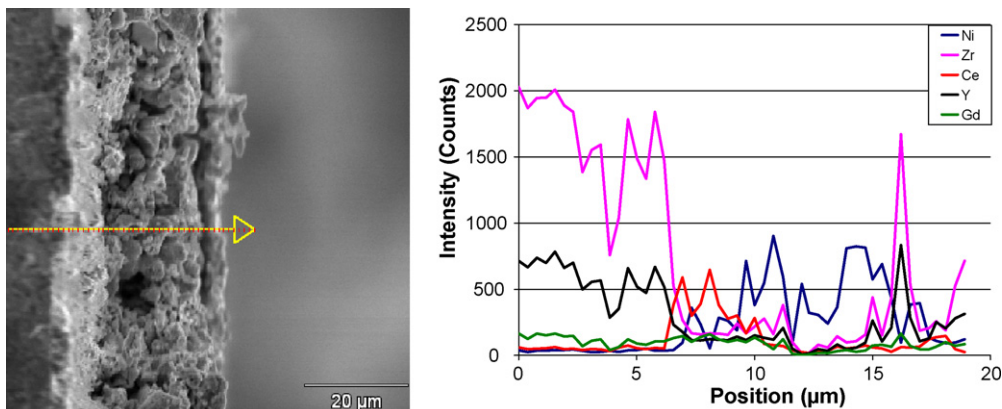


Fig. 9. EDS line scan across SOFC operated at 900 °C with 160 ppm HCl.

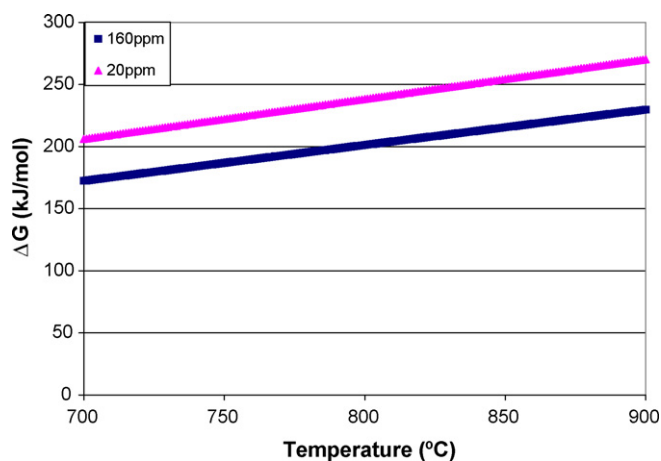


Fig. 10. Gibb's free energy of reaction for Eq. (1) over SOFC operating temperature range, 0.29 atm of  $H_2$ , 20 ppm and 160 ppm HCl.

through mechanisms other than secondary nickel phase formation. The next section will discuss a possible degradation mechanism, the evidence regarding this, and the needs for future coal-gas-cleanup systems regarding HCl.

### 3.4. Discussion of results

The results presented in this paper show that HCl does impact the performance of an SOFC anode. However, the data strongly indicates that the impact of HCl is not a result of the formation of a stable chloride phase in the anode of the SOFC. Previous studies investigating the effect of  $H_2S$  and HCl on the performance of SOFCs have shown that both cause similar effects on the performance of SOFCs [18]. However,  $H_2S$  causes much more severe performance degradation than HCl. Similar tests of the effects of 160 ppm of  $H_2S$  and HCl showed that the  $H_2S$  caused approximately a 110% increase in the ohmic-resistance of an SOFC compared with only a 20% increase in ohmic-resistance of an SOFC supplied with HCl over an 8-h-time period [18]. This behavior caused by  $H_2S$  has also been reported elsewhere in literature [19,20]. In addition, Fig. 4 has shown that the removal of both contaminants from the coal-syngas mixture resulted in nearly full recovery of the SOFCs' performance. These similarities in the resultant losses and recovery of the fuel cell systems exposed to  $H_2S$  and HCl suggest that both chemical species may be affecting the anode system in a similar manner.

One possible theory is that adsorption of chlorine onto Ni surfaces, as shown in Eq. (2), causes the performance losses seen with HCl.



As chlorine is adsorbed onto Ni, the chlorine blocks possible reaction sites at the anode/electrolyte interface of the SOFC used for the electrochemical oxidation of the fuel species,  $H_2$  and CO. As with  $H_2S$  poisoning of the SOFC anode, the experimental HCl data also shows that the proposed chemical mechanism shown in Eq. (2) reaches an equilibrium based upon the total amount of HCl present in the supplied fuel. If this were not the case the performance of the fuel cell would continue to degrade

over time as reaction sites would continually become blocked with adsorbed chlorine. In addition the data in Fig. 4 clearly shows that removal of HCl from the fuel allows the SOFCs to recover to its operational state before injection of HCl, which shows that the adsorbed chlorine is released back into the fuel stream. Previous research has shown that although  $H_2S$  concentrations may be found well below those needed to form bulk metal sulfides, irreversible poisoning may still take place [20]. This irreversible poisoning has been shown to have been caused by the formation of stable surface metal sulfides. This mechanism has been shown to profoundly effect the performance of SOFCs in the presence of 100 ppm  $H_2S$  or greater [21]. The information presented in Fig. 4 also shows that stable surface nickel chloride does not form due to the reversibility of the poisoning caused by HCl. If a surface chloride phase were to form on the nickel catalyst in the SOFC anode then irreversible poisoning would have been found to have taken place. This information shows that although the formation of nickel chloride in the presence of low levels of HCl is not feasible, the physical adsorption of chlorine onto nickel is evidently favorable.

While the effect of different current loadings has not been studied for this present work, the effect of current loading could be easily conjectured from the present data. Given the results of the data which show reversibility of the surface chloride with varying bulk HCl concentration, it is likely that the equilibrium concentration of adsorbed chloride at the electrochemical interface results from equilibrium kinetics between HCl adsorption/desorption at the electrochemical interface while in competition with the same for  $H_2$ . As a result, the surface concentration of chloride is directly related to the gas concentration of HCl near the electrochemical interface. The two primary effects of changing current load are: (1) change the concentration of gas species at the interface due to diffusion limitations in the electrode; (2) change the number of available active sites at the interface for competed  $H_2$  and HCl adsorption. Since the reaction paths leading to final adsorption of either  $H_2$  or HCl at an active site are unlikely modified by the availability of active sites, the latter effect of changing current load on the HCl surface concentration is unlikely to be significant. While the former effect (diffusion) generally occurs, because the present experimental studies used very thin electrodes, the effect of changing current load on diffusion had only minor effects on specie concentration at the electrochemical interface. This was confirmed with anode electrode transport simulations using the Mean Pore Transport Model and Dusty Gas Model, which has been previously presented in literature [22], which showed that as the current density of the fuel cell is increased from 0.5 to 1.5  $A\ cm^{-2}$  the partial pressure profile of HCl and  $H_2$  (absolute concentrations) throughout the anode of the SOFC is insignificantly impacted. Hence, for the present work with the presently employed cell designs, current density effects on contaminate degradation would likely be insignificant.

## 4. Conclusions

The effects of coal syngas containing hydrogen chloride on the performance of solid oxide fuel cells at various opera-

tional temperatures were studied. The results indicated that coal syngas without HCl does not significantly affect SOFCs operating between 800 and 900 °C. The introduction of 20–160 ppm of HCl had an immediate impact on the SOFC performance. Results showed a 13.3–51.8% loss in performance over the temperature and concentration levels tested. At 800 °C the tests showed that HCl at these levels was detrimental to SOFC operation and that the cells tended to reach a steady operation after only 100 h of exposure to the trace specie. These performance losses were shown to be mostly associated with the increase in charge-transfer resistance associated with the electrochemical system at 800 °C. At 900 °C these performance losses were found to be more substantially affected by increases in the ohmic-resistance and charge-transfer resistance across the SOFC. The higher rates of ohmic-resistance degradation at 900 °C, compared with 800 °C, are believed to be caused by the delaminating of the current-collection mesh away from the anode of the SOFC. However, results did indicate that although the SOFCs did suffer performance losses due to the introduction of HCl into the system, the fuel cells tended to achieve steady-state operation after 100 h of operation with HCl. Past research has also shown that SOFCs exposed to the same level of HCl tend to recover back to initial operating conditions after the removal of HCl, showing that although a breakthrough event in a cleanup system will cause performance losses, the losses will not remain permanent [18].

Although the work presented in this paper was based on worst-case cold-gas-cleanup conditions, the results may also be used to draw conclusions as to the required effectiveness of future IGFC warm/hot-gas-cleanup systems to remove HCl to levels that will not cause anode performance losses. Previous literature has shown that sorbents used in warm/hot-gas-cleanup systems can remove HCl to levels below 1 ppm [21–26]. Prior research has shown that low levels of H<sub>2</sub>S (<1 ppm) do not cause performance degradations in nickel-based SOFC anodes. Previous information has also shown that both H<sub>2</sub>S and HCl have very similar effects on the performance of an SOFC, although H<sub>2</sub>S has been shown far more detrimental. This information suggests that both trace species are poisoning the anode of the SOFC by similar mechanisms. Since literature has shown that technologies being considered for warm/hot-gas-cleanup systems to be used with future IGFC systems have the ability to remove HCl to levels below 1 ppm, it suggests that HCl will not cause any detrimental effects to SOFC performance. To confirm this, additional testing of SOFC performance with HCl at lower temperatures (approximately 750 °C) might be done at lower concentration levels. This work is important to move forward,

given the increased effect of H<sub>2</sub>S and HCl at lower temperatures and the continued desire to lower the temperature of SOFC technology.

### Acknowledgements

This work was supported by the National Energy Technology Laboratory. The authors would like to thank Dr. Christopher Johnson for use of the XRD equipment and Mr. James Poston for use of the SEM and EDS equipment.

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