

Review

Failure Modes, Mechanisms, Effects, and Criticality Analysis of Ceramic Anodes of Solid Oxide Fuel Cells

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Abstract: Solid oxide fuel cells (SOFCs) are a highly efficient chemical to electrical energy conversion devices that have potential in a global energy strategy. The wide adoption of SOFCs is currently limited by cost and concerns about cell durability. Improved understanding of their degradation modes and mechanisms combined with reduction–oxidation stable anodes via all-ceramic-anode cell technology are expected to lead to durability improvements, while economies of scale for production will mitigate cost of commercialization. This paper presents an Ishikawa analysis and a failure modes, mechanisms, effects, and criticality analysis (FMMECA) for all-ceramic anode based SOFCs. FMMECA takes into account the life cycle conditions, multiple failure mechanisms, and their potential effects on fuel-cell health and safety.

Keywords: solid oxide fuel cells; ceramic anodes; degradation mechanisms; Ishikawa diagram; failure modes; mechanisms; effects; and criticality analysis

1. Introduction

The high efficiency of SOFCs is based on the direct conversion of chemical energy into electrical energy in one step, eliminating unnecessary losses in conventional multi-step conversion systems [1–5]. A schematic representation of an SOFC is depicted in Figure 1. Oxide ions are produced by the oxygen reduction reaction at the cathode. The high ionic conductivity and density, but high electrical resistance, of the electrolyte allows only O^{2-} to migrate through it from cathode to anode. At the anode, oxide ions oxidize fuel (e.g., H_2 and CO), liberating their electrons and producing electricity. This is because SOFCs use oxide-ion conducting ceramic materials as the electrolyte. The electrolyte management issue that arises with liquid-phase electrolyte in other fuel cells is absent here. Moreover, because of their high operating temperatures (above $500\text{ }^\circ\text{C}$), natural gas fuel can be easily reformed within the cell. High operating temperatures of SOFCs also provide the ability to handle a wide range of hydrocarbon fuels. SOFCs require less fuel to produce a given amount of electricity because of their high efficiency, as compared to other power generation techniques, which corresponds with lower carbon dioxide (CO_2) emissions. SOFCs generally provide the lowest greenhouse gas emissions of any non-renewable power generation method [6]. Furthermore, the efficiency of SOFCs can be increased to 80% by joining fuel cell technology with combined heat and power (CHP) systems or cogeneration methods [6–10].

Long-term stability is a key requirement for the commercial application of SOFC technology. The fundamental issues associated with SOFC durability are still insufficiently characterized and identified [11–14]. Most review papers focus on a small number of specific degradation mechanisms. Since SOFCs can take many different paths toward failure, a methodology to illustrate all causes of failure is desirable. Additionally, there has been less failure mode analysis on newly developed

reduction–oxidation stable SOFCs using ceramic anodes, as compared to more conventional Ni-cermet anodes. In this paper, an Ishikawa analysis is performed for ceramic anodes of SOFCs and a comprehensive failure modes, mechanisms, effects, and criticality analysis (FMMECA) methodology is applied to ceramic anodes to prioritize the failure mechanisms considering reliability and durability of SOFCs. Ishikawa diagrams and FMMECA are root-cause analysis techniques that can be used to hypothesize root cause. Which analysis technique should be utilized is determined by the specific problem. Ishikawa diagrams do not provide level of importance. Rather, they serve as an organized way to summarize all possible ways to observe failure. The FMMECA highlights the potential failure mechanisms, root causes and failure modes, the likelihood of occurrence, severity and detection of the associated failure mechanisms. It is the aim of this paper to catalog known failure modes and mechanisms information, with the purpose of assisting future researchers in assessing the durability and reliability of ceramic anodes of SOFC technologies. Section 2 of this paper describes the anode requirements, followed by a discussion of anode degradation mechanisms in Section 3. The degradation and failure mechanisms are then summarized and categorized in a section using Ishikawa analysis. The final section discusses FMMECA.

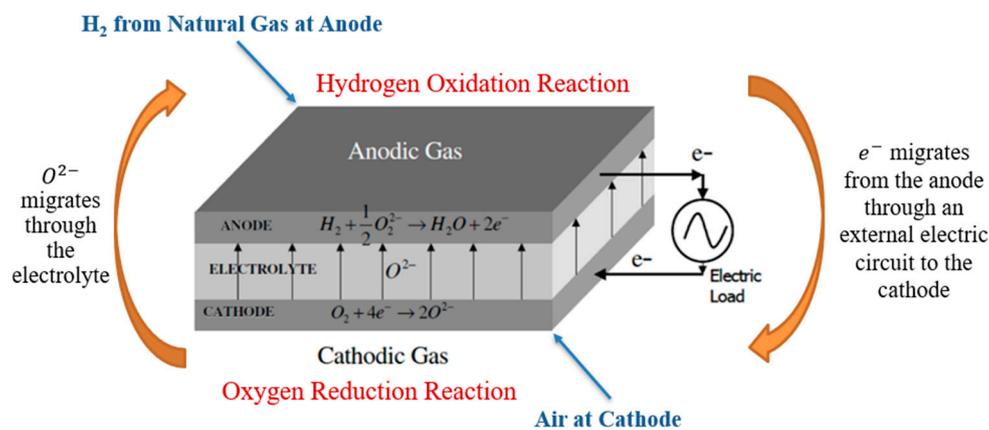


Figure 1. Schematic representation of an solid oxide fuel cell (SOFC).

2. Anode Composition and Requirements

To begin the failure analysis, the requirements and composition of the anode are summarized below. The anode of SOFCs not only functions as a site for electrochemical oxidation of the fuel, but also transfers charge to a conducting contact. Therefore, both the catalytic and electronic conductivity of the anode are critical. In addition, the anode materials must be compatible (chemical and thermal compatibility) with other components (the electrolyte and interconnects) [15]. Typically, the three major functions of the electrodes of an SOFC are: (1) allowing access to reacting gases, (2) allowing transport of electrons as well as ions, and (3) providing active catalytic sites. To accommodate these functions, the anode requires porosity of 30–40% [16]. Design of anode materials should also consider the operating temperatures of SOFCs which is usually above 500 °C [17]. This requires materials which do not degrade or alter at high temperatures and should be non-reactive with electrolyte. Coefficient of thermal expansion of anode materials should be close to electrolyte and cathode materials in order to prevent interfacial delamination and cracking at high-temperature operations. Ceramic–metallic (cermet) anodes, especially nickel-based anodes, can produce a combination of these required properties and hence, have been used as traditional anode materials for SOFCs [18]. However, traditional nickel-based anode material for SOFCs have disadvantages, such as volumetric changes during the initial reduction of NiO to Ni resulting in stress in the cell and susceptibility to catastrophic mechanical failure in the event fuel is unintentionally lost during operation with consequent oxidation of the Ni to NiO. All-ceramic anodes have been developed to solve these problems and make this technology cost-effective.

Since, it is very difficult to devise oxide-based anodes with high electronic and ionic conductivity, and good chemical compatibility with electrolytes, it has been proposed to decouple the anodes into substrate and functional layers [19]. The substrate layer forms the thicker portion of the anode. It serves as a mechanical support and a current collector in the cell, but it does not play a role in the electrochemical reaction that takes place at the anode end. The thickness of the substrate is around 500–1500 μm [19]. The functional layer provides the site for the electrochemical reaction to take place. The thickness of this layer is generally around 10–15 μm [19]. It is possible to decouple these two layers because of functional differences between them by using different materials for each component based on the desired chemical, thermal, and physical characteristics [20]. For instance, the substrate material should have a high electronic conductivity to reduce ohmic losses, whereas ionic conductivity is not essential. In the case of the functional layer, a high ionic conductivity is required, whereas the electronic conductivity may be lower than the substrate. Thus, using materials that have different properties allows anodes to be more flexible. The desirable properties of both these components are tabulated in Table 1 [19].

Table 1. Desirable properties of the anode substrate and functional layer materials [19].

Property	Anode Substrate	Anode Functional Layer	Comments
Electronic conductivity (at 800 °C)	>10 S/cm	>1 S/cm	Basic properties required for functioning
Ionic conductivity (at 800 °C)	Not required	>0.02 S/cm or comparable to that of yttria-stabilized zirconia (YSZ electrolyte)	
Good electro-catalytic activity for H ₂ /CO oxidation	Not required	Required	
Chemical stability in anode atmosphere (H ₂ , CO, CO ₂ , H ₂ O, CH ₄)	Required	Required	Compatibility with working environment
Thermal expansion coefficient	10.5–13 ppm/K	10.5–13 ppm/K	
No detrimental effect solid-state reaction with electrolyte (e.g., YSZ)	Not required but preferred	Required	
Linear expansion or shrinkage upon redox cycling	<0.2%	<1%	Important for the reliability of anode supported cells
Tolerance to dry hydrocarbons (no carbon buildup)	Required	Required	Further simplification of fuel pre-processing
Tolerance to sulfur poisoning	Required	Required	

Ceramic Anodes for SOFCs

To infer the research and progression in the area of ceramic anodes of SOFCs, a benchmark from previous work is detailed in this section. While ceramic–metallic (cermet) anodes have been used in the past because of their high performance in syngas (a mixture of CO and H₂ formed by hydrocarbon reforming); these cermets are sensitive to presence of sulfur in the fuel [21,22], they cannot tolerate re-oxidation during shut-down and start-up cycles, and tend to form carbon in presence of dry hydrocarbons [23]. In order to improve reliability, ceramic materials for the anodes of SOFCs have been investigated extensively because of their tolerance to reduction–oxidation (red-ox) cycling and excellent thermal stability [24–26]. To this end, ceramic anodes should have: (1) negligible dimensional changes during red-ox cycles (less than 0.1 to 0.2% of linear expansion), (2) electrical conductivities higher than 10 S/cm, (3) stability in reducing atmospheres and air and compatibility with the electrolytes, (4) thermal expansion coefficients close to that of the electrolyte, and (5) good catalytic activities for H₂ and CH₄ oxidation. Ionic conductivities should be >0.02 S/cm [27]. Ceramic materials have also been used as electrodes in different energy storage devices, such as batteries and supercapacitors [28].

However, the performance of ceramic anode has been modest as compared to cermet because of their low oxide ion conductivity and poor catalytic activity for hydrogen oxidation and their requirement of operating temperatures of more than 900 °C to achieve the comparable performance which can be achieved at 700 °C using Ni-based cermet [29,30]. Several types of ceramic anodes have been investigated because of their tolerance to coking and sulfur poisoning [31]. Much of the effort has focused on perovskite materials because they provide: (1) mixed ionic electronic conductivity, (2) structurally stable chemistries throughout a wide range of oxygen partial pressure and temperatures, and (3) no reactivity with other components [24,32,33]. The perovskite $\text{La}_{1-x}\text{Sr}_x\text{CrO}_3$ material has been thoroughly investigated as a potential anode material because of its chemical stability through a wide range of partial pressure of oxygen and temperatures [34]. The polarization resistance of chromium-based perovskite anode is generally too high for efficient operation of SOFCs. However, replacing chromium with vanadium improves efficiency by reducing coke deposition, although it does not reduce polarization resistance [35]. The other transition elements into the B-site of $\text{La}_{1-x}\text{Sr}_x\text{Cr}_{1-y}\text{M}_y\text{O}_3$ ($\text{M} = \text{Mn, Fe, Co, Ni}$) have also been used to reduce the polarization resistance where Ni was found to be most successful [35]. Nickel oxide is not stable in fuel atmospheres, so, introduction of Ni raises concerns about long-term stability of SOFCs. Vanadium-doped perovskite, $\text{Sr}_{1-x/2}\text{V}_x\text{Ti}_{1-x}\text{O}_3$ (SVT) and $\text{Sr}_{0.2}\text{Na}_{0.8}\text{Nb}_{1-x}\text{V}_x\text{O}_3$ (SNNV) achieved high conductivities and performance as high as 500 mWcm^{-2} as compared to 350 mWcm^{-2} for conventional SOFCs. Gadolinium-doped ceria (GDC) electrolyte supported cell was fabricated with $\text{Sr}_{0.2}\text{Na}_{0.8}\text{Nb}_{0.9}\text{V}_{0.1}\text{O}_3$. Performance was measured in hydrogen and methane, respectively. Due to vanadium's intrinsic problems, such as long-term stability problems associated with the liquid phase sintering [36], the vanadium-doped anode-supported cell has not been commercialized.

In 2013, symmetric solid oxide fuel cells (SSFCs) with the configuration of $\text{Sr}_2\text{Fe}_{1.5}\text{Mo}_{0.5}\text{O}_{6-\delta}$ (SFM)/LSGM/SFM, in which SFM was proposed as a promising electrode [37–39], reached 835 and 230 mWcm^{-2} in wet H_2 and CH_4 , respectively. In order to improve the further catalytic activity and electrochemical performance of SSFCs, modified SFM by cobalt-substitution was developed [40]. The presence of cobalt is beneficial to the hydrogen oxidation reaction (HOR) and contributes to low polarization loss. The cobalt as dopant not only affects the catalytic activity of anodes but also improves oxygen ionic conductivity. Sivaprakash et al. [41] presented a new A-site layered double perovskite–manganese oxide which exhibit superior SOFC anode performance and fuel flexibility. Recently, iron-doped double perovskite $\text{Sr}_2\text{CoMoO}_6$ (SFCM) has been developed as a promising anode [42], through which the conductivity was improved over one order of magnitude and performance reached 2 Wcm^{-2} .

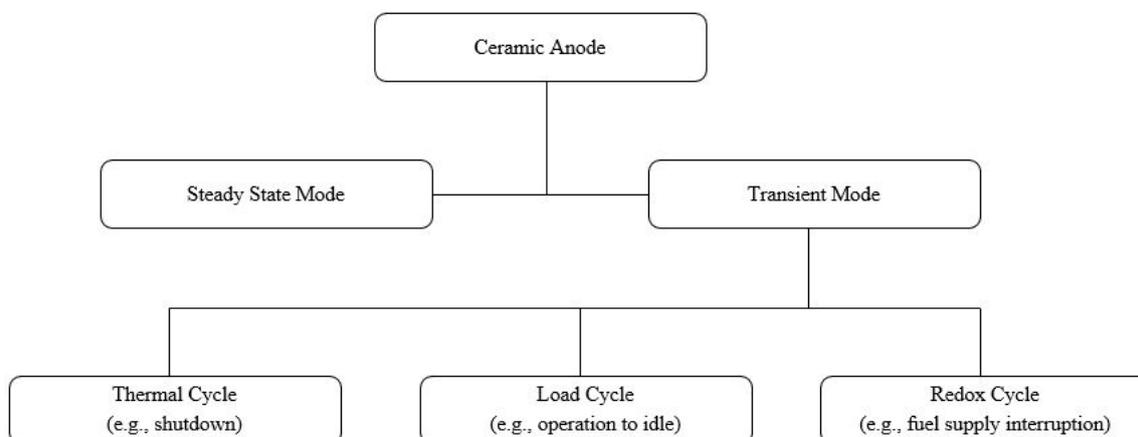
3. Ceramic Anode Degradation Mechanisms

The mechanisms of degradation respective to different failure modes need to be defined for FMMECA and Ishikawa analysis of ceramic anodes. Different failure mechanisms for ceramic–metallic anodes have been studied extensively [43–46]. However, the organization and prioritization of failure mechanisms along with effect of these mechanisms on different anode materials is required to assess and improve reliability of SOFCs. Red-ox instability, which refers to the chemo-mechanical instability of the SOFC anode and support under oxygen partial pressure variation during reduction and oxidation at high temperature (500–1000 °C), is one of the main limitations for cermet anodes [47]. Besides that, cermet anodes are prone to carbon deposition, sulfur poisoning, and reduction in porosity upon prolonged use. The ceramic anodes appear promising because of their high red-ox stability, high sulfur tolerance, and resistance to coking [17]. However, ceramic anodes suffer from low electronic conductivity in reducing atmosphere, and reduction in catalytic activity because of phase decomposition in presence of high humidity [11,17]. The different failure modes for cermet anodes and ceramic anodes on the basis of possibility of occurrence are shown in Table 2.

Table 2. Failure modes for ceramic–metallic anodes and all-ceramic anodes [17,43–46].

Failure Modes	Possibility of Occurrence in Ceramic–Metallic Anodes	Possibility of Occurrence in All-Ceramic Anodes
Interfacial delamination or cracks due to red-ox instability	High	Low
Coke deposition	High	Low
Sulfur adsorption onto metal catalyst	High	Low
Reduction in porosity	High	Low
Corrosion of anode	Low	High
Reduction in catalytic activity	High	High

A basic organization of operating conditions of the SOFC is shown in Figure 2. The anodes of SOFCs can operate in steady state mode (constant stress conditions) and transient mode. Typically, the transient mode is more deleterious and can cause sudden failure of SOFCs because of interfacial delamination or cracking of anodes due to thermal cycles, load cycles, or red-ox cycles. Degradation is usually defined as performance degradation as well as mechanical failure such as crack formation and propagation. Systematic investigations of such degradation phenomena can be done with several tests: durability tests, thermal-cycling tests, red-ox stability tests, and accelerated aging tests. To predict the lifetime of a stack, it is essential to understand the physicochemical reasons for respective degradations. Furthermore, degradation may occur as a result of related deteriorations that take place sequentially. These deterioration-chain phenomena are currently not well-understood for ceramic-anode-supported SOFCs.

**Figure 2.** Operating conditions of SOFCs.

The kinetics of most of the anode degradation mechanisms are influenced by the operating conditions of the SOFC. The key operating parameters for anode degradation in the steady-state mode are temperature [48], gas composition (especially the partial pressure of water), and current density (i.e., the working potential) [49]. In contrast, the number of red-ox and thermal cycles is the most critical parameter in the transient mode [50]. Electrolyte cracking is a major threat to the anode-supported cell under redox cycling conditions. Varying operating conditions of SOFCs can lead to the following degradation mechanisms: thermomechanical, chemo-mechanical, material transport, and deactivation and passivation.

3.1. Thermomechanical Mechanisms

Thermomechanical mechanisms pertain to variation in the mechanical properties of anode material with temperature. An SOFC's typical operating temperature is $>500\text{ }^{\circ}\text{C}$, which leads to severe

thermal stresses caused by the differences in mechanical properties during thermal cycling [51,52]. For anode-supported SOFCs, the stress field in the anode may arise due to thermal expansion mismatch between the anode and other components, residual stresses, and stresses resulting from thermal cycles. These stresses can cause delamination and micro-cracking in the anode/electrolyte interface and lead to performance degradation and eventual failure [53]. Another factor leading to degradation is the generation of thermal gradients due to uneven thermodynamic reactions that occur in the triple-phase boundary of the cells [16]. The release of large amounts of thermal energy in different sections of the anode is likely to accumulate thermal stresses that are capable of weakening the bonds between materials.

3.2. Chemo-Mechanical Mechanisms

As discussed above, chemo-mechanical mechanisms involve both chemical and mechanical action and can lead to catastrophic failures of the SOFC. The effect of the red-ox cycle on the performance of SOFCs has been widely studied [54]. It has been found that red-ox cycling is the most damaging because it primarily affects the SOFC anodes, unlike thermal cycling where there is bulk volume displacement in the whole SOFC due to changes in temperature. The bulk strain induced by the oxidation of the ceramic anode has been shown to lead to high tensile stresses in the thin electrolyte layer [54]. The ceramic anode cannot expand freely and remains constrained by the dense electrolyte substrate, leading to strain accumulation and delamination or bulk degradation of the anode layer.

Ceramic anodes are typically mixed-ionic electronic conducting single-phase materials. Researchers have shown that during operation, changes in oxygen partial pressure result in significant departures from stoichiometry in mixed ionic and electronic conducting oxides [55]. This large change in oxygen vacancies often leads to significant dilation of the lattice known as chemical expansion, which results in large stresses and ultimately leads to mechanical failure. However, the strain associated with chemo-mechanical expansion of non-stoichiometric anodes is still much less than the strain associated with, e.g., oxidation of Ni to NiO, a completely different phase.

3.3. Material Transport Mechanisms

Typically, the ceramic anode will have a metal catalyst added to it to increase electrochemical performance. The material transport mechanism is driven by two key phenomena: changes in the metal catalyst surface morphology and an increase in the metal catalyst particle size [56]. Both of these phenomena are driven by the tendency of the metal catalyst to reduce its surface free energy under the operating conditions of the SOFC. First, this mechanism causes a reduction in the available surface area of the metal catalyst, thereby reducing the number of active catalytic sites and ultimately increasing the polarization resistance. Second, the increased particle size causes a disconnection among the metal catalyst particles, thus decreasing the electrical conductivity [56,57]. Material transport mechanisms can also occur during the storage of ceramic anodes. The exposure of ceramic anodes to high humidity and temperature may lead to morphological and resistance changes which can affect the reliability of SOFCs (comprehensive detail will be provided in a follow-up paper).

3.4. Deactivation and Passivation Mechanisms

Deactivation and passivation mechanisms primarily include sulfur poisoning and coking of the anode. Sulfur poisoning mainly occurs when there are sulfide impurities in the fuel used in the SOFC [22,58]. The performance degradation is attributed to the surface adsorption on the exposed metal catalyst in the anode, e.g., Ni, which blocks H₂ dissociation from taking place. However, these short-term effects were reversible for conventional Ni-based anodes, and the cells eventually regained their performance. Permanent damage to the cell was observed on prolonged exposure (on the order of tens of hours) to H₂S [58].

Coking is of concern when hydrocarbon-based fuels are used in the SOFC. Hydrocarbons such as CH₄, when used along with Ni-impregnated ceramic anodes, lead to carbon deposition over the metal

The degradation causes that can ultimately lead to change in material morphology and material properties and result in failure of the anodes are classified in the **Material** category. Variation in material properties can affect the performance of SOFCs. The main degradation causes are decreased porosity of the anode catalyst material and decreased catalytic activity of the metal catalyst. Change in metal catalyst surface morphology can occur due to tendency of metal catalyst to diffuse outward and due to inward oxygen transport. Morphological and phase changes of anode material is one other important failure cause under this category. This can occur due to exposure to excessive humidity or other corrosive atmospheres (e.g., Cl impurities in fuel from waste). These physical and chemical changes can severely deteriorate the structural integrity of the anode, thus hampering performance.

Environmental factors that can degrade the performance of anodes mainly include excessive humidity and corrosive atmospheres and are shown in the **Environment** category. Both of these factors can change material properties by corroding the top layer of ceramic anode, which will decrease the catalytic activity of the anode. The effect of environmental factors on the structural integrity of conventional Ni-based anodes has been studied [65], but the effects of these factors on the performance of new ceramic anode materials have not been studied.

Coking and sulfur poisoning are the degradation causes under the category of **Fuel**. Both of these mechanisms can affect the performance and reliability of fuel cells. Coking mainly occurs when hydrocarbon-based fuels are used directly, without any steam or dry reforming, which leads to no shift reaction and results in coke deposition [66]. Sulfur poisoning occurs when there are sulfide impurities in the fuel, which blocks hydrogen adsorption and hence reduces the performance of the SOFC. Zhangbo et al. [67] presented wet impregnation/infiltration techniques to improve carbon and sulfur tolerance of Ni-based anode materials. The impact of this degradation mechanism on all-ceramic anodes needs further research.

5. Failure Modes, Mechanisms, Effects, and Criticality Analysis for Ceramic Anodes

SOFCs consist of multiple components, each with its own failure mechanisms and criteria. The anode is believed to be one of the most sensitive components in SOFC degradation and is the focus of this study. This paper developed the FMMECA for ceramic anodes. The FMMECA will play a key role in the development of degradation and failure test plans for assessing SOFC reliability.

Failure modes, mechanisms, and effects analysis (FMMEA) is “a systematic methodology to identify potential failure mechanisms and models for all potential failure modes, and to prioritize failure mechanisms” [68] and is the cornerstone of the physics-of-failure (PoF) approach to reliability assessment of systems, subsystems, and components. When extended by criticality analysis (CA) procedures, FMMEA is known as failure modes, mechanisms, effects, and criticality analysis (FMMECA). Failure mechanisms are identified as the “processes by which physical, electrical, chemical, and mechanical stresses induce failures” [69]. These mechanisms describe the fundamental manner in which a device or component can fail. Failure modes, on the other hand, are defined as the manner by which a failure is physically observed. The mode may not be easily observed in situ; however, a complete failure analysis would reveal the source of the failure. The cause of failure is the driving force behind the failure mechanism and can be the result of either internal or external stresses. The failure effect is how the failure mechanism impacts the usability of the device or component. Finally, the criticality analysis ranks all failure modes and mechanisms in order of importance to help prioritize maintenance work [70].

It is necessary to understand which failures are the most severe and how reliability can be improved by mitigating the effects of those failures. One way to determine which failures to focus on is to rank the failure mechanisms from 1 to 10 with respect to likelihood of occurrence, degree of severity, and detectability. Scores are assigned for each of these three considerations, and the results are combined into an overall risk priority number (RPN). The RPN is the product of the severity rating, the occurrence rating, and the ease of detection (e.g., $1 \leq \text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \leq 10$) [71], with larger numbers meaning a greater risk. For example, a failure mechanism that has a high

likelihood of occurrence, high severity, and is not easy to detect would be ranked above all other failure mechanisms. A failure mechanism that is easy to detect would not be ranked as high as other failure mechanisms. Additionally, the calculated RPN value is dependent on the application and the expected use conditions. Using Institute of Electrical and Electronics Engineers (IEEE) standardized RPN methodology and evaluation criteria [72], a criticality analysis for ceramic anodes of SOFCs is shown in Table 3. The RPN technique can be used by industry groups to perform comprehensive criticality analysis in the presence of field data. For example, if the customer is dissatisfied with the product because of the specific failure mechanism but still managed to execute the task and the degradation is within warranty then severity will get rating of 3. Occurrence will get rating of 3, when the degradation rate is low for specific failure cause but there is lack of understanding of responsible mechanisms, while with the clear understanding of responsible mechanisms for same failure cause will get occurrence rating of 2. Finally, detection will get rating of 3, when there are chances that failure cause will be identified and removed before it can cause the failure. It should be noted that a criticality analysis anticipates the future, so the numerical rating is a subjective value, not an objective one [73].

Table 3. Criticality analysis for ceramic anodes.

Rating	Degree of Severity	Likelihood of Occurrence	Ease of Detection
1	The adverse effect is insignificant	Remote	Certain that potential failure will be found or prevented
2	Customer will experience annoyance due to slight degradation of performance	Low failure rate with supporting documentation	Almost certain that the potential failure will be found
3	Customer dissatisfaction due to reduced performance	Low failure rate without supporting documentation	Low likelihood that potential failure will reach the customer
4	Customer is made uncomfortable due to continued degradation (degradation within annual goal)	Occasional failures	Controls may not detect or prevent the potential failure
5	Degradation beyond annual goal results in warranty repair	Moderate failure rate with supporting documentation	Moderate likelihood that potential failure will reach the customer
6	Violation of governmental regulation with less degradation in performance	Moderate failure rate without supporting documentation	Controls are unlikely to detect or prevent the potential failure
7	Shutdown of system due to component failure	High failure rate with supporting documentation	Poor likelihood that potential failure will be detected or prevented
8	Shutdown of system and violation of governmental regulations	High failure rate without supporting documentation	Very poor likelihood that potential failure will be detected or prevented
9	Customer endangered due to immediate shutdown without warning	Failure is almost certain based on warranty data	Controls probably will not even detect the potential failures
10	Customer endangered due to the adverse effect of operation results in fire in system	Assured of failure based on warranty data	Absolute certainty that the controls will not detect the potential failure

In the absence of field data, more generalized rating techniques (shown in Table 4) can be used to identify and prioritize the potential failure modes and mechanisms. The severity, occurrence, and detectability of failure depend on a combination of factors such as type of user, purpose of usage, and environmental conditions. The numerical rating of severity, occurrence, and detectability is a subjective value and will change from installation to installation. The authors have generalized

numerical ratings for criticality analysis into high, moderate, and low classes as shown in Table 4. Severity gets high ratings in the scenario where failure affects the users instantly and causes immediate shutdown and safety issues. A moderate severity rating is assigned when the degradation meets or exceeds failure criteria but there are no sudden shutdown or associated safety issues. When the degradation is within the failure criteria then it gets a low severity rating. Occurrence of failures is also categorized into these three classes of high, moderate, and low. For a specific failure cause, a high occurrence rating indicates the degradation is certain while moderate and low occurrence ratings indicate occasional failures and when the chances of failure are very low, respectively. Contrary to severity and occurrence ratings, the detection rating is assigned on the basis of ease of detection. Failure causes that are easy to detect and can be prevented get a low detection rating. Failure causes that are very unlikely to be detected and have a very poor likelihood of prevention get high detection ratings. Failure causes with moderate likelihood of prevention before reaching the end-user get a moderate detection rating.

Table 4. Severity, occurrence, and detection rating for SOFC power system.

Rating	Degree of Severity	Likelihood of Occurrence	Ability to Detect
Low	Performance degradation within annual goal	Chances of failure is low	Easy to detect and can be prevented
Moderate	Performance degradation beyond annual goal	Occasional failures	Moderate likelihood that potential failure will be detected and prevented
High	Immediate shutdown, safety issues	Failure is almost certain	Very unlikely to detect and prevent the potential failure

The FMMECA in Table 5 was constructed for design and operational stages, where one can physically observe degradation in situ. It is easier to identify causes and mechanisms behind degradation when one has an FMMECA. This analysis will help manufacturers understand the root causes of failure, improve reliability, and perform corrective actions during repair. It provides a comprehensive list of the failure modes from the user's perspective, the potential causes that drive failure mechanisms, potential failure mechanisms, and whether the failure is brought on by abrupt overstress or by progressive degradation (wearout).

Criticality analysis can be conducted by assigning numerical ratings to different failure modes and mechanisms and by calculating RPNs according to their usage and requirements. Because RPNs are relative, mechanisms that are assigned higher RPNs are considered critical. Anode-electrolyte interfacial delamination is one of the critical failure modes which can cause failure of a system instantaneously. It is assigned a high severity rating. However, the occurrence of this failure mode has been dramatically reduced with the development of ceramic anodes, resulting in a low occurrence rating. Failure causes such as volume changes in the anode and mechanical stress, responsible for anode-electrolyte interfacial delamination, are very unlikely to be detected and hence, prevented, before actual failure. Thus, a high detection rating has been provided. Redox cycling is one of the critical failure causes that can result in both overstress and wear out failure mechanisms, as shown in Table 5. Change in metal catalyst surface morphology and reduction in catalyst porosity are failure modes that can occur from redox cycling. They can also cause wear out degradation of the anodes of SOFCs. With the development of ceramic anodes, severity of these failure modes has been reduced. Hence, moderate severity ratings have been provided. Since these are wear out degradation mechanisms, there is moderate likelihood that these failure modes can be detected and prevented via any gradual decrease in performance of the SOFCs. Reductions in porosity are assigned moderate occurrence ratings because they are more certain with each redox cycle, even with ceramic anodes. Further research is required for preventing the occurrence of these failure modes.

Table 5. Failure modes, mechanisms, effects, and criticality analysis (FMMECA) for ceramic anodes.

Potential Failure Mode	Failure Causes	Potential Failure Mechanisms	Failure Mechanism Type	Observed Effect	Severity	Occurrence	Detection
Anode-electrolyte interfacial delamination	Volume change in anode due to re-oxidation reaction (~1%)	Strain accumulation due to irreversible volume expansion	Chemo-mechanical mechanism—overstress	Decrease in conductivity, voltage drop, system shutdown	High	Low	High
Anode-electrolyte interfacial delamination	Mechanical stress due to thermal cycling	Strain accumulation due to CTE mismatch	Thermomechanical mechanism—overstress	Decrease in conductivity, voltage drop, system shutdown	High	Low	High
Change in metal catalyst surface morphology	Red-ox reaction	Outward metal diffusion and inward oxygen transport	Material transport mechanisms—wear out	Decrease in conductivity, voltage drop	Moderate	Moderate	Moderate
Reduction in catalyst porosity	Red-ox reaction	Ostwald ripening/coarsening	Material transport mechanisms—wear out	Decrease in conductivity, voltage drop	Moderate	Moderate	Moderate
Crack	Air leakage (lack of fuel, shutdown and startup without reducing gas) causing anode oxidation during operation.	Fatigue of anode material	Thermomechanical mechanism—overstress	Sudden drop in voltage and CO formation.	High	Moderate	Low
Crack	Fuel supply fluctuation, unexpected hydrogen shortage causing partial re-oxidation	Fatigue of anode material	Thermomechanical mechanism—overstress	Drop in voltage, CO formation	High	Moderate	Low
Crack	Current overload	Fatigue of anode material	Thermomechanical mechanism—overstress	Drop in voltage	High	Moderate	Low
Corrosion of anode	Impurities in water/steam, humidity exposure, corrosive atmosphere	Chemical corrosion reaction	Deactivation and passivation mechanisms—wear out	Voltage drop	Low	Low	Moderate
Sulfur adsorption onto metal catalyst	Presence of sulfur impurities in fuel	Chemical reaction (metal particle migration)	Deactivation and passivation mechanisms—wear out	Sudden voltage drop initially and then gradual performance degradation.	Moderate	Low	Moderate
Coke deposition	No shift reaction (incomplete oxidation of fuel)	Coking	Deactivation and passivation mechanisms—wear out	Decrease in conductivity, voltage drop	Moderate	Low	Moderate

Cracking can occur in the anodes of SOFCs due to any of the three possible causes listed in Table 5 and can cause instantaneous failure of the system. Hence, the assignment of high severity ratings. However, the failure causes responsible for cracking, such as air leakage, fluctuations in fuel supply and current overload, can easily be detected and prevented before the failure of the system. So, a low detection rating is provided. The occurrence of crack failure mode is given a moderate rating because of the occasional nature of this failure cause. Corrosion of anode, sulfur poisoning, and coke deposition are failure modes which can occur due to humidity exposure or impurities in fuel. The severity of sulfur poisoning and coke deposition has been reduced with the development of ceramic anodes as compared to ceramic–metallic anodes where these were major critical failure modes. The occurrence of these failure modes has been significantly reduced for ceramic anodes; hence, a low occurrence rating has been provided. Moreover, since deactivation and passivation failure mechanisms are wear-out mechanisms, which result in gradual performance degradation, moderate detection ratings have been assigned.

It was found that redox cycling and thermal cycling are the critical failure causes that can cause sudden failure of a system and are also responsible for a number of wear-out degradation mechanisms. Hence, accelerated thermal and redox cycling testing should be performed to determine the reliability of anodes and to ensure high thermal and redox cycling durability, for preventing the catastrophic failure of systems. Additionally, use of air-leakage and fluctuations in fuel-supply detection systems is highly encouraged to prevent failure due to cracking in anodes of SOFCs.

6. Summary and Conclusions

Solid oxide fuel cells (SOFCs) are complex systems that are susceptible to many different degradation mechanisms, each of which individually and in combination can lead to performance degradation, failure, and safety issues. As a result, it is necessary to identify the ways an SOFC can degrade and assess the risk of each type of degradation process and failure mechanism. The development of an FMMECA is the first step in making a transition from empirical to physics-based SOFC failure models to account for the stresses experienced by ceramic anodes of SOFCs during their life cycles. The FMMECA's most important contribution is the identification and organization of failure mechanisms and models that can predict the onset of degradation or failure.

To assess root cause and impact of failures, an Ishikawa analysis and a failure mode, mechanisms, effects, and criticality analysis (FMMECA) of ceramic anodes for SOFCs have been developed. It was found that anode-electrolyte interfacial delamination and cracks are the critical failure modes which can cause the abrupt failure of SOFCs. Hence, one should carefully design the ceramic anodes of SOFCs for redox cycling and thermal cycling as these are the dominant failure causes for aforementioned critical failure modes. It is worth noting that though mechanical failure due to redox cycling is still a concern with ceramic anodes, the susceptibility to the failure mode is expected to be dramatically reduced as compared to Ni-cermet cells. Additionally, these analyses can be used to develop degradation and failure test plans for ceramic anodes and to facilitate assessment of the reliability of anodes as well as the entire SOFC system. Standards organizations and industry groups can design better qualification and safety tests based on the findings of these analyses. Such assessments not only can predict a given application's life-cycle stresses on the SOFCs, but also capture the interactions between different failure mechanisms that exacerbate failure. Improved design and testing influenced by these analyses can lead to safer and more reliable SOFC systems.

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