PROBLEMS in analysis of solid oxide fuel cell (SOFC) test data are described. Tests and analysis should be conducted in a way that allow comparison between results of different types of tests and results from different sources. A major point in this context is the correction for fuel and oxidant utilization. Easy approximate methods for this are presented. The experimental set-ups for SOFC tests at Risø are described and problems involved in practical tests are addressed for two examples. It is shown that in case the open circuit potential is much below the theoretical electromotive force, performance measures like the area specific resistance as derived from the slope of the i-V-curve may be misleading. In this case it is of special importance to assure that the temperature of the cell is measured correctly.

INTRODUCTION

The solid oxide fuel cell (SOFC) is an all-solid state device with gaseous reactants, and thus it has its own special problems different from those of testing electrochemical cells in general. Here, cell testing is defined as testing of the electrochemical performance. Such cell testing may have several different purposes, and thus varying problems are associated with the testing. Many different cell test data have been reported, see e.g. (1-6). However, no general agreement on the test procedure exists, very few details are given about the actual set-ups, and the concept of area specific resistance (ASR) is used in several different ways in reporting of the results. This makes it difficult to compare results from different sources.

The aim of this paper is to describe some of the Risø cell testing experiences. An example of an apparently sound cell test result, which proved to be erroneous, is given. The importance of the choice of cell test housing material is exemplified. The importance of, and problems related to, separate tests of electrodes and electrolytes are outlined. The cell test results depend on a rather large number of parameters, which are difficult to interpret unless detailed knowledge on the cell components is available. Some recommendations are given, but a general test procedure is not recommended. The purpose of the test will determine the appropriate procedure.
The results of cell tests may be presented in different ways. For instance, the result of a cell test may be given as a single number such as an area specific resistance (in $\Omega \text{cm}^2$) or as a power density (W/cm$^2$). Such numbers are unfortunately ambiguous. It is necessary to specify both how the number was derived from the test results and the detailed test conditions. If the test conditions and the derivation procedures are different e.g. in case of two different cell developers, then the numbers are not directly comparable. These aspects will also be discussed below.

**TYPES OF CELL TESTS**

In case of "quick and dirty" tests as a tool for development of a specific type of cell only relative results are needed, i.e. it is not necessary to know the exact performance. It is sufficient to make current density - voltage curves (i-V-curves) which will show if a certain modification of the cell is an improvement or not. Such a type of cell test using a safe low concentration (<9%) of hydrogen was described previously (7). It is quite cheap mainly because of the avoidance of instrumentation for safety surveillance.

Other cell tests are done in order to compare the quality of cells with the results for other cell types and designs and from different SOFC developers. In this case the wish is to get results which exclude the test circumstances as much as possible. In case other cell developers do not make tests in a way that is directly comparable to your own, there is a need to correct the data for the effects of the circumstances, or if this is not possible, to estimate the importance of the differences. This is often possible by breaking down the total i-V-curve or cell resistance into the contributions from the individual components of the cell and the circumstances. This is further described below.

Finally, cell testing is done in order to demonstrate performance including durability and economic feasibility under given circumstances relevant to future commercial cell stack operation conditions. This cell test is by far the most expensive, and therefore there is a strong interest in establishing a solid basis for relating the outcome of such tests with the results of the cheaper test types.

**TYPES OF TEST RESULTS**

The full validation of a cell type includes a large number of i-V-curves for different conditions such as temperatures and fuel and air utilization and for different points in time over a long lifetime of ideally 40000h or more. This amount of data is rather inconvenient in many contexts, e.g. for comparing different cell types from various developers, or for economical modeling. It might be argued that the only important parameter is the power density (W/cm$^2$). However, if a reasonably accurate characterization of a cell by say at a maximum three quantities (three numbers) is wanted, it is not practical to use power density, because it is grossly dependent on fuel composition and cell polarization. As the i-V-curves are often approximately linear some SOFC developers have found it more convenient to use the concept of ASR (area specific resistance, $\Omega \text{cm}^2$). Unfortunately, ASR has no generally accepted definition, but as in the case of SOFC it is much less dependent on test circumstances than power density, and therefore, it seems worthwhile to investigate the ASR concept further.
From an economic evaluation point of view the fuel cell stack should be regarded as a "black box" into which hydrogen (gas) and oxygen (air) is fed, and out comes electricity and exhaust gases. Together with the "black box" follows an operation instruction describing how the stack should be started up, maximum heating and cooling rates etc., and a specification of the design point. From this point of view the relevant and logical definition of the ASR is:

\[
\text{ASR} = \frac{\text{Emf} - U}{i}
\]

where \(\text{Emf}\) is the electromotive force of the inlet fuel and air, and \(U\) is the cell voltage at the current density, \(i\), is the design point, e.g. 0.6V at 1000°C, a fuel utilization of 85% and an air flow of 4 times the stoichiometric amount ("4 stoichs"), corresponding to an oxygen utilization of 21% (85%/4), i.e. the air inlet contains 21% and the outlet 16.5% of \(O_2\). The cell voltage, \(U\), should be measured independently of the leads carrying the current, i.e. separate potential probes should be used. This ASR is useful input for cost analysis models because it is in most cases not very sensitive to small variations in cell voltage and fuel utilization. By determining the ASR at a few different temperatures an apparent activation energy, \(E_A\), may be derived. Thus, in a cell voltage interval from say 0.5 - 0.7V, a temperature interval of e.g. from 950 to 1050°C and a fuel utilization from 80 - 90%, the cell may be characterized with fair approximation by two numbers only, namely ASR at one temperature and \(E_A\).

In case the i-V-curve is concave it may be tempting to use a differential ASR (i.e. the tangent) at high current densities as this gives a nice low value. Such a number is in general not as useful as the quantity defined by Eq. 1, as it does not reflect the cell performance over the full polarization range.

Often, cell tests are done with very low fuel and air utilization. This is easier than the "realistic" tests, and the results reflect the performance of the cell as such much more directly. In case of insignificant fuel and oxygen utilization, the relevant definition of ASR is again that of Eq. 1, but the insignificant utilization makes this number incomparable to ASR derived from experiments with high fuel utilization, because the concentration polarization resistance due to the fuel and air conversion may be of the same order as the cell resistance at negligible utilization. Thus, in the general case it is necessary to specify also the fuel and oxygen utilization together with temperature and apparent activation energy. Furthermore, the experience is that using almost dry hydrogen, as is common practice, it is not easy to conduct experiments with a real negligible fuel utilization, because even small current densities will change the Emf of the hydrogen versus air significantly. Therefore, and in order to be able to compare results for different fuel utilization, a need exists for an ASR corrected for the effect of fuel utilization. Before it is described how this may be done, it is useful to look at the various contributions to the total ASR.
BREAKDOWN OF THE ASR

Overall the ASR may be divided into ohmic resistance, $R_o$, and electrode polarization resistance, $R_p$. The ohmic resistance originates from limited electrical conductivity of the electrolyte, the electrode materials and the current collection arrangement. This is very much dependent on geometric factors such as thickness of the components and the detailed geometry of the contact between current collection and electrodes, and between electrodes and electrolyte. The electrode polarization resistance should be divided into the contributions from the various rate-limiting steps. However, it is in general not possible to derive with any accuracy the individual contributions from cell test data. Therefore, it is necessary to do tests of individual electrodes using three electrode set-ups and to characterize the materials and contacts in terms of conductivity. Often results of tests of realistic cells using one or more reference electrodes have been reported (8-11). However, in case of thin film electrolytes this is extremely difficult, and there is a great risk that the results will be erroneous (12,13).

Here, the ASR is broken down in 5 terms:

$$ASR = R_e + R_c + R_{p,act} + R_{p,dif} + R_{p,con}$$

where $R_e$ is the calculated electrolyte resistance, $R_c = R_T - R_e$ is the resistance due to non-optimized contacting and current collection, $R_{p,act}$ is the activation polarization, which here is taken as the contribution from the processes on the electrode surface, in the bulk electrode material and on the electrolyte-electrode interface, $R_{p,dif}$ is the contribution from the gas phase diffusion, and $R_{p,con}$ is the contribution due to gas conversion, i.e. fuel and oxygen utilization. This division is based on what is possible to measure and calculate reliably rather than on basic physical and electrochemical theory.

**Table 1.** Contributions to ASR for an anode supported cell at 850°C tested in a plug flow type configuration in case of 5 and 85% fuel utilization (FU). $R_e$ is calculated using a specific conductivity of YSZ of 0.045S/cm, $R_c$ is an estimation based on in house experience, $R_{p,act}$ is the sum of typical anode and cathode polarization resistance measured in separate electrode experiments, $R_{p,dif}$ is calculated using a diffusion coefficient of 10cm²/s, 30% porosity, a tortuosity factor of 3 and a thickness of 0.1cm, and $R_{p,con}$ is calculated using Eq. 10 with $i = 0.5A/cm^2$.

| Resistance type | Contribution ($\Omega \cdot cm^2$) |
|-----------------|-----------------------------------|
| $R_e$           | 0.06                              |
| $R_c$           | ca.0.1                            |
| $R_{p,act}$     | 0.15                              |
| $R_{p,dif}$     | 0.06                              |
| $R_{p,con}$     | 0.06                              |

Some of the terms in Eq. 2 should thus be thought of as “equivalent resistances”, e.g. the Emf drop due to changes in gas composition resulting from the fuel utilization is translated to an equivalent resistance.
Values for these contributions for an anode-supported cell with a 1 mm thick support fed with hydrogen (3% steam) are given in Table I for 5% and 85% fuel utilization (FU). It is seen that the contributions from the concentration polarization, $R_{p,dif} + R_{p,con}$, are dominating. In a supported cell the limitation of gas diffusion through the support is a cell relevant resistance, whereas $R_{p,con}$ results from operation demands, and it is thus of interest to be able to correct for this effect.

**CORRECTION FOR FUEL UTILIZATION**

If a significant amount of fuel is consumed in the cell (stack) under test, a resistance derived on the basis of the Emf of the inlet gas (c.f. Eq. 1) will be an overestimation of the “true” cell resistance. The larger the fuel utilization the larger will be the overestimation. A comparison between cell test results obtained under different and non negligible fuel utilization must thus, to be meaningful, be based on a resistance measure, $ASR_{cor}$, where the effects of changes in gas composition over the cell area has been taken into account. How this should be done depends on how the gases are fed to the cell. Here, two idealized cases are considered, namely the cases where the fuel compartment may be considered a continuously stirred tank reactor (CSTR) or a plug flow reactor.

**CSTR**

If the fuel compartment can be considered CSTR-like due to effective mixing because of a turbulent gas stream and fast gas diffusion, $ASR_{cor}$ should be calculated from the expression

$$ASR_{cor} = \frac{Emf_{avg} - U}{i}$$  \[3\]

where $Emf_{avg}$ signifies the Emf of the outlet gas. An example of such conditions is reported elsewhere [14].

**Plug Flow**

The plug flow case is slightly more complex. Under the assumptions that the local area specific resistance is independent of position and that the flow pattern is co-flow, $ASR_{cor}$ may be calculated from the expression [15]:

$$ASR_{cor} = \left\{ \frac{i}{X'H_2 - X^°H_2} \int_{X^°H_2}^{X'H_2} \frac{dXH_2}{Emf(XH_2) - U} \right\}^{-1}$$  \[4\]

where
\[ \text{Emf}(X_{H_2}) = E^0 - \frac{RT}{2F} \ln \left( \frac{X_{H_2}^{i} + X_{H_2}^{o} - X_{H_2}^{o}}{X_{H_2} \sqrt{\frac{X_{O_2}^{o} - \frac{N_f}{2N_a} (X_{H_2}^{i} - X_{H_2}^{o})}{P_a / \text{atm}}}} \right) \]  

Here \( X \) is the molar fraction, \( P_a \) is the air pressure and superscripts \( i, o \) signify inlet and outlet, respectively. \( N_f \) and \( N_a \) are the molar flows of fuel and air.

The assumption of a position independent local area specific resistance is an approximation, which is not always justifiable. Part of the anode polarization resistance is dependent on fuel composition. However, often this part is small. If the cell is not isothermal the local resistance will vary with position due to its temperature dependence. Also the actual flow pattern may be much more complex than co-flow. However, even so, if fuel utilization is large, \( \text{ASR}_{\text{cor}} \) derived from Eqs. 4 and 5 will always be a better characteristic of the cell than a value derived neglecting the fuel utilization (Eq. 1). More precise evaluation of \( \text{ASR}_{\text{cor}} \) requires rigorous 3D modeling of the cell test.

For purpose of evaluation of Eq. 4 the integral may be approximated by a sum:

\[ \text{ASR}_{\text{cor}} = \left( \frac{1}{N} \sum_{j=0}^{N-1} \frac{1}{\text{Emf}(X_{H_2}(j)) - U} \right)^{-1} \]  

where \( \text{Emf}(X_{H_2}(j)) \) is given by Eq. 4 with

\[ X_{H_2}(j) = X_{H_2}^{i} + \frac{j + 1}{N} (X_{H_2}^{o} - X_{H_2}^{i}) \]  

Trivially, the more terms one includes in the sum the better is the approximation.

A “first order” correction for the effects of finite fuel and air utilization may be obtained taking only one term in the sum in which case \( \text{ASR}_{\text{cor}} \) should be evaluated from Eq. 3 with

\[ \text{Emf}_{\text{avg}} = E^0 - \frac{RT}{2F} \ln \left( \frac{\bar{P}_{H_2}^{i} + \bar{P}_{H_2}^{o}}{\bar{P}_{H_2} \sqrt{\bar{P}_{O_2} / \text{atm}}} \right), \]

where the bar indicates “average”, i.e.:

\[ \bar{P}_{H_2} = \frac{P_{H_2}^{i} + P_{H_2}^{o}}{2}, \quad \bar{P}_{H_2} = \frac{P_{H_2}^{i} + P_{H_2}^{o}}{2} \quad \text{and} \quad \bar{P}_{O_2} = \frac{P_{O_2}^{i} + P_{O_2}^{o}}{2} \]

If no significant leaks are present in the cell or the set-up then both fuel and air utilization, and from this the compositions, may be calculated from the flow rates and the current using Faraday’s law. Alternatively, the composition of outlet fuel and air may be

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obtained by gas analysis. Also the conversion resistance, $R_{p, con}$, may be calculated using the concept of $Emf_{avg}$:

$$R_{p, con} = \frac{Emf_{inlet} - Emf_{avg}}{l}$$

**CELL TESTING AT RISØ**

The cell testing at Risø has been focused on the directly cell-related resistances rather than commercial operation related aspects. This means that constant fuel and oxidant composition over the cell area have been attempted. Test of the effects of compositional gradients is not to be performed until the cell development has proceeded so far that the economical demands to cell performance and durability under the simpler test conditions are fulfilled.

**Cell Test Set-ups**

Two types of set-ups are used at Risø as shown in Figs. 1 and 2 and referred to as type 1 and type 2, respectively. The very flexible type for test of cell areas of about 6 to 10 cm$^2$ (Fig. 1) was derived from the previously described "quick and dirty" cell test equipment. It is flexible in the sense that both the cell housing and the current collection may be changed without any changes to the basic construction. Its drawback is that the sealing at the cell edges is not perfect. In the set-up shown in Fig. 2 a larger area of 16 cm$^2$ is tested in a set-up with realistic and effective glass sealings. The cell current collectors may also here be changed easily. In both set-ups two sets of potential probes are used in order to ascertain whether the in-plane conductivity of the current collector is sufficient, and if not so, to be able to correct for it. The testing in the two set-ups gives very similar results. An example of a typical i-V curve is shown in Fig. 3 for a Ni-cerment/YSZ/LSM cell.

![Figure 1. Sketch of the cell test set-up type 1.](image-url)
Figure 2. Sketch of the cell test set-up type 2.

Figure 3. Typical i-V curve for a Risø Ni-cermet/YSZ/LSM cell with an electrolyte thickness of ca 180μm.
Effect of Housing Material

The type 2 set-up was first constructed using Kanthal metal of the APM type (22% Cr, 5.8% Al, bal. Fe). However, this cell housing seems to destroy the cells within a few hours. Therefore, the housing material was changed to alumina. Fig. 4 shows a comparison between test results of nominally equal cells in case of the two different cell-housing materials. It is clear that the Kanthal housing causes a very rapid poisoning of the otherwise durable cell. The interpretation is that evaporation of CrO₃ from this alloy poisons the cathode even though it is an alumina forming alloy i.e. the surface oxide layer consists mainly of Al₂O₃.

![Graph showing comparison of specific resistance (ohm cm²) over time (hours) for Kanthal and Alumina cell housing materials.]

Figure 4. ASR as a function of time for nominally equal cells tested in two different cell housing materials, a Kanthal metal alloy and an alumina ceramic.

Cell Test with a Leak

Fig. 5 shows an i-V-curve, which at a first glance looks normal. Only the open circuit voltage (OCV) is much lower than the calculated Emf of the inlet hydrogen, and the curve is bending slightly downwards. The low OCV means that some leakage of air into the anode compartment takes place. If the OCV value is used in Eq. 1 instead of the Emf...
of the inlet gas, an ASR of 0.16Ωcm² at 1000°C is found. However, an ASR between 0.30 - 0.4Ωcm² has been well established for this type of cell at 1000°C. (Using the Emf instead of the OCV and the current density at the cell voltage of 0.75V an ASR of ca. 0.35Ωcm² is in fact obtained. However, this may be fortuitous).

Figure 5. i-V-curve for a Risø Ni-cermet/YSZ/LSM cell in a test with a significant leak.

The experimental results are interpreted as follows. A large localized leak of air into the anode compartment, probably along the rim of the cell, causes an increase in the temperature due to hydrogen combustion. This temperature increase is not registered because the thermocouple is positioned at the cell center. The increased temperature decreases the cell resistance locally. This, however, is not the full explanation. The current lead and the potential probes at the rim are gold wires, and as they did not melt the temperature has not been much above 1064°C for any appreciable fraction of the cell area. And as the apparent activation energy for this kind of cell is about 1.5eV the temperature increase cannot explain more than max half of the deviation of the apparent ASR from the true value. Now, the in-plane conductivity of the current collector is seen to be good as the cell voltages at the center and rim are similar, i.e. the current collectors are approximately equipotential planes. When the fuel composition due to the localized leak varies significantly over the cell area, this induces internal currents in the cell, i.e. the part of the cell in areas with high local Emf are loaded in the fuel cell mode whereas other parts with Emf below the OCV will be loaded in electrolyser mode. When the cell
is externally loaded the internal currents will decrease with decreasing cell voltage. Both the distribution of temperature and fuel composition will vary accordingly and thus also the local internal resistance varies.

Finally, as the leak was never proved to be a gas leak, an electronic leak through the electrolyte is in principle an alternative explanation. If the electronic conductivity in such a leak decreases with cell voltage (in analogy to the case of ceria based electrolytes (8)), a very flat curve may be obtained.

As it is often the case with "failed" experiments a clear reason is not easily established. Anyway, the first lesson of this experiment is that great care should always be taken when the OCV is far from the theoretical Emf. Only in case it is in some way verified that the leak is evenly distributed over the cell area, the OCV value may be used instead of the Emf of the inlet gas when deriving area specific resistances. The second lesson is that skepticism to reports giving non-reproducible, very low internal resistances is allowed, and that such results are not necessarily a proof that extremely high performance may be obtained in reality.

CONCLUDING REMARKS

It is recommended that cell test results be reported in a way that makes it easy to derive from the i-V-curves an area specific resistance (ASR). Sufficient information should be provided such that an ASR not including effects of finite fuel utilization can be derived. The choice of fuel composition should preferably reflect realistic conditions. The ASR should be derived using the Emf and a cell voltage in the range of 0.5 - 0.7V and its corresponding current density. In case of a grossly non-linear i-V-curve a differential ASR-value is of little practical use and may in fact give rise to confusion as it is not suitable for purpose of comparison.

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