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Evaluation of fuel cell system efficiency and degradation at development and during commercialization

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Abstract

Two primary parameters stand out for characterizing fuel cell system performance. The first and most important parameter is system efficiency. This parameter is relatively easy to define, and protocols for its assessment are already available. Another important parameter yet to be fully considered is system degradation. Degradation is important because customers desire to know how long their purchased fuel cell unit will last. The measure of degradation describes this performance factor by quantifying, for example, how the efficiency of the unit degrades over time. While both efficiency and degradation concepts are readily understood, the coupling between these two parameters must also be understood so that proper testing and evaluation of fuel cell systems is achieved. Tests not properly performed, and results not properly understood, may result in improper use of the evaluation data, producing improper R&D planning decisions and financial investments. This paper presents an analysis of system degradation, recommends an approach to its measurement, and shows how these two parameters are related and how one can be "traded-off" for the other.

Keywords: Degradation; Fuel cell; System; Standards

1. Introduction

The promotion and marketing of power generation technology in general depends highly on their demonstrated ability to convert fuel to electric energy, and to do so at low cost. Technology with high fuel efficiency has an advantage over competing technology, so long as its overall cost remains acceptable. Low overall cost implies low capital costs and/or long operating lifetime so that the overall amortized cost is low. Presently, fuel cell technology provides high efficiency fuel conversion, but it continues to have high capital costs and relatively short lifetimes as compared to competing technology (e.g., gas turbines). Because of their relatively short lifetimes, the issue of degradation is of greater concern for fuel cell technology, and is therefore the main subject of this paper.

1.1. Degradation

The issue of fuel cell performance degradation has long been appreciated. Various levels of examination have occurred over the years, including systems level studies, subcomponent level studies, experimental testing, and model prediction. Each technology (solid oxide, polymer electrolyte, molten-carbonate, alkaline, etc.) has already been assessed in some limited way, and each one has its own set of technical issues. For example, Mazumder et al. [1] provide a method of systems level modeling for the effects of power conditioning and load on solid oxide fuel cell (SOFC) performance. The work identified that certain power conditioner types may be detrimental to SOFC operation. Other modeling work has been done at the cell level to examine effects of sintering of nickel during SOFC operation (Ioselevich et al. [2]). For polymer electrolyte membrane fuel cell (PEFC) technology, Kulikovsky et al. [3] propose that cell degradation occurs as a wave over the cell which effectively removes active area over time. They provide a phenomenological model for these effects, and then predict cell degradation performance. Fowler et al. [4] provide a generalized model that treats three proposed degradation methods in PEFC technology; namely, electrolyte humidification, catalytic activation loss, and mass transfer losses.

Experimental work on the degradation of ceramic and polymer electrolyte systems has also been performed by Haeringa et al. [5] and Meyer et al. [6], respectively. Haeringa et al. [5]

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suggest that a transformation of defects occurs in 8% YSZ which causes the decrease in conductivity over time. Meyer et al. [6] identified a thermoactivated chemical degradation mechanism for sulfonated polyimide membranes.

Numerous experimental investigations of electrode degradation for a variety of technologies have also been performed. Schulze and Christenn [7] showed how the hydrophobicity of PEFC electrodes evolves with time as the hydrophobic agent, polytetrafluoro-ethylene, degrades. As the hydrophobicity changes in time, an initial increase in performance is seen, but then decrease in performance as operation continues. Chen et al. [8] showed how direct methanol fuel cells degrade as the particle size of the electrocatalysts increase with time. Schulze and Gülzow [9] showed the degradation of alkaline fuel cells due to disintegration of nickel anodes. Taniguchi et al. [10] showed how SOFC electrode–electrolyte interfaces can be deactivated due to chromium evolved from metal interconnects. Other work has also suggested that conductive pastes in SOFC technology (Chervin et al. [11]) and specific operational conditions in PEM technology (Taniguchi et al. [12]) may also cause degraded fuel cell performance.

The fuel source can also affect cell lifetime. Sulfur compounds are contained in most commercial fuels. Matsuzaki and Yasuda [13] show that nickel anodes for SOFC's can be poisoned by such sulfur-gas to different amounts depending on time, temperature and impurity concentration. However, Aguilar et al. [14] show that degradation of SOFC's operated on sulfur containing fuels can be potentially improved with advances in new anode material.

Structural degradation can also impact cell performance. Weil et al. [15] show how sealing can degrade (delaminate along the electrolyte) on SOFC systems which can then cause a loss in voltage potential as reactant gases mix and burn rather than react electrochemically.

As highlighted above, most of the degradation work to date has been at the cell level, and very little has been done at the system level which will be the subject of this paper. Because of the rapid advances still being made in fuel cell technology, any of the aforementioned mechanisms may be successfully removed in the coming years. Even so, it is likely that degradation will still be important to customers, both present and future.

1.2. Present and future fuel cell customers

Fuel cells continue to be the subject of extensive research and development. To provide the resources for R&D work, both public and private funds are being employed. Currently, the U.S. Department of Energy's Solid State Energy Convergence Alliance program (SECA) is funding the development of solid oxide fuel cell technology for both stationary power and auxiliary power applications (Williams et al. [16]). The program is divided into three phases, and following each phase, testing is performed to ensure that progress is being made toward the goal of a viable commercial unit having power in the range of 3–10 kW and a cost less than \$400 kW^{-1}. Much of the present work is in the development of subcomponents and their optimal integration into complete systems, e.g., interconnects, cathode interlayers, reformer catalysts, etc. The main performance goal of the program is to have at least 40% LHV efficient systems that can operate on natural gas, gasoline, and diesel. Other fuel cell technologies are also being sponsored by the U.S. Department of Energy, such as PEM fuel cell technologies which are being considered for automotive applications under the Hydrogen Program [17]. Many states within the U.S. also have programs for supporting advanced fuel cell power generation technology, and many also perform demonstrations, evaluations and assessments of fuel cell technology. In addition to federal and state government sponsorships, many private and semi-private companies also sponsor demonstrations of fuel cell technology so that they can get a firsthand look at the progress being made by fuel cell developers. To obtain a measure of the progress being made by developers, sponsors (which are today's fuel cell customers) look closely at two critical system performance parameters, fuel cell efficiency and lifetime. Looking forward from these development and demonstration efforts, commercially viable units will be offered to the public for their use and benefit, and they too will be looking closely at the efficiency and lifetime capability of these new systems.

1.3. Electrical efficiency

There are many definitions of system efficiency, but one that defines a precise thermodynamic performance of a fuel cell system is given by the ASME PTC-50 fuel cell performance test code. In particular, we have for the electrical efficiency:

$$\eta_{\text{el}} = \frac{E_{\text{n}}}{Q_{\text{total}}} \quad (1)$$

where E_{n} is the *net* electrical energy developed by the fuel cell over the duration of the test (defined in detail below) and Q_{total} is the total energy into the system which is comprised of: (1) the chemical + pressure + thermal energy of the fuel input, (2) thermal input energy of any co-generation fluid, (3) pressure and thermal energy content of the input air, and (4) any shaft work input to the system. The efficiency shown in (1) is often based on the lower heating value of the fuel. The PTC-50 code explains very clearly how the parameters of (1) are defined and measured. The method to calculate the measured uncertainty in the efficiency is also prescribed. While there may be particular features of a fuel cell system that prevent following the PTC-50 code precisely, prescribing the use of PTC-50 for a performance test is an excellent way for sponsors to ensure proper measurement and reporting of efficiency performance.

1.4. Lifetime

Explicit in the goals of the SECA program is to have systems that can survive over long periods of operation. Forty thousand hours is a commonly cited value for the lifetime of a fuel cell system, and this value is considered "minimum" for commercially viable stationary power units. A performance parameter describing the "lifetime" of a fuel cell system, however, will not be helpful as a standard, since it provides less information about the capability of the system, and also depends on each user's definition of lifetime—each user might accept a different definition of lifetime. Such a parameter provides less information about the capability of the system, because it only shows the system's overall capability, rather than information that depends on operation. (The analogy to efficiency performance assessment would be if industry used some "overall energy usage" parameter, rather than the definition of efficiency given above which depends on the instantaneous operating condition, i.e., efficiency can be determined as a function of load.) Instead, a parameter that provides the rate of decay (degradation), and that would be operation dependant, would provide the most useful definition and would provide information about the system that is consistent with the present definition of efficiency. For example, performance curves of degradation versus load can be developed similar to that developed for efficiency. Thus far, however, no industry standard exists for quantifying fuel cell degradation, neither for complete systems nor individual subcomponents. Interestingly, other technology such as gas turbines and IC engines also do not have test standards for assessing degradation. This can be attributed to the fact that these technologies are much more mature, and as a result degradation is less of a concern for them.

Because the issue of lifetime will remain an important technical issue in the coming years (informed buyers will undoubtedly be looking for such a performance specification in product literature), it is important that the fuel cell community prepare to define this performance parameter, just as it already has for efficiency. Part of the goal of this paper is to initiate discussion on this topic, in hope that those interested in this issue can join to pursue the development further.

1.5. Load profiles—standards to be developed

As is true of many power generation technologies, fuel cell system efficiency is not constant with applied load (see Fig. 6). With all inputs and boundary conditions held fixed, the fuel cell stack itself normally has better efficiency at lower load. Depending on the design of the rest of the system components, the overall efficiency may have an increasing or decreasing slope over a significant portion of its operating range. At the higher load conditions, this dependency results from the fact that the performance of the various subsystems within the fuel cell system depends on their operating condition (e.g., current draw through an inverter, mass flow rate supplied by the air compressor, operating temperature, all of which depend on electric load applied to the system). At low net power output conditions, the efficiency can quickly fall due to a fixed minimum internal power need of the fuel cell system to sustain itself in a near idle mode.

Because of the variation in efficiency with load and because end-users often have widely variable load conditions (especially for the 3–10 kW application range), for those users that have a near common load cycle (e.g., home load cycles), it is helpful to have a net cycle efficiency determined for a given representative application. Hence, in the future, the fuel cell market may be benefited from the development of specific standard load profiles (e.g., for a "standard home," "standard small business," etc.). Such standards have been developed, for example, to assess the energy consumption of automobiles via various defined "driving cycles."

1.6. Technical objective

The first objective to be achieved from the present work is an improved understanding of the technical factors that influence the measurement of systems level efficiency and degradation, and to layout how these two parameters are physically coupled. The second objective to be achieved is a broader community discussion of degradation, which will allow the development of test standards and protocols for systems level degradation measurement, data analysis and interpretation.

1.7. Paper overview

This paper presents an analysis for fuel cell degradation, and offers one method for defining degradation. Section 2 of the paper reviews the requirements for measuring efficiency as specified in ASME PTC-50. The goal here is to establish the requirements of a viable systems level parameter that can be used to assess degradation. Section 3 presents an analysis of fuel cell systems and especially their subcomponents which will be important to the discussion of degradation given in Section 4. The discussion in these latter two sections is primarily at the systems level, with little detailed quantification of subsystem performance in order to keep the discussion unencumbered by too many details. Finally, Section 5 provides a summary of the findings, and recommendations toward the further development of degradation standards.

2. Requirements for efficiency measurement

A performance standard provides a clear and accurate evaluation of a performance parameter. For example, in the evaluation of system efficiency following ASME PTC-50 (re: Eq. (1)), one determines the net energy output and then divides by the net energy input. While this definition is clear and is in fact common to engineering analysis, in the practical assessment of this parameter numerous conditional statements must be applied. The various conditions are described in detail in the ASME PTC-50 code, which goes to great length to clearly define the various parameters and how they are measured, including the accuracy of instrumentation. Some other key requirements are:

- The evaluation of efficiency is performed over a predetermined period of time, t, during which enough data is taken so that accurate assessment of the efficiency can be determined to within a prescribed uncertainty.
- During time t, the system is held at some steady state load condition to within a given variability. This allows a definite efficiency value to be calculated at the given load.
- During time t, it is also expected that ambient conditions are constant to within a given variability. This also allows a definite efficiency value to be calculated at the given ambient conditions, and which can be corrected to predetermined

ambient reference conditions provided enough system characterization data is provided by the fuel cell manufacturer.
- During time *t*, it is also expected that the fuel composition is held constant to within a given variability so that the input fuel energy can be reliably evaluated.

To ensure that the aforementioned conditions are achieved for a given performance test, numerous data points are taken over time *t* for each of the above parameters. If any data point during time *t* exceeds the predetermined level of variability, then the test must be redone. (Our testing of SOFC systems at NETL has already shown, however, that this requirement can be somewhat problematic, since some fuel cell systems have a variety of process control features and process time scales that span several orders of magnitude (thermal, flow, etc.). Both control features and inherent process timescales can prevent an acceptable steady state operating point from being achieved. Careful test planning is required to help mitigate these potential problems.)

Since much effort has been already spent to develop this existing performance standard for the measurement of efficiency, it is reasonable to propose to use this same parameter as the basis for system degradation evaluation. Using this existing standard allows us to make use of data measured according to a well-defined existing protocol. Just as for efficiency measurement, a key issue to be considered in the evaluation of degradation is that we need to know that the system is being operated at well-defined conditions, and that there are no variations in the variables that effect the degradation performance measurement. This will be particularly challenging, however, since most degradation tests will be taken over many hours (e.g., >1000 h), and often environmental parameters can change significantly over even shorter periods of time.

While it is certainly convenient to use an existing standard as the basis for degradation measurement, as discussed in the following sections there are methods of system control that influence the efficiency and degradation of a system. To properly account for these effects, the customer needs to understand some details on how the system operates. This aspect of degradation testing and evaluation will be considered in more detail in Section 4 where system internal control parameters will be reviewed in light of their ability to impact degradation measurements.

3. Fuel cell subcomponent and system analysis

Fig. 1 presents the major system subcomponents arranged in a fashion representative of a typical solid oxide fuel cell system. For a detailed reference on such systems, the reader is referred to the text by Singhal and Kendall [18]. Other specific arrangements and specific technologies than shown in Fig. 1 can be employed for a given subsystem, but those details are not important for the objectives of the present paper. For example, the reformer box can be a steam reformer, POX reformer, autothermal reformer, etc., and can have the operational features of any of these within the reformer subsystem. Likewise, the exact arrangement of the subcomponents can vary to achieve different thermal management requirements. The analysis presented below, however, is general and can be extended to such other arrangements in a similar way.

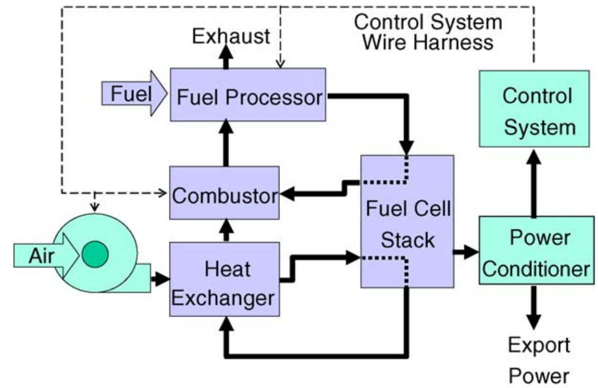

Fig. 1. Solid oxide fuel cell system components.

3.1. Subcomponent analysis

Each of the major subcomponents present in a fuel cell system are now described in detail, and their features that relate to energy production and parasitic energy consumption are highlighted for the subsequent analysis of system degradation provided later in this section.

3.1.1. Air compressor

The air compressor (or blower) takes in ambient air and delivers the necessary flow of air to support the operation of the fuel cell. Air is needed for the fuel cell cathode, of course, but possibly also for fuel reforming (so called partial oxidation reformers), as well as for various subcomponent cooling requirements. For small fuel cell systems considered here, these compressors are powered by an electric motor. The power for the electric motor, P_{AC}, is made available from the power converter through the system controller. Because a relatively large volume of air is needed to support the operation of the fuel cell, this element is one of the largest energy consuming loads on the system. Fig. 2 shows an example for the relation between the amount of air flow supplied to the system (in terms of excess oxygen over that needed for the electrochemical reactions) and the net power achieved by a system. As can be expected, if too much air is supplied to the system, then pumping energy requirements increase faster than that deliverable from the fuel cell.

Compressors can degrade in performance over time as rotating components, especially bearings, wear down and surfaces become contaminated with air-borne dirt, dust and oils, and motor windings overheat and fail. The amount of air managed by a 10 kW fuel cell over a 5 years period, for example, is as much as eight million cubic feet. Standard dust loadings in air are as much as 0.06 ppm (w/w) (Loud and Slaterpryce [19]). Given an average dust size of 30 μm, this amount of dust could coat potentially as much as 5000 cm^2 of surface. While not all dust will deposit on internal surfaces, undoubtedly some will deposit on the blower part surfaces or other internal flow passages to degrade the overall performance of the system. In short, the power needed by the compressor may increase because of

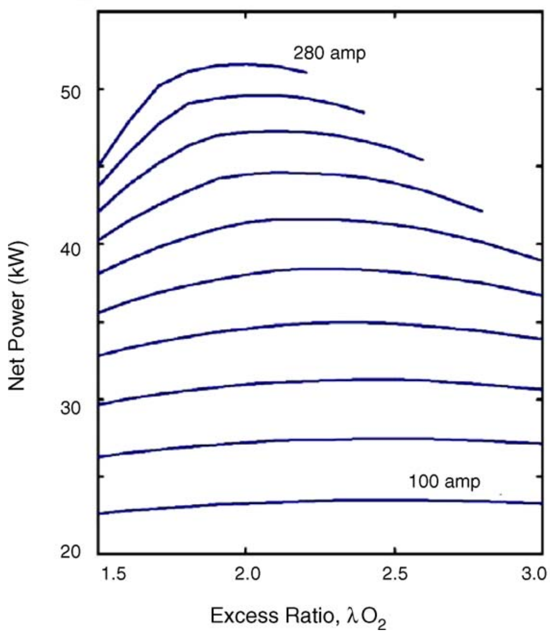

Fig. 2. Fuel cell system net power vs. applied current load to stack and excess air (ref. Pukrushpa et al. [26]).

degradation of the compressor itself, or due to increases in pressure drop through the system which forces the compressor to work harder for the same flow rate. Voltage losses may also increase for cells coated with such material.

3.1.2. Fuel processor

The fuel processor removes contaminates from the hydrocarbon fuel stream and then reforms, or partially reforms, the fuel. It also thermally conditions the fuel prior to entering the inlet to the fuel cell anode. Heat for the reforming and thermal conditioning is taken from the exhaust gas stream following the combustor through suitable heat exchanger hardware. Again, other methods of reforming, including the use of anode gas recycle, can also be considered, but that is not important for the present analysis. As part of this system subcomponent, flow control valves and safety shutoff valves are used and managed by the system controller so as to deliver the proper amount of fuel to the fuel cell for conversion. Because of contaminates in the fuel, season-to-season variability in C_4^+ hydrocarbon and high temperature operation, both the cleanup section and the catalysts used in the reformer (as employed) degrade in performance over time. As some of the references in Section 1 show, degradation can be caused by carbon and particulate build up, sulfur attack on the reforming catalysts, corrosion/erosion of surfaces which fowl the heat exchange surfaces, and thermal induced migration of material leading to deactivation. The degradation results in changes in the composition and temperature of the fuel reactants leading into the anode, which results in a change in fuel cell performance.

3.1.3. High temperature heat exchanger and electric heaters

The heat exchanger shown in Fig. 1 is needed to thermally condition the cathode air stream. The function of the heat exchanger normally does not require active control support; hence, little or no parasitic energy consumption occurs for this subcomponent. Its performance can degrade, however, through corrosion/erosion of surfaces which reduces the effectiveness of the heat exchanger. Some fuel cell systems require electric heaters to help support the thermal requirements of the system, and to add improved process control. The energy needed for these electric heaters, P_{EH}, comes from the fuel cell control system, and can be costly to the overall energy budget of a fuel cell system. Hence, these heaters are only used when necessary. If needed and if properly sized, these heater elements can operate over many thousands of hours with minimal performance degradation.

3.1.4. Fuel cell stack

The fuel cell stack converts the fuel energy to electrical DC energy, P_{FC}, as it attempts to meet the instantaneous load demanded by the power conditioner. The efficiency of fuel conversion depends on the internal losses (effective resistance) within the cells and stack components. As the references in Section 1 show, the internal electrochemically active regions degrade due to gradual attack by contaminates such as sulfur, chromium, and other metals depending on the source of fuel used and metal components present in the system. Also, migration of material in the anode and cathode when operated over a long time at high temperatures can also degrade the fuel cell. Temperature gradients in the cell induce stresses that can cause micro-cracks to develop which can cause degradation in fuel cell performance, and that may ultimately lead to catastrophic failure. Temperature gradients can also affect interfaces between the various PEN multi-layers and seals causing them to delaminate, and again cause performance degradation. Because of the desire to reduce the thickness of the electrolyte, and the limitations of manufacturing tolerances and quality control, pin holes within the electrolyte created during manufacturing cause reactant cross-over and combustion which results in local hot spots that can worsen over time, first causing degraded fuel cell performance until complete cell failure results. The controller is required to monitor the conditions of the stack to ensure proper continuous conversion of fuel within the stack. If cell and/or stack voltages go out of specification, then mitigating control action may be necessary, such as increased fuel and/or air flow, as well as complete shutdown if significant failure has occurred.

3.1.5. Cell

Electrochemical performance on the cell level can change both in a positive and negative fashion, depending on the conditions of operation during or just prior to the performance evaluation period. When a cell goes through the initial start-up period, its voltage potential is typically held at open circuit voltage (OCV) for some prescribed time under an experimentally determined start-up regiment. When current is then allowed to pass through the cell, there is an initial performance level that is achieved followed by a period of cell performance improvement. Fig. 3 shows a typical voltage and current profile as function of time of an SOFC cell during the initial cell start-up and operation. The period of time where no current is being passed through

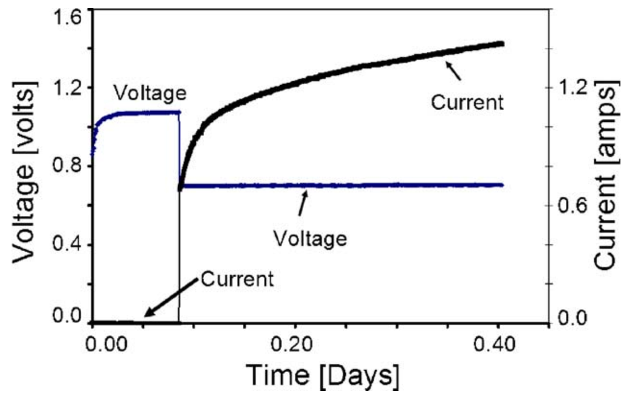

Fig. 3. Voltage and current vs. time during initial cell start-up and operation.

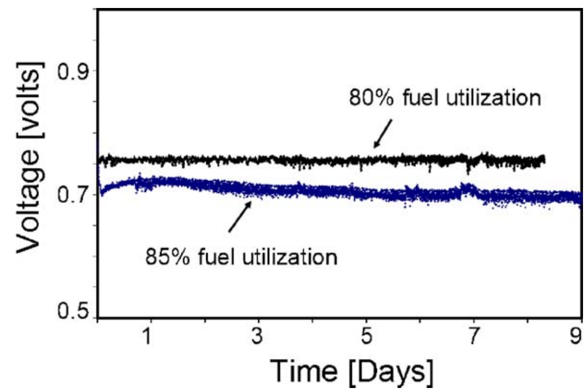

Fig. 4. Voltage vs. time for cells run at a fuel utilizations of 80 and 85%.

the cell represents the time during which the Ni in the anode (in this case a Ni/YSZ cermet) is being reduced from NiO to Ni. Once the anode is completely reduced and a steady open circuit voltage is obtained the voltage is set to a typical operating voltage via the external load (potentiostatic mode). Note that the current at a set voltage continues to increase over a considerable amount of time. It may take several days for the performance level at a given voltage to come to a steady state depending on the materials and geometry of the particular cell tested. This performance enhancement, however, is often removed when operated at other conditions. For example, when the cell voltage is set back to OCV or even just a higher voltage, some of the benefits of the initial "current treatment" are lost. However, recovery is more rapid than the initial start-up treatment, and the rate depends on how long the cell was held at the higher voltage before being brought back to the original voltage setting. Conversely, further temporary increase in performance can be obtained by setting the voltage lower than the initial "current treatment" level, and again time at that setting affects the level of enhancement. Thus, the performance of a cell is related to the current density and time at that current density just prior to its new set level. Therefore, from the standpoint of the cell, it will be important in evaluating system performance to do so based on a standard cell history.

A number of cell level degradation mechanisms can occur because of operating at certain load conditions or because of exposures to certain components in the SOFC environments. Contamination of cells from seals (planar cells), interconnect materials, gas contaminants and so forth, can lead to a number of degradation routes. Many of these are not reversible or only partially reversible. Over utilization of fuel can lead to cell performance decreases that are due to oxidation of the anode material at the electrolyte/anode interface. Fig. 4 shows an example of this process for a cell having a Ni/YSZ anode and YSZ electrolyte. Note that at 80% fuel utilization (97% H_2, 3% H_2O), the performance of the cell reaches a steady state with very small or no degradation, while at 85% utilization, this particular cell degrades relatively quickly. Ultimately, if this process continues, it can lead to delamination of the anode/electrolyte interface.

3.1.6. Combustor

The combustor shown in Fig. 1 is used to both preheat the fuel cell system during start-up and to complete the oxidation of fuel that remains after passing through the stack. To achieve compact (cost effective) designs, good fuel and air mixing is needed which requires sufficient pressure drop for the fuel and air flows. This is made possible by suitably sized injection holes in the fuel supply nozzle, and a blower (compressor) that provides the necessary pressurized air. Additional fuel shutoff valves and a fuel igniter are used and controlled by the system controller. Additional valving may be needed in order to manage the air and fuel mixing over a wide range of operating conditions for the system. During normal steady operation of the fuel cell, the combustor is hot enough so that the exhaust gas from the anode readily burns when mixed with air from the cathode (Gemmen [20]), and it is unnecessary to have such features as swirl stabilization or recirculation zones common to combustor technology which would otherwise cause added pressure drop. However, to broaden the operating range of the combustor (cold start, idle conditions, load upset conditions) such features may be designed into the system, as well as adding catalyst to ensure complete oxidation under all conditions, which has been in development for gas turbine applications (Etemad [21]). While simple, the combustor also can degrade in performance via dust and particulate contaminate build up in the small diameter fuel injector holes, thermal erosion of surfaces, and if used, catalyst degradation (Scheihing and Laurelli [22]).

3.1.7. Power conditioning

The power conditioner shown in Fig. 1 is a DC/AC system that converts the fuel cell electric output to standard AC power output (e.g., 120 V AC at 60 Hz). Efficiencies for these units, which can exceed 90% over a wide range of load, tend to decrease as load increases; see Fig. 5, for an example, power conditioner efficiency.

Provided that the system is properly designed to keep the power electronics components cooled, these systems can have a long stable life at good efficiency. If overly high power densities are used in the design of these systems (which may be attempted to keep costs down), then they can overheat, which causes performance degradation and possibly premature failure. For the present discussion, we will simply assume that a proper design was achieved, and hence, the efficiency of the power conditioner is constant over time. With the assumption of a fixed efficiency,

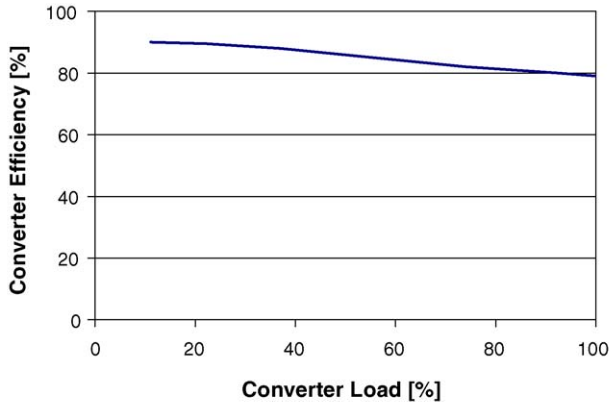

Fig. 5. Example power conditioner efficiency vs. load. (ref. Kimball and Chapman [25]).

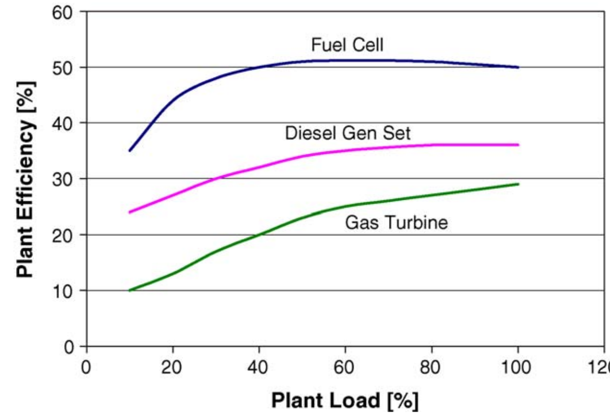

Fig. 6. Variation of system efficiency with load for a representative fuel cell, diesel and gas turbine power generators.

the loss from the power conditioner can be simply lumped into the fuel cell power parameter, P_{FC}, so as to provide a net (fuel cell + power conditioner) power generation value.

3.1.8. Controls

The control system shown in Fig. 1 manages all subsystem operation by turning them on and off, and controlling the amount of power delivered to them for their operation (e.g., compressor energy, fail-safe valves, etc.). The energy needed to operate the controller and the various sensors and valves, P_C, is small relative to that needed for the air blower and heaters, but is still a significant portion of the parasitic power requirements. Various temperature sensors and flow meters may be used to provide the controller with status information that the controller can use to determine if the processor is operating properly.

With the aforementioned description for subsystem component operation and performance behavior, the following subsection provides an accounting at the systems level for both efficiency and degradation.

3.2. System efficiency performance equation

The subcomponents described in the prior section work together, via the operation of the controller, to provide the required power to an external load. Certain of the subcomponents operate via power extracted from the fuel cell system, and therefore, contribute to the overall parasitic load of the system. From the above defined parameters, the net power output to the external load is:

$$P_n = P_{FC} - P_P \tag{2}$$

where P_{FC} is the power produced by the fuel cell and P_P is the parasitic power:

$$P_P = P_{AC} + P_{EH} + P_C \tag{3}$$

P_n is a very important performance parameter for end-users who expect their power system to provide power continuously to meet their applied electrical loads. However, the power output of all power systems, regardless of technology, decays over time, and when it becomes too great, the system must be refurbished, or a new system purchased. Either solution can be expensive.

For future reference, we can expand (1) (in its rate form) using the above equations, and have:

$$\eta_{el} = \frac{(P_{FC} - (P_{AC} + P_{EH} + P_C))}{QR_{total}} \tag{4}$$

where QR_{total} is the rate of energy input to the system. Because, as discussed in the prior section, the performance of each of the power generation and loss terms in (4) have a load dependency, the net system efficiency varies with the amount of load. Fig. 6 shows the system efficiencies for a representative fuel cell system and two representative competing technologies (Abens et al. [23] and Lipman et al. [24]). Hence, ASME PTC-50 prescribes that load conditions applied to the fuel cell system under evaluation be held constant (i.e., to within a specified variation such as 2%) to ensure accurate assessment of system efficiency at specific conditions.

From (2) and (3), the power output decays as a result of a reduction in fuel cell power over time and/or because one or more of the parasitic power loads increases. Because the power output degrades over time, so will the system efficiency assuming constant energy input to the system (Q_{total}). This latter assumption is accepted for the present discussion, and it is in fact a requirement of the PTC-50 standard.

3.3. System degradation performance equation

Like efficiency, the degradation of a *system* can be defined in several ways. For example, the efficiency (1) of a fuel cell system could be monitored over time at a given load condition, and the rate at which the efficiency decays:

$$D = -\frac{d\eta_{el}}{dt} \tag{5}$$

could be used to quantify degradation so that a decrease in efficiency results in a positive value for the degradation parameter. (As with the evaluation of efficiency, it must be assumed that all other external operating parameters are held constant during the performance evaluation period, such as system load, ambient pressure, ambient temperature, fuel composition, etc.)

Applying the derivative to the definition of efficiency to expand the equation, we have:

$$D = -\frac{\frac{dP_{FC}}{dt} - \frac{dP_P}{dt}}{QR_{total}} + \frac{-(P_{FC} - P_P)}{(QR_{total})^2}\frac{dQR_{total}}{dt} \quad (6)$$

However, since external operating parameters should be fixed, the second term on the right of (6) is zero. Using the definition for the parasitic power, we can write (6) as:

$$D = -\frac{\frac{dP_{FC}}{dt} - \frac{dP_{AC}}{dt} - \frac{dP_{EH}}{dt} - \frac{dP_C}{dt}}{QR_{total}} \quad (7)$$

This straightforward analysis simply shows that degradation will depend, primarily, on the rate of decrease in fuel cell power, and any increase in air compressor, electric heating, and control system power consumption.

Efficiency is a function of load, as shown in the above section. Likewise, because degradation behavior of many of the subcomponents presented in prior subsections is load dependent, the system degradation can also be expected to be load dependent. Presently, however, there is very little data to demonstrate this aspect of degradation, but as more systems are evaluated in future years, such information will become available for quantitative discussion and analysis.

4. Discussion

The following discussion is meant to be general in so far as the principles being proposed for the measurement and evaluation of degradation. Several specific examples are given only as a reference for discussion. As mentioned previously, the occurrence of degradation will likely remain a serious consideration of fuel cell technology for years to come, even through commercialization. As a result, proper methods to determine the degradation performance of fuel cell systems will be of interest to both the development and end-use communities. It is proposed here that efficiency be used as the performance parameter for system degradation, and this can be done using the existing PTC-50 standard. Application of PTC-50 requires stable operation of the unit under test so that an accurate assessment of efficiency can be determined for specific conditions. Stabilization of both "external variables" (e.g., load) and "internal variables" (e.g., stack temperatures) is required. Strictly speaking, however, the occurrence of degradation prevents such stable operation. If the degradation is not too great over the test period, however, sufficiently accurate efficiency vs. time information will still be available for the purpose of degradation assessment. This can be achieved, for example, by limiting the duration of testing for each efficiency data point so that the amount of degradation is negligible. Hence, for a given fixed external load, efficiency η_1 at time t_1 can be measured at the start of a degradation test, and then again at the end of the test for η_2 at time t_2. Eq. (5) then can be written as:

$$D = -\frac{\eta_2 - \eta_1}{t_2 - t_1} \quad (8)$$

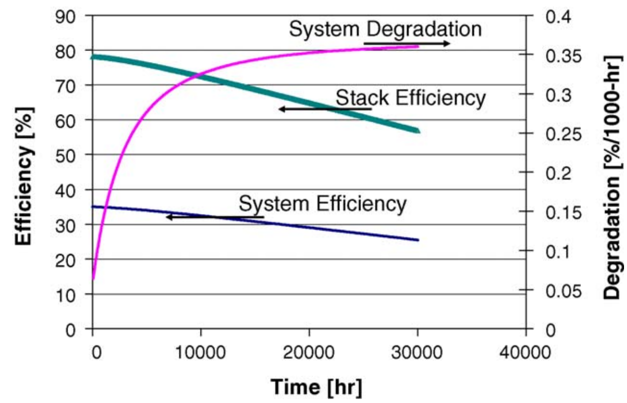

Fig. 7. Base Case results. Example fuel cell system efficiency and associated degradation vs. time for fixed load and assumed stack efficiency.

Provided that the requirements set forth here are met, a meaningful measurement of degradation will be achieved.

4.1. Example system degradation performance results—peak efficiency case

Some other issues to consider with this approach to degradation measurement are now discussed. First, it must be understood that in the design of a system, efficiency and degradation are coupled parameters. To within certain limits, the fuel cell system can be designed to emphasize efficiency or to emphasize long lifetime (low degradation). If one is interested in peak efficiency capability only, and does not care how a fuel cell system degrades, then you would likely specify relatively high fuel utilization. With this approach, the efficiency at the start of testing is at its greatest for a given load, and gradually decreases over time for reasons discussed in the prior section on cell degradation. This system behavior, to be referred to as the "Base Case," is shown in Fig. 7 where an assumed fuel cell *stack* (a.k.a. cell) efficiency degradation rate was used. All other parameters in (7) were held fixed. Such results might be expected, for example, for a stack operating at low current density but high fuel utilization. As shown in Fig. 7, because of the degradation in system components described in the previous section, the system efficiency gradually decreases overtime. Also shown in Fig. 7 is the associated *system* degradation rate determined by the use of (5) which corresponds to the assumed *stack* efficiency curve shown for this analysis. Even though the unit exhibits fine initial efficiency, it unfortunately shows a very poor degradation rate.

4.2. Example improved apparent degradation case

To avoid such strong degradation rates, the fuel cell system can be designed to operate at a lower initial efficiency through, for example, increasing the air flow rate (say to support additional subcomponent cooling) or increasing the fuel flow rate (going to reduced fuel utilization). By providing an initial increase in air or fuel flow rate at the start of operations, certain subcomponent degradation rates may be reduced (e.g., more fuel will mean less chance of anode oxidation problems that may result because of seal leaks that gradually develop, and

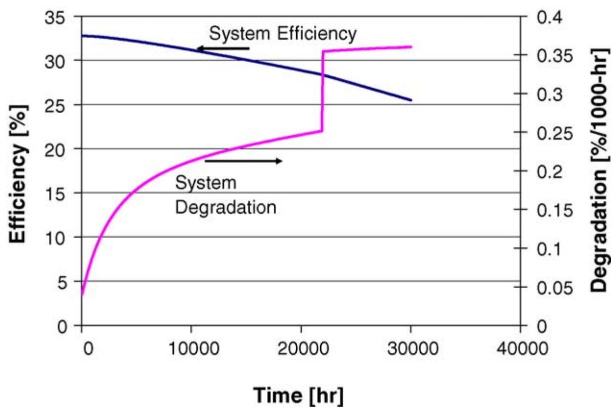

Fig. 8. Case 2 results. Same fuel cell system as in Fig. 7, but the apparent degradation is reduced by sacrificing system efficiency performance via method of air flow management. At about 22,000 h, air flow as been reduced to same value as in Fig. 7, after which the system exhibits Base Case performance results.

more air flow may mean reduced thermal degradation of some of the subcomponents). Despite the lower initial efficiency, the primary objective of reducing the apparent system degradation has been achieved. Subsequently, the air and/or fuel flow rates can gradually be reduced back to the original Base Case rates, thereby lowering the parasitic power load and energy input, respectively, to the system, which results in a nearly constant measured (apparent) efficiency. The result, at the system level and as measured following ASME PTC-50, will be a reduced initial efficiency as compared to the Base Case, along with a nicely reduced measured degradation rate which was the primary objective. These types of results are shown as Case 2 in Fig. 8. Here, the same fuel cell stack is assumed as used in the Base Case (including its stack degradation rate), but an additional load was applied early to the air compressor to provide additional air to the system (which could be used for either cathode or BOP cooling management for example), and then gradually lowered over the duration of the test until it reaches the same value used in the Base Case at 22,000 h. As can be seen, because of the additional loading on the air compressor, there is an increased initial parasitic load, and therefore, a reduced efficiency compared to the Base Case. After 22,000 h, there is no other process parameter that is counter balancing the fuel cell stack degradation, and as a result, the Base Case behavior is reestablished.

4.3. Customer awareness

As is clear from the above discussion, short-term performance measurement may not accurately indicate long-term performance measurement for reasons that significantly depend on the method of BOP energy management. The ASME PTC-50 standard does not setout any requirements for the methods of internal control of the fuel cell system during testing. This is understandable, since it is expected that the fuel cell system manufacturer will provide the proper control requirements of the unit to meet the technical requirements whether for development or for commercialization. However, the customer that receives performance test results for a given system must understand how the unit was operated during testing in order to fully appreciate their meaning, and to properly apply the results to any subsequent decisions. As the examples presented here show, to exhibit low system level degradation, an initially high air flow rate could be employed. Then, as the system subcomponents all degrade, lower air flow can gradually be used. The result is a lower apparent system degradation than what would be exhibited if the air utilization was held fixed, especially at early operation.

4.4. Degradation assessment options

There are potentially other methods of degradation measurement. For example, one could measure the degradation rates of all the individual subsystem components so that their coupling and interaction effects will not be hidden as analyzed at the system level. Such an approach would remove some of the above concerns that would need to be considered for a systems level evaluation of degradation, but would require greater effort. For example, the fuel cell stack power output versus load could be directly measured if its voltage and current were accessible. Doing so may require modifications to the internal system wiring which is inconvenient and an approach that may not always be agreed to by the manufacturer. It also adds complexity to performance evaluation, since each subcomponent would need to be separately evaluated.

Until a formal standard is developed, it is recommended here that personnel performing test and evaluation services simply employ present efficiency standards, ASME PTC-50. As shown in this paper, however, discussions with the developer/manufacturer of the fuel cell system will be important, as they can lead to detailed understanding for how the internal system BOP is managed, and how that management may affect the measurement of performance degradation. So long as the manufacturer and customer understand how the tests were performed, and what the results indicate, proper use of the results can be expected.

5. Summary and conclusion

Degradation remains a particularly important issue for fuel cell technology. This paper provides an initial review of the issues surrounding system degradation, and proposes a method of evaluating this parameter based on a previously developed industry standard for efficiency evaluation. More discussion on this topic is still necessary to develop a better defined test procedure that addresses the needs of the customer who must accurately understand the degradation and efficiency of a fuel cell system for their intended application. As the paper shows, in the operation and testing of fuel cell systems one can promote efficiency over degradation performance, or vice versa. A lengthy test of a fuel cell system (e.g., >5000 h) will demonstrate some measure of balance between the two performance concerns. However, in shortened testing, such as can occur in acceptance testing, one of the two performance parameters can be improved upon at the expense of the other. Hence, caution and proper awareness is needed by the customer to ensure a meaningful test and measurement of both parameters, and a meaningful usage of the resultant data. We recommend that customers carefully review and discuss with the developer how their system is operated and how performance measurements are obtained. It is the customer's responsibility to understand how their system is being tested if meaningful results are to be obtained and utilized. Since there is an increasing number of prototype and commercial beta units being tested every year, and customers will be looking closely at the issue of fuel cell degradation, full discussion of the approach described here would be beneficial to ensure best engineering practices are used.

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