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Pratap Rama, Rui Chen and John Andrews
Loughborough University

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ABSTRACT

A qualitative FMEA study of Polymer Electrolyte Fuel Cell (PEFC) technology is established and presented in the current work through a literature survey of mechanisms that govern performance degradation and failure. The literature findings are translated into Fault Tree (FT) diagrams that depict how basic events can develop into performance degradation or failure in the context of the following top events; (1) activation losses; (2) mass transportation losses; (3) Ohmic losses; (4) efficiency losses and (5) catastrophic cell failure. Twenty-two identified faults and forty-seven frequent causes are translated into fifty-two basic events and a system of FTs with twenty-one reoccurring dominant mechanisms. The four most dominant mechanisms discussed that currently curtail sustained fuel cell performance relate to membrane durability, liquid water formation, flow-field design, and manufacturing practices.

INTRODUCTION

PEFC technology has been the focus of research and development for over five decades. The technology inherently mitigates the need to combust reactant gases directly, which prevents the energy conversion device from being restricted to the Carnot efficiency. The fundamental processes of hydrogen-oxidation and oxygen-reduction results in water as the product, eliminating vehicular carbon, NO_x and particulate matter emissions. As the cost per kW of PEFC technology approaches USD35 /kW, it is conceivable that the technology can become cost-competitive with conventional ICE technologies.

Automotive fuel cells are expected to operate under load-following or load-levelled modes and expected to withstand variations in environmental conditions, particularly in the context of temperature and atmospheric composition. Additionally, fuel cell powerplants are expected to survive under these conditions over the duration of their expected operational lifetimes i.e., around 5,500 hrs, while undergoing as many as 30,000 startup/shutdown cycles. The challenge for modern-day fuel cell research and development for automotive propulsion is to ensure that the technology is shaped for the delivery of safe, reliable and apt performance over its expected lifetime, whilst

maintaining a level of transparency in the financial risk implied on those investing in fuel cell technology at both pre- and post- commercialization phases.

The continual drive to bring PEFC technology closer towards maturity is resulting in a vast multitude of materials, designs, manufacturing processes and considerations for the different components of a cell [1,2,3]. This reflects the fact that there are a multitude of factors that govern the performance of the cell, all of which are related to some element of physical design or operational practice that can be altered to improve an aspect of cell performance. The current work aims to provide a structured insight into the factors that govern the reliability and safety of PEFCs by considering the cause and effect of the underlying phenomenological processes.

In the context of fuel cells, failure can occur as a consequence of gradual processes; certain operating conditions and operational routines can cause a systematic degradation of structural and electrokinetic properties of PEFC assemblies and culminate in the irreversible loss of performance below critical thresholds. PEFCs are generally susceptible to multiple modes of performance loss; five top events are considered in the current study which reflect either performance degradation or failure:

- (1) activation losses
- (2) mass transportation losses
- (3) Ohmic losses
- (4) fuel efficiency losses
- (5) catastrophic cell failure

This study forms part of a larger failure analysis which incorporates Failure Modes, Effects Analysis (FMEA) [4,5]. FMEA is a structured, qualitative and quantitative analysis of a system aimed at facilitating the identification of potential system failures modes, their causes and the effects on the system operation. The general procedure of FMEA is to consider each potential failure mode and to determine its effect on the system. The overall objective of the analysis is to identify reliability and

criticality elements of a system to determine where modifications may be required to the system design or operating methodology, or where certain established competencies in fuel cell design and operation should prevail. The first part of the study is presented here, where through a literature survey, the different degradation mechanisms that induce potentially irreversible performance losses in the context of the five loss mechanisms are understood and mapped into diagrammatic form via FTs [6]. An FT is a top-down representation of the state of a system (top event) in terms of the state of its components (basic events).

PERFORMANCE DEGRADATION AND FAILURE ANALYSIS

LOSS MECHANISMS

Activation Losses – Activation losses are attributed to the slowness of reactions occurring in the fuel cell electrodes. The anode kinetics are much faster than the cathode kinetics. Activation losses can increase during the course of cell operation if the electrochemically active surface area (EASA) reduces in the fuel cell catalyst layers. The most prominent mechanisms that induce performance degradation through activation losses are as follows;

- agglomeration and/or ripening of platinum particles: subjecting PEFCs to repetitive on/off load cycles induces a susceptibility to platinum sintering. Sintering results in a loss of EASA.
- platinum migration: when the PEFC is operated through hydrogen-air open circuit to air-air open circuit, platinum can become soluble and liable to transportation through adjacent layers. Loss of catalyst results in a loss of EASA
- exposure to sub-zero operating conditions: the repetitive freezing and melting of water residing within the catalyst layer is likely to deform the structure of the catalyst layers by increasing the pore size and reducing the EASA
- atmospheric contaminants: air impurities such as NO_2 , SO_2 and H_2S have a negative impact on cell performance due to their adsorption on platinum catalyst sites. Cyclic voltammetry can be applied to recover the cathodic EASA for contaminant concentrations less than 5 ppm.
- fuel contaminants: operating PEFCs on hydrocarbon reformat yields a susceptibility of exposing the anode catalyst layer to CO in the concentration range of 10-100ppm. CO adsorbs onto Pt more strongly than H_2 which thereby compromises the EASA for hydrogen oxidation. Additional CO can form through reverse water-gas shift reactions or through the electro-reduction of CO_2 (CH_4 reformation typically yields an 80/20 hydrogen/ CO_2 stream with CO in the mentioned concentrations). CO can also affect the cathode catalyst layer through crossover.
- carbon corrosion: if a single cell has insufficient fuel to support the current drawn, carbon in the catalyst

layer as catalytic support can corrode to supply protons to support the current above that provided by the fuel. This compromises the stability of the catalyst layer and the EASA in the anode. Platinum agglomeration can be instigated through carbon corrosion.

- chemical degradation of chemical seals: seals in fuel cell stacks are made of silicone and serve to avoid the mixing of hydrogen and oxygen. The acidic nature of the polymer electrolyte membrane and the thermal stresses applied to the silicone seal can cause it to chemically degrade. The decomposition products react with catalysts to form particles containing silicone, oxygen and platinum. This therefore also compromises the EASA.

Mass Transportation Losses – these losses occur when there is a disparity between the rate at which reactant are supplied and the rate at which they are consumed. The disparity is induced by an impedance to the supply of reactants to the catalyst sites and can be instigated by a number of processes;

- cell flooding: the formation of liquid water in the cathode, restricting the transport of oxygen
- loss of hydrophobic material: porous fuel cell layers such as the gas diffusion layer (GDL) are often treated with hydrophobic polytetrafluoroethylene (PTFE) to facilitate liquid water removal. The PTFE is susceptible to mechanical and electrochemical degradation particularly when subjected to thermal cycles, which can subsequently cause the rate of liquid water accumulation to increase
- excessive ionomer loading in the catalyst layer: limited control during fabrication can result in excessive ionomer loading or the formation of ionomer skins on catalyst sites, impeding reactant transport
- ice formation: residual water in a single cell can freeze and remain in a solid state during subsequent start-up and short periods of operation. This too impedes the transport of reactant gases
- over-compaction: over-tightening during stack construction can cause pores to collapse in the GDL. This has the effect of reducing the overall porosity and the pore connectivity, resulting in a loss in permeability

Ohmic Losses – both the resistance to proton transport and electron transport in respective ion-conducting cell materials contribute towards Ohmic losses. Resistance to electron transfer is largely attributed to the bipolar plate (BPP) material;

- stainless-steel (SS) BPP: passivating layers such as Cr_2O_3 are developed on the surface of stainless steel for corrosion resistance. These thin films, however, possess high interfacial contact resistances (ICR), the magnitude of which depends upon the Cr and Ni content of the SS

- SS substrate coating: SS can be coated with conductive polymers for corrosion resistance while maintaining low ICRs. Loss of coating and subsequent surface corrosion can lead to high ICRs compared to pristine SS
- Inhomogeneously-mixed polymer-carbon BPPs: injection-moulded BPPs can suffer from polymer-rich boundaries during the moulding process, particularly if the material is not homogeneously mixed prior to injection. This results in compromised electron conductivity close towards the surface

Resistance to proton transfer is attributed to the polymer electrolyte material;

- dehydration: protons are transferred through the polymer electrolyte membrane via a *Grotthus* hopping mechanism, which fundamentally depends upon the presence of water. As such, by ensuring that the membrane is kept well hydrated the proton conductivity can be maintained and Ohmic losses can be minimised. Inadequate water management can lead to dehydration and resistance to proton transfer. Membrane dehydration can be induced by the following two mechanisms;
- impurity ion penetration in the polymer electrolyte membrane: impurity ions penetrating through to within the polymer electrolyte membrane can reduce the diffusion coefficient of water in the membrane and can increase the water transfer coefficient. This prevents water from being uniformly distributed through the membrane and raises Ohmic losses. Sources of impurity ions include impure reactant gas feeds, corroded materials in the fuel cell stack or reactant supply system, fittings, tubing or ions in the water or coolant supply
- anisotropic expansion: it is permissible that when the polymer electrolyte membrane swells anisotropically due to water uptake, the local through-plane conductivity can decay as diffusion pathways in the membrane are forced to collapse.

Efficiency Losses and Catastrophic Cell Failure – Loss of efficiency and catastrophic cell failure can be induced when the strength and stability of fuel cell materials are degraded irreversibly by mechanical or chemical attack.

- Mechanical attack: thermal hotspots can form in regions of the cell for example at the beginning of rib areas where current enters the GDL from the BPP, regions where there are high reaction rates or spots of high compression. Other factors include manufacturing defects that give rise to irregularities in the electrolyte membrane. Thermal hotspots result in the electrolyte membrane failing mechanically and the formation of pinholes. Other factors include environmentally-induced vibration which can induce fractures in rigid elements such as the BPP.
- Chemical attack: susceptibility to chemical attack of polymer electrolyte membrane can occur due to the presence of defects in the polymer groups. End groups can interact with active radicals, resulting in the chemical degeneration of the membrane.

FAILURE ANALYSIS SUMMARY

Table 1a and 1b summarises the full list of failure modes and causes compiled from the literature. Twenty-two faults are recognised which expand into forty-seven potential causes.

FAULT TREE ANALYSIS

As indicated in Tables 1a and 1b, the top events in the context of fuel cell performance degradation and failure reflect the five mechanisms listed in the introduction. The processes described in Table 1 subsequently allow the construction of a system of FT diagrams including five main diagrams for the top events and twenty-one transfer events.

The transfer events reflect self-contained, reoccurring mechanisms that can contribute towards inducing other mechanisms and which ultimately lead on to performance degradation or cell failure. Figures 1 to 5 illustrate the five top events. The FT diagrams for all of the transfer events are not illustrated here, but summarised in Table 2. As an example, however, transfer event 20 – loss in dynamic pressure in BPP channels – is given in Figure 6. A description of all the basic events in the system of fault trees is given in the appendix. Here, the four most frequent transfer events are discussed, in descending order of frequency in the complete system of FT diagrams.

Uptake of Water – Table 2 reveals that the uptake of water in the ionomer membrane is the most commonly occurring process in all the events that lead to the five top events. Water uptake is an inherently occurring process that permits the mobility of protons from anode to cathode, however, it is evident that its occurrence is also conducive of events that contribute towards the four loss mechanisms and catastrophic cell failure. Water uptake can cause the membrane to swell anisotropically, depending upon local fluid-dynamic properties of the reactant gases passing either side of each cell and therefore the local current density as well. For the regions where swelling is most extensive, the expansion of the ionomer can cause the interfacial contact forces between layers to increase, thereby resulting in localised spots of high compaction. These regions can become thermal hotspots, where subsequent punctures in the membrane are likely to develop. The ensuing pinhole formation leads on to efficiency losses or indeed catastrophic cell failure. Simply the repeated swelling and contraction of the membrane due to the water uptake cycles can precipitate membrane puncture.

Degradation / Failure Mode	Fuel Cell Component	Fault	Cause	References
D1. Increase of Activation Losses	Platinum catalyst	(1) Platinum agglomeration causing loss of EASA	(1) Repetitive on/off load cycling (2) High voltage induce at cathode equivalent to OCV due to residual hydrogen (3) Loss of carbon support (4) Solubility of platinum when cell is operated through hydrogen-air open circuit to air-air open circuit (5) Air impurities such as NO ₂ , SO ₂ and H ₂ S (6) Fuel impurities such as CO and CO ₂ (7) Chemical degradation of silicone sealant (8) Residual water in catalyst layers	[7] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18]
		(2) Platinum migration causing loss of catalyst material (3) Adsorption of atmospheric contaminants on platinum causing loss of EASA (4) Adsorption of fuel impurities on platinum causing loss of EASA (5) Loss of catalyst due to chemical attack and formation of silicone/oxygen/platinum particles (6) Deformation of catalyst structure by freezing and melting water, resulting in increased pore size and reduced EASA (7) Corrosion of carbon to support the current above that provided by the fuel when the cell is supplied with insufficient fuel to support the current drawn (8) Flooding caused by the accumulation and condensation of water vapour to induce two-phase flow (9) Loss of hydrophobicity in porous regions of the cell treated with hydrophobic material	(9) Fuel starvation (10) Partial coverage of hydrogen on catalyst sites (11) Localised flooding (12) Low flow rate of channel gases (13) Low pressure in gas flow channels (14) Flow-field geometry (15) Degradation of polymer electrolyte in catalyst layer due to impurity ions (16) Gradual loss of material due to repeated thermal cycling (17) Delamination caused by repeated thermal cycling (18) Damage to material caused by exposure to sub-zero conditions (19) Cell over-compression, impacting the GDL (20) Ionomer expansion on water uptake causing pores to collapse (21) Excessive ionomer loading (22) Formation of ionomer skins on catalyst layers during the standard decal/hot-press-transfer method (23) Presence of residual water from previous shut-down (24) Operation at sub-zero temperatures (25) Over-compression and inhomogeneous compression, induced during cell assembly or by warping of injection-moulded BPPs (26) Impedance to electron transfer due to passivating layer on SS surface (27) Coating defects such as pinholes and micro-cracks when coated with TiN (28) Degradation of conductive coating (29) Degradation of conductive polymer coating (30) Formation of polymer-rich boundary during injection-moulding process (31) Loss of membrane hydration (32) Replacement of protons by impurity ions causing decrease in the water diffusion coefficient and increase in water transfer coefficient (33) Anisotropic swelling of membrane causing the water diffusion coefficient to decrease	[19] [20] [19] [20] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44]
		(10) Impedance to transport attributable to presence of ionomer (11) Impedance to transport attributable to ice formation (12) Loss of porosity, increased flooding and reduced gas permeability (13) Loss of surface electrical conductivity (-) Loss of surface electrical conductivity		
		(14) Low electrical conductivity (15) Loss of proton conductivity		
D2. Increase of Mass Transportation Losses	Carbon support in catalyst layer			
	Porous and void regions of the cell; catalyst layers, GDLs, BPP flow fields			
D3. Increase of Ohmic Losses (D3)	Geometric structure of catalyst layer			
	GDL			
	Stainless-steel BPP			
	Coated stainless-steel BPP			
	Injection-moulded BPP			
	Polymer Electrolyte Membrane			

Table 1a: Summary of PEFC Failure Modes and Causes: Activation, Ohmic and Mass Transportation Losses

Degradation / Failure Mode	Fuel Cell Component	Fault	Cause	References
D4. Increase of Efficiency Loss, potentially leading to Catastrophic Cell Failure	Polymer electrolyte membrane	(16) Formation of cracks and pinholes	(34) Increased roughness of electrolyte membrane surface, inducing by sub-zero operating conditions (35) Mechanical stresses induced by thermal hotspots in regions of strong electrical contact (i.e., GDL and BPP shoulder), high compression, and high reaction rates (36) Defects during the manufacturing process (37) Peroxide and peroxide radical attack of polymer end groups (38) Repetitive swelling/contraction due to excursion of membrane to states of deep hydration and deep dehydration (39) Excessive pressure differential between anode and cathode gas supply	[30] [45] [46] [47] [48] [49]
	GDL/catalyst layer/membrane	(17) Delamination of layers	(40) Thermal cycling including exposure to sub-zero conditions	
	Catalyst layer	(18) Excessive adsorption of atmospheric and fuel impurities (19) Cracking	(41) Loss of contaminant tolerance	
	BPP		(42) Inhomogeneous compression (43) Mechanical shock/vibration (44) Irregularities in cell/stack construction (45) Low initial rigidity of polymer matrix	[38]
	Seal Polymer electrolyte membrane	(20) Warping (21) Gas leakage (22) Short circuit	(46) Oxidation of seals (47) Formation of electrical network due to mal-distribution of platinum within (self-humidifying) membrane	[17] [49]

Table 1b: Summary of PEFC Failure Modes and Causes: Efficiency Losses and Catastrophic Cell Failure

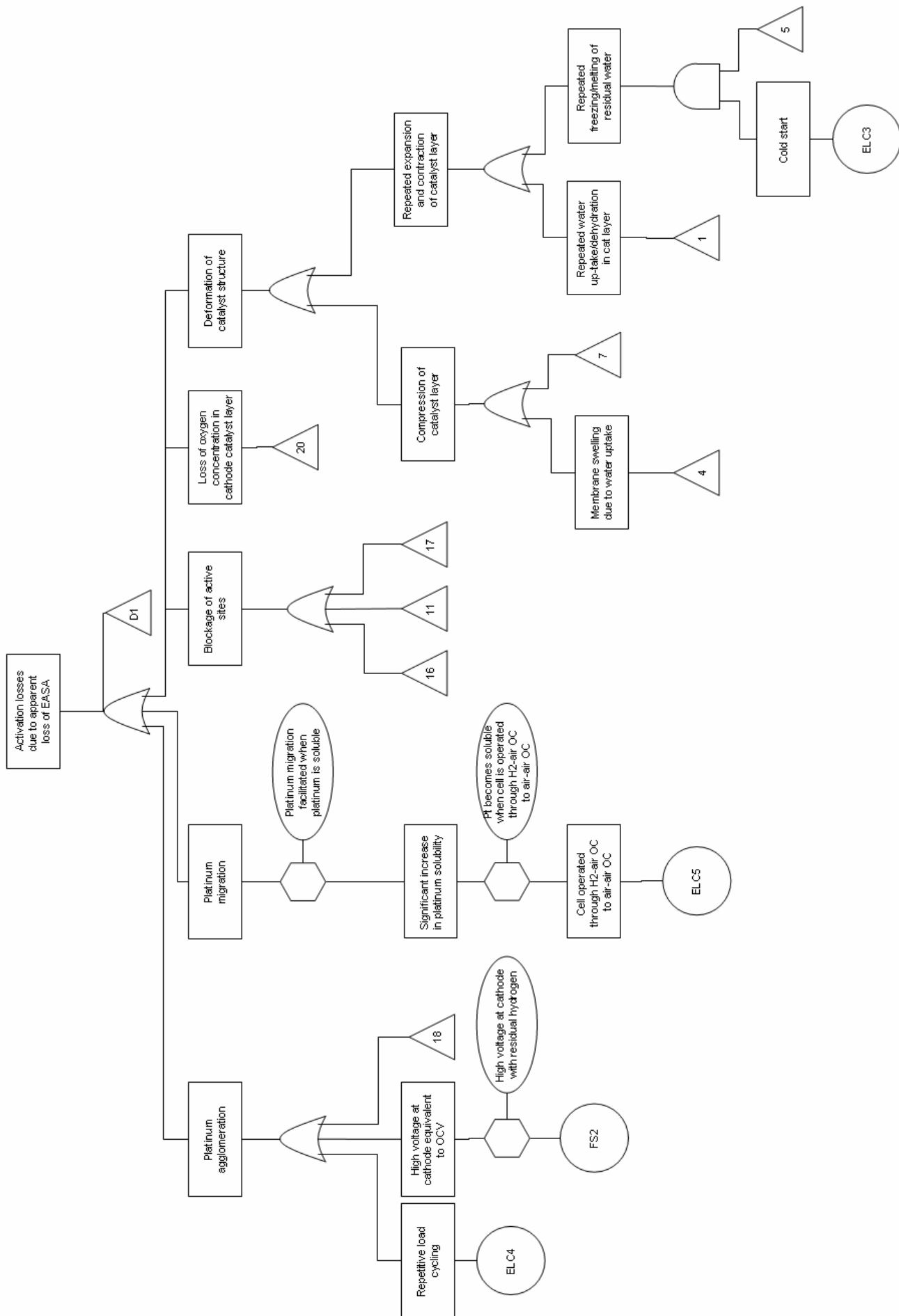


Figure 1: Fault Tree Diagram for Activation Losses

Figure 2: Fault Tree Diagram for Mass Transportation Losses

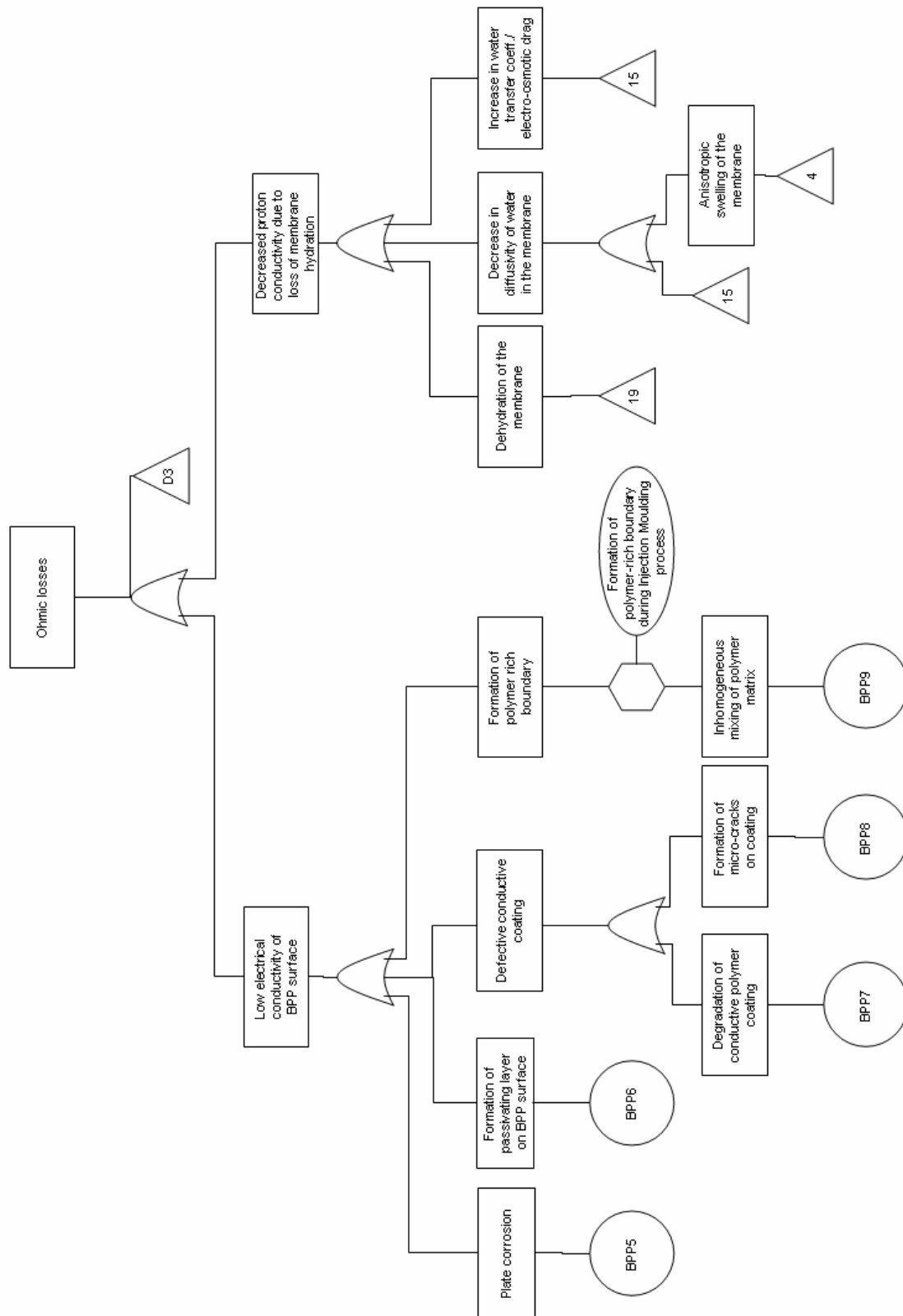


Figure 3: Fault Tree Diagram for Ohmic Losses

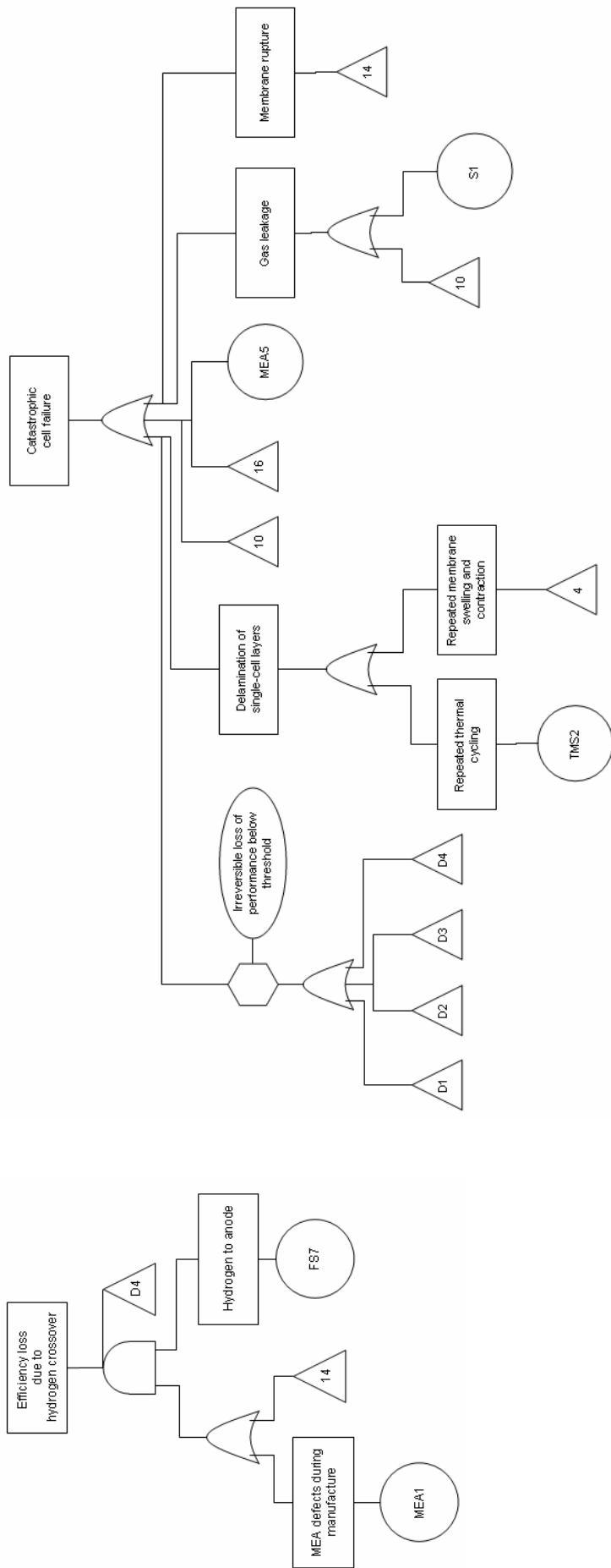


Figure 4: Fault Tree Diagram for Efficiency Losses

Figure 5: Fault Tree Diagram for Catastrophic Cell Failure

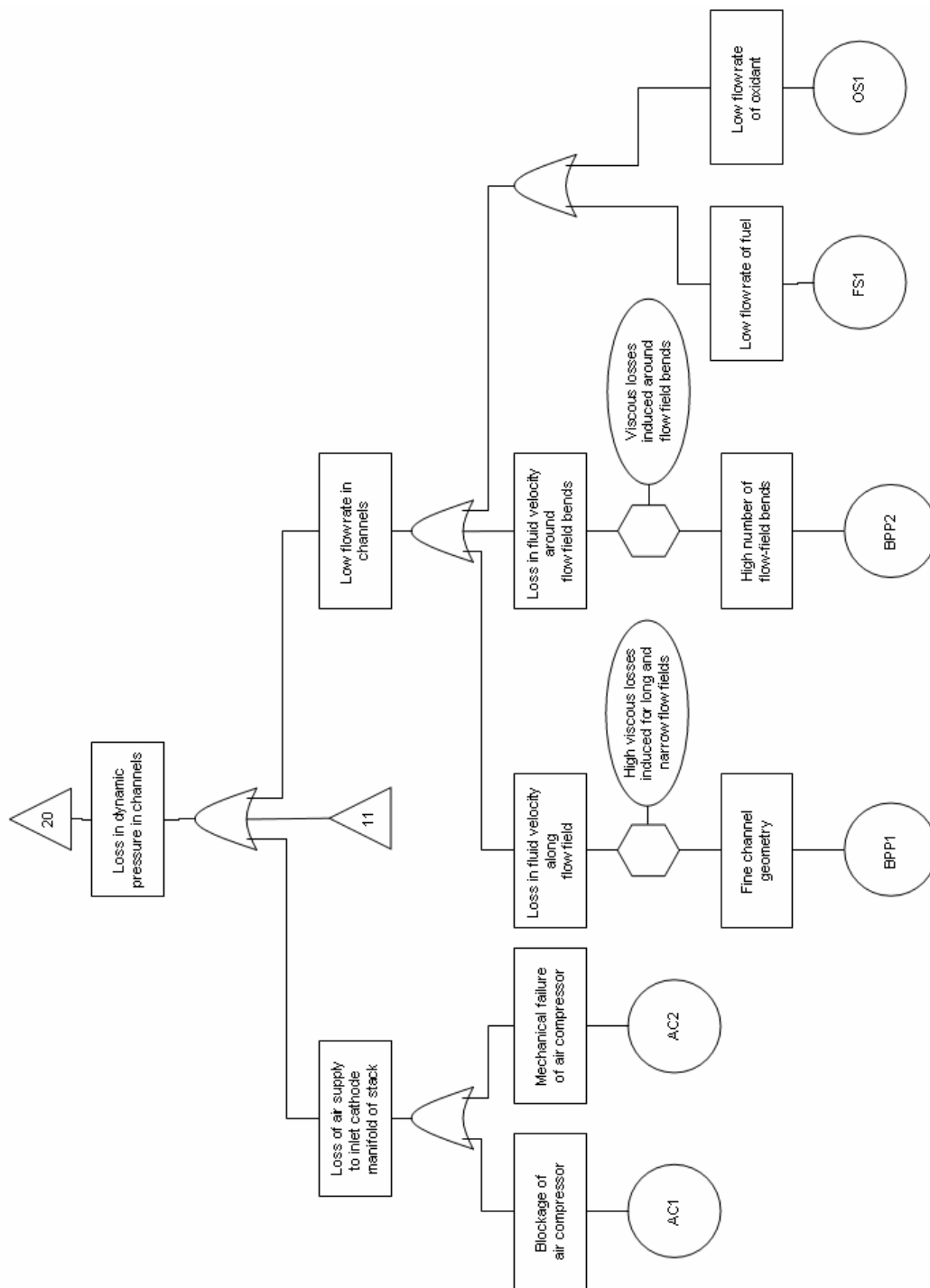


Figure 6: Fault Tree Diagram Transfer Event: Loss of Dynamic Pressure in BPP Channels

Event	Frequency	Top Events Affected				
		OL	AL	MTL	EL	CCF
4. Uptake of water in the ionomer membrane	10	X	X	X		X
20. Loss in dynamic pressure in channels	5	X	X	X		
3. Liquid water accumulation	4	X	X	X		X
7. Over-compression during stack assembly	4		X			X
1. Water production at the cathode	3	X	X	X		X
9. Collapse of GDL pores	3		X	X		
11. Cathode flooding	3		X	X		
13. Penetration of impurity ions	3	X			X	X
5. Residual water	2		X	X		
6. Increase in internal compaction force	2				X	X
8. High compression between GDL fibre and MEA	2				X	X
10. Cracking of BPP	2					X
12. Formation of hydrogen peroxide	2				X	X
14. Pinhole formation	2				X	X
15. Replacement of protons in the membrane by impurity ions	2	X				
16. Adsorption of impurities on active sites	2		X			X
17. Formation of silicone/oxygen/platinum particles	2		X	X		
19. Inadequate heat removal	2	X		X		
21. Inhomogeneous compression	2		X	X		X
2. Liquid water formation	1	X	X	X		X
18. Loss of carbon support	1		X			

Table 2: FT Transfer Events; frequency and top events affected

This mechanism of repeated swelling and contraction induces a number of other significant processes. The process can also cause a repeated compression of the catalyst layer, eventually resulting in the deformation of the catalyst layer structure which reduces the EASA and thereby results in the increase of activation losses. It also affects mass transportation losses, as evident in Figure 2. First, the swelling and contraction causes the hydrophobic material in the GDL to become mechanically stressed, causing it to erode. This then compromises the removal of liquid water, and therefore hastens the onset of cell flooding. Second, Figure 2 shows that if the ionomer membrane in the catalyst layer expands on water uptake, the pores and pore networks in the catalyst layer are likely to collapse, again, inducing an impedance to reactant transport through a decrease in porosity and permeability respectively. Swelling and contraction can also eventually precipitate catastrophic cell failure by causing the layers of a single cell to delaminate. Water uptake also facilitates the transport of impurity ions

through a leaching mechanism. This then promulgates towards increased Ohmic losses either by decreasing the diffusivity of water or by increasing the electro-osmotic drag in the ionomer membrane.

Pressure Losses in BPP Flow Fields– Table 2 reveals that channel pressure losses can induce ohmic, activation or mass transportation losses. Ohmic losses can be hastened if low pressure in the channels prevents liquid water to be removed by advection or convection, such that leached impurities remain within the cell with the liquid water. Carbon corrosion can occur in the presence of excess liquid water, which can thereby hasten platinum agglomeration and cause an eventual increase in activation losses. Pressure drops are coupled to a drop in reactant mass flow rate. If viscous forces in the flow fields induce pressure losses, the rate at which reactants are supplied also correspondingly drop, thereby inducing mass transportation losses, as evident in Figure 2. At the same time, since the partial pressure and therefore the concentration of oxygen in the cathode catalyst layer will drop, activation losses will increase.

Liquid Water Accumulation – The accumulation of liquid water is also a critical process. Predominantly, it leads on to cathode flooding which raises mass transportation losses and can also cause the pressure to drop in the reactant supply channels. Liquid water accumulation in the cathode catalyst layer also forces a decrease in the local concentration of oxygen, thereby inducing an increase in activation losses. Active sites in the catalyst layer become covered by films of liquid water, creating a barrier through which oxygen would have to diffuse. The degree of inaccessibility would increase with the degree of flooding in the catalyst layer. Since the uptake of water in the ionomer regions is augmented when equilibrated by liquid water [47], it is correspondingly coupled to the mechanisms already discussed.

Over-compression – Over-compression in a stack is also evidently a significant issue. It impacts the activation losses because it can cause a deformation of the catalyst layer structure, reducing the EASA as shown in Figure 1. Critically, however, it can induce catastrophic cell failure through different mechanisms. First of all, over-compression can cause bipolar plates to crack, which can also lead on to reactant leakage. In addition, it is possible to trace over-compression as a phenomenon that can also hasten the formation of thermal hotspots and punctures, as discussed.

DISCUSSIONS

The results from Table 2 provide an insight into where there is necessity to favourably reform some elements of fuel cell design, manufacturing and operational practices with the aim of retarding performance degradation and failure. These are discussed herein.

Membrane Mechanical Strength and Dimensional Stability – It is evident that the dimensional stability and the mechanical strength of the membrane are key

attributes which if improved can extend fuel cell survivability by curtailing the effects of repeated membrane swelling and contraction, and indeed by improving resistance to the formation of pinholes and punctures.

Water uptake is intrinsic to the way in which the membrane operates, but it is the effects of its expansion which can be problematic. The adjacent fuel cell layers have to absorb the expansion and thereby undergo further localised compaction which can compromise their internal structures with time. Adverse effects are also apparent at the layer interfaces, which repeatedly transmit the forces due to expansion and also become regions that are mechanical weak with respect to time. Layers are likely to delaminate from one another and hydrophobic coatings are likely to degenerate. The mechanical strength can dictate the susceptibility to pinhole formation, especially in regions of thermal hotspots and especially for thin membranes purposely employed for improved and more uniform hydration.

Membrane expansion could be restrained by the compaction of the cell. However, it has already been argued that the stresses actually experienced in operating fuel cells are likely to be less than those required to sufficiently constrain the membrane [50]. Reinforcing the membrane structurally however could provide a more robust method. Some methods recently explored in the literature include dispersing PTFE fibrils within membranes (fibril content of 2.7 wt.%), termed Flemion Rf2 membranes [51], dispersing carbon nanotubes within Nafion membranes (CNT content of 1 wt.%) [52] and the use of porous, expanded PTFE (ePTFE) sheets that are bonded with membrane resins on both sides [53,54,55].

It is arguable that the mechanical properties of conventional membranes become key issues because of the large fraction to which they absorb water [56]. Therefore, if the dependence upon the uptake of water and its subsequent interaction with end groups to produce proton conductivity can be mitigated then membrane durability can ultimately be extended. One possible way is by modifying existing membranes to enable self-humidification and another is through radical re-engineering of polymer systems.

Maintaining Vapor-Phase Water – Through the fault tree analysis it is possible to identify that liquid water accumulation can induce mechanisms that increase ohmic losses, mass transportation losses, activation losses and can indeed catastrophic cell failure. The formation of liquid water is in part permitted by operating at low temperatures, i.e., 80 °C or below. The saturation vapour pressure at these temperatures is below 0.5 atm, which means that the relative humidity of the reactant gases can quickly reach and exceed unity, particularly if they are already supplied close to full humidification. This is especially true for the cathode side where water is produced. When the reactant gases become over-saturated, the vapour-phase water undergoes a phase change through condensation to form liquid water.

Condensation causes a release of latent heat and the resulting liquid-phase limits the amount of heat energy that can be removed from the cell in the form of sensible heat. This commands the use of complex thermal management systems to maintain the operating temperature. Operating above 100 °C, however, raises the saturation vapour pressure, enhancing the capacity to which reactant gases can hold high concentrations of water in vapour phase, which thereby delays the onset of liquid water formation and cell flooding. In addition, since water remains in the vapour phase, the latent heat is retained and more heat energy can be removed from the cell in the form of sensible heat, i.e., through steam. Operating at higher temperatures commands the development of higher temperature membrane technology, including corresponding screening and diagnostics capabilities.

Flow-Field Design – It has long been known that flow field design alone can strongly dictate the performance of the fuel cell. The flow field design essentially governs the uniformity to which reactant gases are supplied over the active cell area and the extent to which continuous pathways can be maintained for the removal of unspent gases, unimpeded by liquid water. As such, it is evident that the performance of the cell can be improved by optimizing the fluid dynamics of the flow within the flow fields independently of MEA development. This area has therefore already received much attention and resulted in various patents [57]. There are generally two dominant flow field configurations, namely parallel and serpentine. These configurations can be applied in the form of single or multiple channels and the flow fields can indeed be either continuous or interdigitated (discontinuous).

In the general case, pressure losses along single channels can be minimised if the overall flow field path length is kept short and if the number and abruptness of bends are minimised. Indeed recent studies have highlighted that uniform flows with typically small pressure drops can be established particularly for flow fields with straight, parallel channels [58] and for serpentine channels that have shorter path lengths and larger numbers of multiple channels rather than longer path lengths and fewer channels within the same cell area [59]. Such measures can ensure that the channels remain pressurised along their entire lengths and reduce the chance of flooding whereby high upstream pressures and low downstream pressures are established causing liquid water to be pushed down and accumulate in downstream regions of the flow fields [60]. Liquid water can inevitably accumulate in any region where the gas-phase flow becomes stagnant, particularly in abrupt 180° bends often seen for serpentine flow fields [61,62,63].

The optimization of the flow field, however, must be conducted without neglecting the properties of the GDL. In effect, both of these materials serve similar purposes from a mass transportation perspective in terms of ensuring that the active area of the MEA is persistently covered by reactant gases, and in terms of ensuring that unspent gases and excess water are constantly removed. The flow field geometry in effect therefore has

to be matched with the porosity and the permeability of the GDL [64,65].

Manufacturing and Quality Control – Manufacture and quality control intrinsically dictate the performance, reliability and safety of fuel cells and fuel cell stacks. At present, fuel cell manufacturing comprises of several discrete low-volume processes primarily based on scaled-up laboratory fabrication methods and heavy reliance on manual intervention, particularly for overall stack assembly [66]. Many of the mechanisms detailed in the fault tree diagrams are induced because of these current practices, for example, excessive ionomer loading in the catalyst layers and over-compression during stack assembly. Fuel cell manufacturing should incorporate processes capable of supporting highly-automated high-volume, low-cost manufacture which ensure repeatability with accuracy in the context of exacting dimensions. At present, the entire area of fuel cell technology development is still very much in a fluid state, and many of the current low-volume manufacturing processes employed reflect this. It is possible, however, to foresee that some of the susceptibilities to degradation and failure that are introduced to fuel cells via manufacturing could be minimised or eradicated altogether by progressively applying manufacturing processes and quality control practices that have become highly-developed - and proven their worth - in similar industries. These include the recording media, semiconductor, battery and photovoltaic industries [66].

CONCLUSIONS

The current work has focused on amalgamating the reported findings with respect to design, manufacturing and operational aspects that impact fuel cell performance and longevity, and also on translating these into a hierarchical structure of events in the form of fault tree diagrams. The general conclusions from the current study are as follow;

- A literature review has identified that fuel cells are susceptible to at least twenty-two faults induced by forty-seven general causes.
- The information gathered from literature has been translated into fifty-two basic events and a system of fault trees that reflect how basic events culminate in performance degradation and cell failure.
- The five top events for the system of fault trees are; activation losses, mass transportation losses, Ohmic losses, efficiency losses and catastrophic cell failure.
- In constructing the fault trees, twenty-one reoccurring dominant mechanisms have been identified that hasten performance degradation and cell failure. In the system of FTs these appear as transfer events.
- The most frequent four dominant mechanisms have been traced and discussed in terms of the mitigation

mechanisms that can be implemented to curtail their effects on performance degradation and cell failure. These are summarised in Table 3.

Event	Mitigation Mechanisms	References
The uptake of water in the ionomer membrane	<ul style="list-style-type: none"> • Improving overall dimensional stability and mechanical strength of current membranes <ul style="list-style-type: none"> • Dispersion of PTFE fibrils • Dispersions of CNT • Use of ePTFE thin sheets • Self-humidifying membranes <ul style="list-style-type: none"> • Dispersions of silicone oxide-supported Pt particles • Developing alternative polymer systems 	[51] [52] [53,54,55] [54] [56]
Loss in dynamic pressure in channels	<ul style="list-style-type: none"> • Minimising overall flow-field path • Minimising number and abruptness of flow-field bends • Optimising cross-sectional channel geometry • Tapering flow fields • Matching GDL to BPP flow field design 	[58] [59] [67,68,69] [70,71] [64,65]
Liquid water accumulation	<ul style="list-style-type: none"> • Operation at higher temperatures (>100 °C) • Use of high-temperature membranes 	[72,73] [74,75,76]
Over-compression during stack assembly	<ul style="list-style-type: none"> • Applying manufacturing practices capable of repeatability with accuracy in the context of exacting dimensions • Adoption of proven practices from similar industries • Applying statistical quality control practices to manage continual process improvement 	[77]

Table 3: Summary of mitigation mechanisms for common fault-inducing events

From a strategic point of view, the current analysis identifies the following areas of fuel cell research and development that are ultimately critical to enabling fuel cell marketability, and which are strongly related to reliability and performance;

1. Membrane development:
 - alleviating the necessity for water retention in the polymer membrane
 - improving the mechanical strength and dimensional stability of the polymer membrane
2. BPP development:
 - improving the homogeneity of flows through channels and porous media
 - establishing BPP materials, material preparation and treatment processes for high mechanical

strength, high electrical conductivity and low susceptibility to chemical attack

3. Manufacturing and quality control:

- adopting and preparing scalable manufacturing processes and practices from similar established industries
- establishing repeatable precision processes
- adopting quality control practices

It is evidently clear that both novel developments for membrane and BPP materials have to conform with concepts of high-volume and low-cost mass reproducibility from the outset.

The current work has focused on a qualitative assessment of factors that govern fuel cell performance and reliability. Future work will focus on populating the fault tree with reliability data in order to evaluate the statistical significance of failure events and to evaluate the minimal and sufficient conditions needed to induce cell degradation or indeed failure.

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CONTACT

Pratap Rama
The Department of Aeronautical and Automotive Engineering
Loughborough University
Leicestershire
LE11 3TU
United Kingdom
Email: p.rama@lboro.ac.uk

APPENDIX

BASIC EVENT	DESCRIPTION
Electronic Load Control	
ELC1	Stack operating current > 0A
ELC2	High operating stack current density
ELC3	Cold start
ELC4	Repetitive load cycling
ELC5	Cell operated through H ₂ -air open circuit to air-air open circuit
Humidity Control	
HC1	Relative humidity of reactant supply approaching unity (RH ≤ 1)
HC2	Humidification of fuel supply to anode
HC3	Humidification of oxidant supply to cathode

Mechanical Components	
AC1	Air compressor blockage
AC2	Mechanical failure of air compressor
CP1	Mechanical failure of coolant pump
HS1	Impurity ions released from FC hardware and system piping upstream of stack
GDL1	Irregularity in GDL carbon fibre structure
S1	Chemical degradation of silicone seals
Thermal Management System	
TMS1	Coolant flow rate set too low by thermal management system
TMS2	Repeated thermal cycling
Bipolar Plate	
BPP1	Fine channel geometry of BPP design
BPP2	High number of flow-field bends in BPP design
BPP3	Warping of injection-molded BPP
BPP4	Low thermal conductivity of designed BPP
BPP5	Corrosion of stainless steel BPP under acidic and high humidity FC conditions
BPP6	Formation of passivating layer on stainless steel BPP surface
BPP7	Degradation of conductive polymer coating of coated stainless steel BPP
BPP8	Formation of micro-cracks on TiN coated stainless steel BPP
BPP9	Inhomogeneous mixing of polymer matrix and conductive filler for polymeric injection-molded BPP
Fuel Supply (to anode)	
FS1	Low flow rate set for fuel supply to anode
FS2	Un-purged shut-down of anode side
FS3	Low pressure set for fuel supply to anode
FS4	Crossover of impurities in the fuel supply
FS5	Impurities in the fuel supply to anode
FS6	Crossover of fuel to cathode side
FS7	Fuel supply to anode
FS8	High flow rate of fuel supply to anode
Oxidant Supply (to cathode)	
OS1	Low flow rate set for oxidant supply to cathode
OS2	Un-purged shut-down of cathode side
OS3	High pressure set for fuel supply to cathode
OS4	Crossover of impurities in the oxygen supply
OS5	Crossover of oxygen to anode side
OS6	Air bleed to anode side
OS7	Oxidant supply to cathode
Stack Assembly	
SA1	Over-compression during stack assembly
SA2	Inhomogeneous compaction during stack assembly
Environmental Effects	
E1	Sudden mechanical shock transmitted to FC powerplant via chassis
E2	Vibration transmitted to FC powerplant via chassis
E3	Sub-zero operating environment
E4	Atmospheric impurity ions in the oxidant supply to cathode (charged)
E5	Atmospheric impurities in the oxidant supply to cathode (zero valence)
MEA	
MEA1	Defects during membrane polymerisation process
MEA2	Excessive ionomer loading in catalyst layer during MEA manufacture
MEA3	Formation of ionomer skins on catalyst layers during the standard decal/hot-press transfer method
MEA4	Available EASA of platinum catalyst
MEA5	Short circuit due to platinum network in self-humidifying membranes