Report on the reliability test program for the simulation validation

D5.1

PROSOFC

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Contact Person	Vincent Lawlor	Organization	AVL Austria GmbH
Phone	+43 664 8523895	E-mail	Vincent.lawlor@AVL.com

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Table of Contents

List of Figures

List of Tables

Authors

Name, Partner	E-mail
Vincent Lawlor, AVL	Vincent.lawlor@AVL.com

1 Failure mode identification and rating

1.1 Introduction

The main focus of the activities in WP5 are the establishment of a solid basis for the development of the new cell design and its final assessment, regarding required **reliability and durability levels** needed for subsequent **industrializations**.

Relevant failure modes are to be identified, based on the experience made in other projects, like ASysI, DESTA, METSAPP, CATION, SOFC-Life and SchIBZ. This process is carried out in expert rounds, **led by AVL**. Based on the definitions from task 5.1 the failure modes will be rated and the most critical ones will be chosen for the inclusion into the simulation tasks. It was decided that since PROSOFC is concerned with cell development **that mechanical type failure modes** should be **scrutinized** on the cell and interconnect layers.

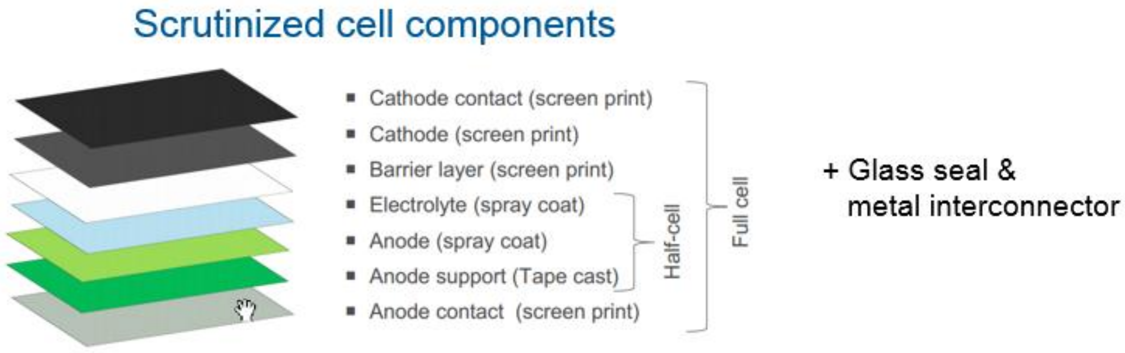


Figure 1: Scrutinized components in PROSOFC

For those failure modes a review of the known failure mechanisms will be performed and they will be linked to specific (operating) parameters, which should form the **link between simulation and tests**.

1.2 Methodology

1.2.1 The AVL Load Matrix Process

With the aid of a state of the art methodology originating from AVLs **automotive branch** called AVL **Load Matrix™,** a specifically tailored and well-balanced, cost optimized failure mode orientated validation test program can be developed. For engine development AVL has developed the Load Matrix™ tool, which systematically develops validation test programs and is a **used by several OEMS**.

In general the SOFC community focuses on developing **Full Physical Models**, which are an essential tool for initial functional development, especially for SOFCs. However, they are inherently **limited** with respect to reliability and durability themes, since they are reliant on precise material data, computational resources and pre-processing, calculation and post-processing time. AVL uses its **Relative Damage Approach** and Load Matrix™ tool in order to offer a complete service **for designing functional, durable and reliable systems**. In AVL's approach Full Physical Models and Relative Damage Models offer the following

The full physical model will provide:

- 3D representation of damage distribution for a selected stressor history =>
  - Design rules, sensitivities and parameters / location(s)
  - Optimization demands
  - Concept comparisons

The Relative Damage Approach will provide (in an effective way relative to a full physical model):

- Acceleration factors of all conditions considered relative to the reference duty cycles =>
  - Identification of most demanding conditions
  - Operation rules for minimization of stressor duties
  - Evaluation of system demonstrable reliability potential relative to strength scatter of manufactured components and assemblies
  - Balancing of entire test programs for all failure modes under consideration

An illustration depicting how AVL's load matrix is coupled to hardware and coupled CFD & FEA simulations in order to design validation test programs is shown in Figure 2

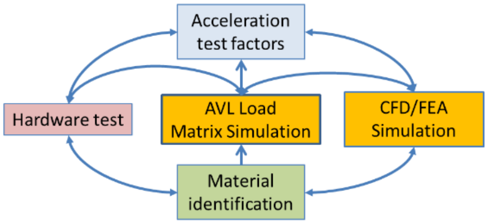
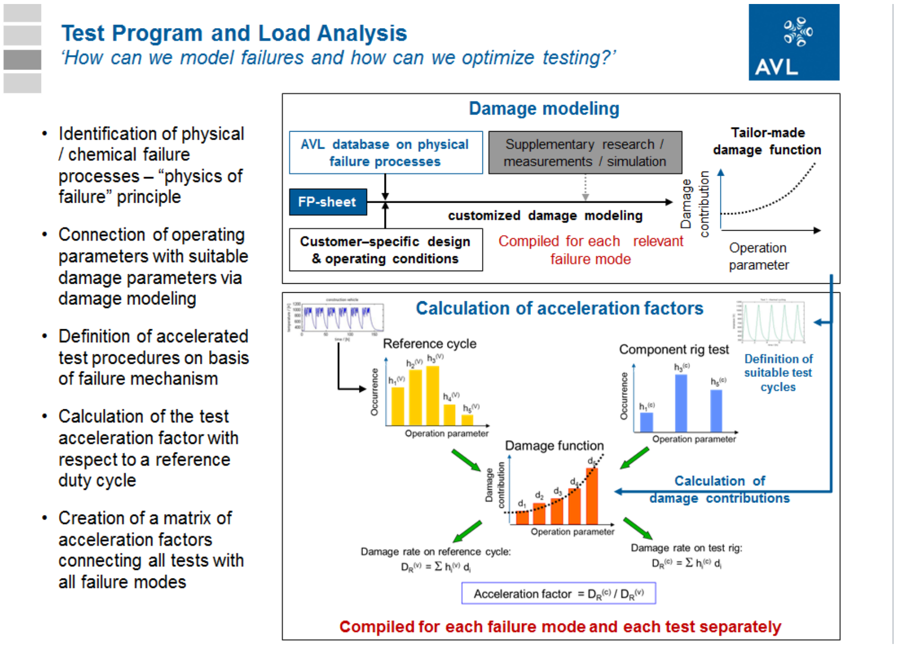


Figure 2: Load matrix at the heart of the front loading and reliability and durability validation test program design and execution.

The main idea behind the Relative Damage Approach, in combination with the Usage Space Analysis, is the definition of validation relevant **Reference Cycles** by the Usage Space Analysis and the subsequent calculation of **Acceleration Factors**, achieved by test cycles assessed relative to these Reference Cycles. As the Relative Damage Approach, calculates Acceleration Factors relative to the Reference Cycles, many **model parameters required by the full physical model can be eliminated**, without losing the consistency with the full physical model.

Figure 3 shows how **damage models** are used within the Load Matrix™ methodology in order to **define tailor made validation test programs.** The primary purpose of the damage model is to connect all relevant operating parameters to a suitable damage parameter, with consideration of the physical or chemical damaging mechanism. The damage parameter for damage accumulation representation is selected such that the **provoked damage may be accumulated** and furthermore quantified in a meaningful way. A key requirement is that the damage accumulation quantification should be computable based on the range of physical and chemical conditions induced by **tolerable stack or Balance of Plant (BOP) operation**. The lower part of Figure 3 shows how the models are used in the further process. Initially, since boundary conditions, secondary influences and interactions with other failure modes need to be considered, this information is carefully scrutinized in order to **define appropriate test cycles**. Test cycles are designed that load as many failure modes simultaneously, in order to **minimize costs and effort**, while not imposing conditions that accelerate any damage mode too fast or induce unsuitable or un-advised conditions for SOFC operation. Furthermore, measures may be taken to isolate damage modes within test cycles by reducing the stack functionality or avoiding certain operating conditions. Normally, multiple failure modes are simultaneously stressed, even when not the specific target of a test. Thus **every test,** even those producing low acceleration factors for any given failure mode, **contributes to the overall statistical evaluation**.



Test Program and Load Analysis

'How can we model failures and how can we optimize testing?'

- Identification of physical / chemical failure processes – "physics of failure" principle
- Connection of operating parameters with suitable damage parameters via damage modeling
- Definition of accelerated test procedures on basis of failure mechanism
- Calculation of the test acceleration factor with respect to a reference duty cycle
- Creation of a matrix of acceleration factors connecting all tests with all failure modes

Damage modeling

AVL database on physical failure processes

Supplementary research / measurements / simulation

FP-sheet

customized damage modeling

Customer–specific design & operating conditions

Compiled for each relevant failure mode

Tailor-made damage function

Calculation of acceleration factors

Reference cycle

Component rig test

Definition of suitable test cycles

Damage function

Calculation of damage contributions

Damage rate on reference cycle: $D_R^{(v)} = \Sigma h_i^{(v)} d_i$

Damage rate on test rig: $D_R^{(c)} = \Sigma h_i^{(c)} d_i$

Acceleration factor $= D_R^{(c)} / D_R^{(v)}$

Compiled for each failure mode and each test separately

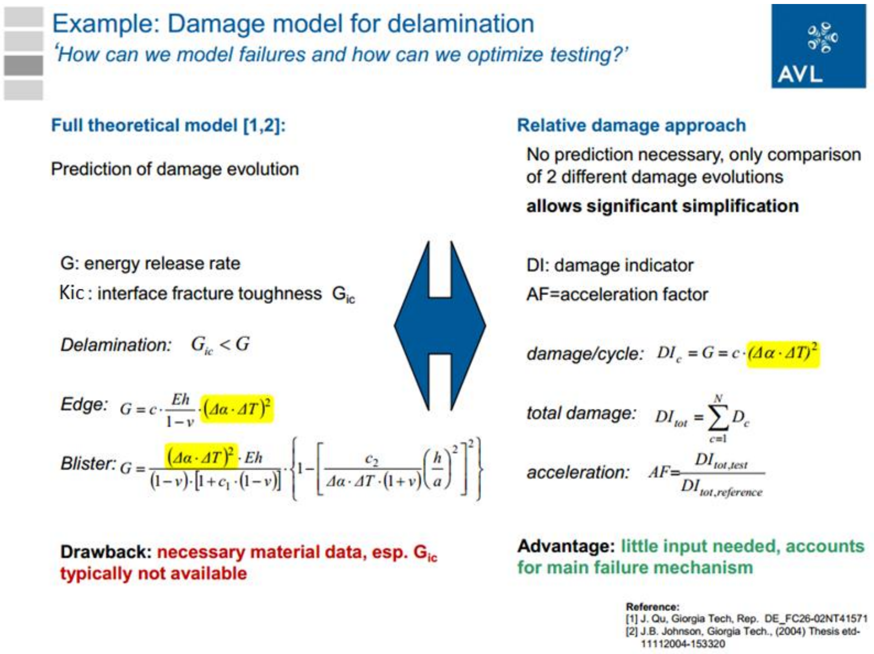
Figure 3 The Load Matrix™ methodology description

In the Load Matrix™ approach it is **not predicted when the subject will fail**, but rather it is used to **determine a validation program's features** that inherently provide the greatest guarantee with a **sufficiently high confidence** that the tested **subject will fulfill reliability and durability targets** in real life usage, with minimum costs and effort. Whether or not the tested subject fulfills these requirements is not evident until the subject has completed and passed the test program.

Figure 4 shows the formulation of AVL's simplification of the SOFC layer delamination issue. How this simplified in damage model approach is complementary to the full physical damage model can be visualized by following **example** for assessing the damage caused by the **delamination of two layers**. It should be noted that the SOFC is comprised of numerous sintered µm thick layers. The obvious damage parameter would appear to be the delaminated area. However, this parameter is very computationally intensive to calculate, since it strongly depends on the local geometry. A more **suitable parameter** would be the **fracture toughness** of the layer to layer interface. The material's fracture toughness value reduces as a function of time and load cycle. This measurable physical characteristic is responsible for the eventual layer delamination. Yet this **parameter is typically not available** for the material combinations associated with SOFCs, thus the energy release rate for crack growth is calculated. In this case the energy input due to the load cycle and temperature variation leads to a stress within the material. Assuming that micro-cracks, flaws or other sources for eventual delamination are already in the material, the stress is reduced by energy release via crack growth. The **total energy release** is then a representative **measure for the SOFC layer delamination**. Figure 4 shows the formulation of this valid simplification, noting that the interface fracture toughness Kic and critical energy release criterion Gic are related via [2]

$$\mathrm{K_{ic}} = \sqrt{E.G_{ic}} \quad (1)$$

where E is the material's Young's modulus. It should be noted that correlations provided by measurements or indeed full physical models may also be used in order to establish acceleration factors.



Example: Damage model for delamination

'How can we model failures and how can we optimize testing?'

Full theoretical model [1,2]:

Prediction of damage evolution

G: energy release rate

Kic : interface fracture toughness G_{ic}

Delamination: $G_{ic} < G$

Edge: $G = c \cdot \frac{Eh}{1-\nu} \cdot (\Delta\alpha \cdot \Delta T)^2$

Blister: $G = \frac{(\Delta\alpha \cdot \Delta T)^2 \cdot Eh}{(1-\nu) \cdot [1 + c_1 \cdot (1-\nu)]} \cdot \left\{ 1 - \left[\frac{c_2}{\Delta\alpha \cdot \Delta T \cdot (1+\nu)} \left(\frac{h}{a} \right)^2 \right]^2 \right\}$

Drawback: **necessary material data, esp. G_{ic} typically not available**

Relative damage approach

No prediction necessary, only comparison of 2 different damage evolutions

allows significant simplification

DI: damage indicator

AF=acceleration factor

damage/cycle: $DI_c = G = c \cdot (\Delta\alpha \cdot \Delta T)^2$

total damage: $DI_{tot} = \sum_{c=1}^{N} D_c$

acceleration: $AF = \frac{DI_{tot,test}}{DI_{tot,reference}}$

Advantage: **little input needed, accounts for main failure mechanism**

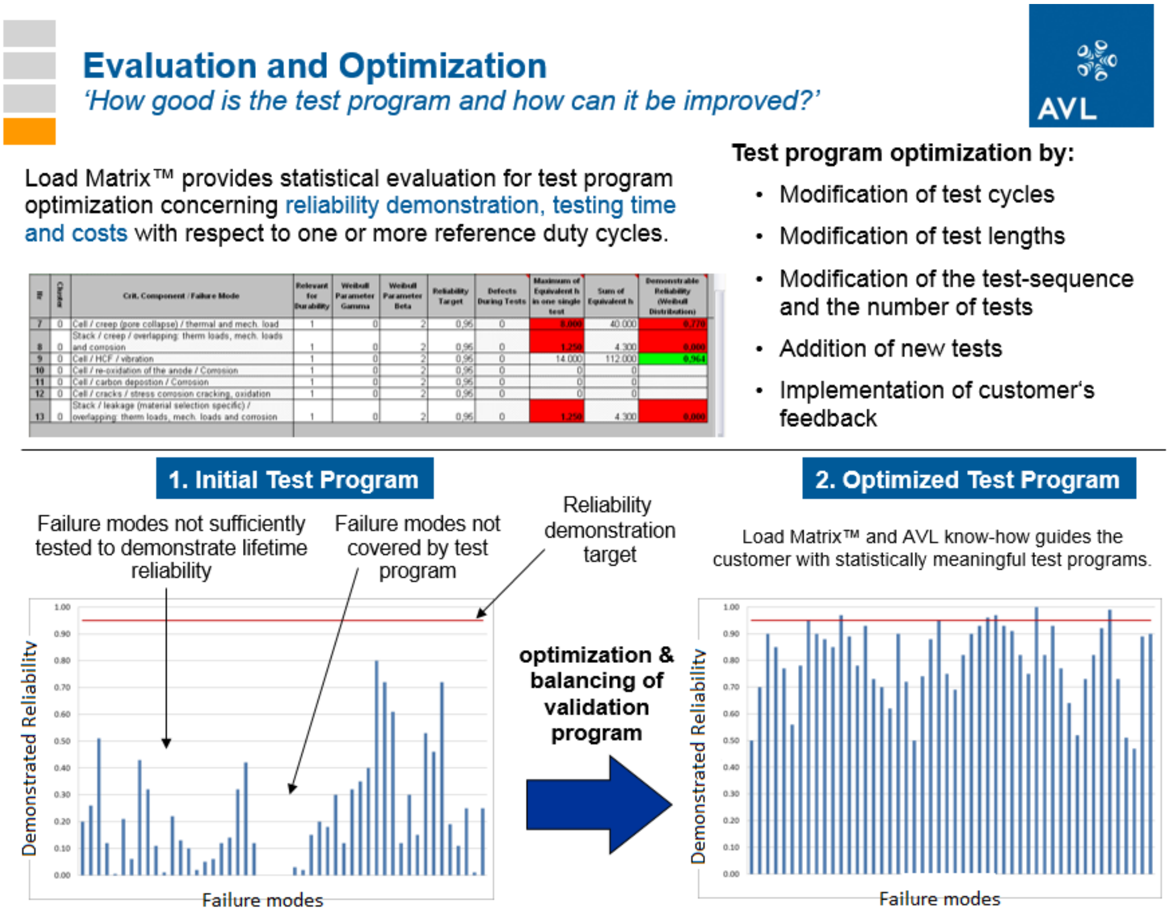
Reference:
[1] J. Qu, Giorgia Tech, Rep. DE_FC26-02NT41571
[2] J.B. Johnson, Giorgia Tech., (2004) Thesis etd-11112004-153320

Figure 4 Formulation of AVL's simplification of SOFC layer delamination

In the second step, a **quantification of the test acceleration is performed**. Initially this is performed for the reference cycle and every designed test cycle's damage accumulation for each failure mode is compared. The ratio of these values provides the **acceleration factor** of any given test. The treatment of linear as well as nonlinear damage evolutions is possible with this method within AVL's Load Matrix™ software tool.

The determination of **"relative damage" is a major aspect to the modeling** within the Load Matrix™ process. This approach **allows major simplifications** of the models. In the aforementioned example for a delamination damage parameter, a prediction of the actual detached area is a complicated process. The local energy release rate in the microstructure needs to be compared to the local fracture toughness, which changes over time. In the Load Matrix™ these steps can be neglected, because in the relative approach exactly the same component is virtually subjected to different loads. Thus the material response to the energy release rate will be the same for comparable load cases, but with different time constants. Therefore, it is **sufficient to compare the energy release rate**, because all **further calculation steps would be the same** for both load cases and **would not change the ratio** any more. Due to the relative approach even most of the **material parameters cancel themselves out**, which allows damage comparison with very little input needed. In the open literature there are many models and test data for various failure modes that can be used as inputs to the relative models. Because this methodology has been developed over many years on a technology that is fundamentally better understood and with much field data **AVL has an insight into developing accelerated testing protocols** that will not be available elsewhere.

AVL uses this powerful **FEA tool and work flow** in order to **pin point the location** where the **damage is most likely to occur**. Then the operating conditions at this location can be either recoded on a test bed or simulated in order to load the simplified load matrix models. The time, cost and effort savings achieved by AVL's Load matrix™ Relative Damage Calculation methodology and powerful Detailed Modeling simulation chain provide the SOFC community with unrivaled well rounded service that facilitates a **functional reliable and durable Stack & BOP design**. Both modeling methods when compared can provide a degree of validation when testing is not afforded or readily performed. AVL strongly recommends and performs proportionally targeted validation efforts within development projects. The approach is illustrated in Figure 5.



Evaluation and Optimization

'How good is the test program and how can it be improved?'

Load Matrix™ provides statistical evaluation for test program optimization concerning reliability demonstration, testing time and costs with respect to one or more reference duty cycles.

Nr	Cluster	Crit. Component / Failure Mode	Relevant for Durability	Weibull Parameter Gamma	Weibull Parameter Beta	Reliability Target	Defects During Tests	Maximum of Equivalent h in one single test	Sum of Equivalent h	Demonstrable Reliability (Weibull Distribution)
7	0	Cell / creep (pore collapse) / thermal and mech. load	1	0	2	0,95	0	8.000	40.000	0,770
8	0	Stack / creep / overlapping: therm loads, mech. loads and corrosion	1	0	2	0,95	0	1.250	4.300	0,000
9	0	Cell / HCF / vibration	1	0	2	0,95	0	14.000	112.000	0,964
10	0	Cell / re-oxidation of the anode / Corrosion	1	0	2	0,95	0	0	0	
11	0	Cell / carbon depostion / Corrosion	1	0	2	0,95	0	0	0	
12	0	Cell / cracks / stress corrosion cracking, oxidation	1	0	2	0,95	0	0	0	
13	0	Stack / leakage (material selection specific) / overlapping: therm loads, mech. loads and corrosion	1	0	2	0,95	0	1.250	4.300	0,000

Test program optimization by:

- Modification of test cycles
- Modification of test lengths
- Modification of the test-sequence and the number of tests
- Addition of new tests
- Implementation of customer's feedback

1. Initial Test Program

Failure modes not sufficiently tested to demonstrate lifetime reliability

Failure modes not covered by test program

Reliability demonstration target

optimization & balancing of validation program

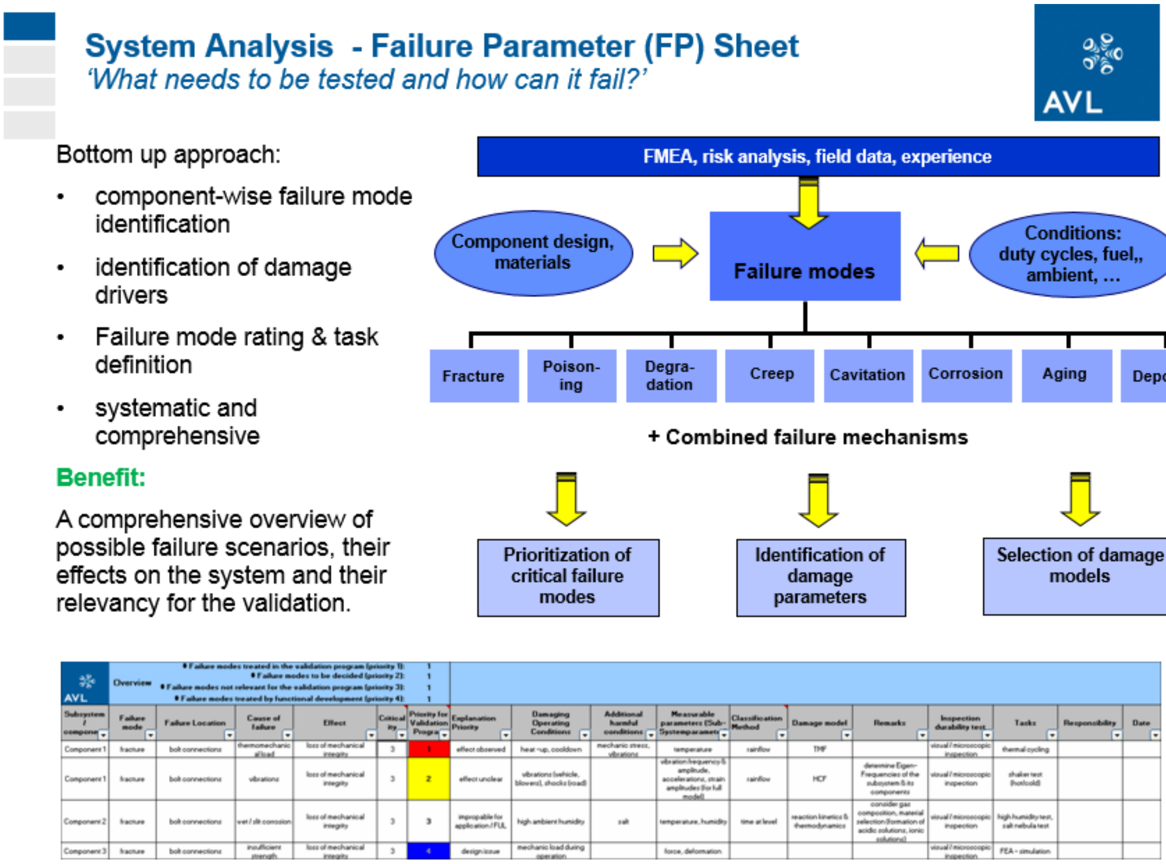
2. Optimized Test Program

Load Matrix™ and AVL know-how guides the customer with statistically meaningful test programs.

Figure 5: From initial test programs to optimized validation test programs demonstrating optimized strategy for demonstrating reliability.

1.2.2 Process kick off AVL's Failure Parameterization (FP) Sheets

Before any modelling takes place the SOFC system and **boundary operating conditions** need to be firmly established. Each SOFC system and its intended use must be specifically analyzed. For example there is no point in modelling sulfur poisoning on the anode if a desulfurizer and adequate maintenance plan is being used. Furthermore, if for example, it is known that the anode is not redox tolerant then conditions that facilitate oxidation should be avoided. However, if for example the degradation of other components may cause oxidation as a consequence the **failure mode should be assessed at the source**. This is a key step is simplifying the problem at hand, by establishing **fixed boundary conditions** in order to maintain the operating conditions for a durable and reliable system. AVL uses **failure parameterization (FP) sheets**, which are completed with expert input in order to establish the key failure modes that need to have their reliability/durability be demonstrated as part of a validation test program. The basic information and sources for that information is shown in Figure 6, where **experts provide key information** which is documented in a systematic and tried and tested manner, which leads to a **final failure mode prioritization** based on AVL's criticality and failure mode priority scoring. The priority rating determines whether a failure mode should be applicable to the **next step of the process which is the modelling and test program optimization** procedure which has been discussed in the previous section.



System Analysis - Failure Parameter (FP) Sheet

'What needs to be tested and how can it fail?'

Bottom up approach:

- component-wise failure mode identification
- identification of damage drivers
- Failure mode rating & task definition
- systematic and comprehensive

Benefit:

A comprehensive overview of possible failure scenarios, their effects on the system and their relevancy for the validation.

Overview
- Failure modes treated in the validation program (priority 1): 1
- Failure modes to be decided (priority 2): 1
- Failure modes not relevant for the validation program (priority 3): 1
- Failure modes treated by functional development (priority 4): 1

Subsystem / compone	Failure mode	Failure Location	Cause of failure	Effect	Critical ity	Priority for Validation Progra	Explanation Priority	Damaging Operating Conditions	Additional harmful conditions	Measurable parameters (Sub-Systemparamete	Classification Method	Damage model	Remarks	Inspection durability test	Tasks	Responsibility	Date
Component 1	fracture	bolt connections	thermomechanical load	loss of mechanical integrity	3	1	effect observed	heat -up, cooldown	mechanic stress, vibrations	temperature	rainflow	TMF		visual / microscopic inspection	thermal cycling		
Component 1	fracture	bolt connections	vibrations	loss of mechanical integrity	3	2	effect unclear	vibrations (vehicle, blowers), shocks (road)		vibration frequency & amplitude, accelerations, strain amplitudes (for full model)	rainflow	HCF	determine Eigen-Frequencies of the subsystem & its components	visual / microscopic inspection	shaker test (hot/cold)		
Component 2	fracture	bolt connections	wet / slit corrosion	loss of mechanical integrity	3	3	improbable for application / FUL	high ambient humidity	salt	temperature, humidity	time at level	reaction kinetics & thermodynamics	consider gas composition, material selection (formation of acidic solutions, ionic solutions)	visual / microscopic inspection	high humidity test, salt nebula test		
Component 3	fracture	bolt connections	insufficient strength	loss of mechanical integrity	3	4	design issue	mechanic load during operation		force, deformation				visual / microscopic inspection	FEA - simulation		

Figure 6 Basic information regarding FP-Sheets & their value.

1.2.3 Sources of SOFC degradation

As demonstrated below in Figure 7 SOFC **failure** can occur as a consequence of a **number of simultaneous modes**. Up to now, traditional full physical models on all scales have been developed to some degree. The challenge is to now take the issue a step further in order to design accelerated test programs for reliability and durability. For a stationary SOFC system the tolerance of the system to **mechanical type failures** is a critical and is not well examined feature that can be a source or degradation and also a system breakdown. A key consideration for SOFCs is how close to their limits should they be allowed to operate in order to maintain durability. It has been shown that even relatively small changes of fuel utilization for a 97% $H_2$and 3%H_2O mix had a significant impact over significant periods of time [1]. For 80% fuel utilizations no observable degradation occurred while for 85% fuel utilization significant degradation per day occurred. This degradation was a result of some **fuel starvation** and **subsequent anode oxidation and induced anode volume expansion** at the higher fuel utilization. This is an example of how SOFCs work perfectly well close to their limits, but **exceeding a limit can have catastrophic consequences on durability**.

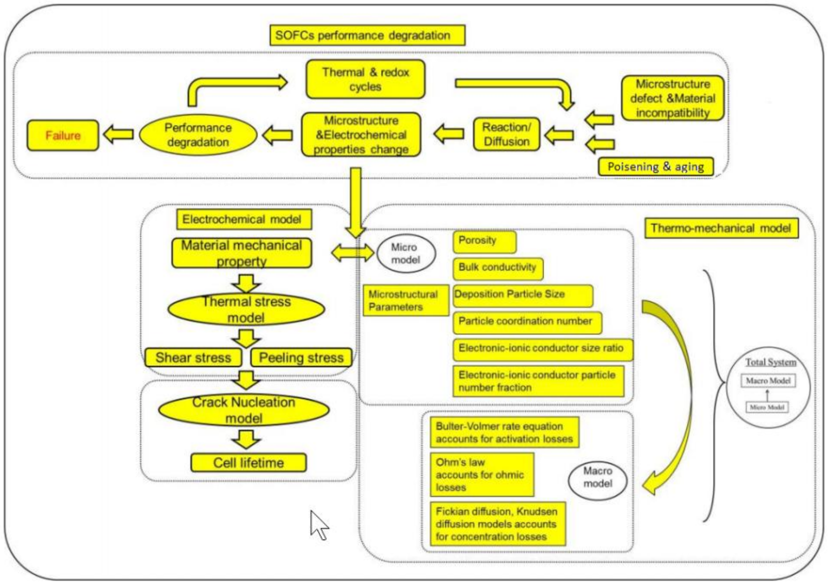


Figure 7: Break down of SOFC degradation leading to reduced durability or a sudden break down, both of which constitute system failure, modified from [3].

For PROSOFC it was decided that mechanical type failure modes should be targeted. In order to aid the analysis the mechanical failure modes were roughly broken down into but not limited to the following, as seen in Table 1.

Table 1: Failure modes associated with mechanical type failure modes.

	Failure mode	Defination	Cause	Results
1	**Buckling**	Under compressive forces a material will tend to deform perpindicular to the applied force.	Compressive forces	Deformation -->Delamination-->Voids/Fracture
2	**Ceep**	Tendency of a solid material to move slowly or deform permanently under the influence of mechanical stresses. It can occur as a result of long-term exposure to high levels of stress that are still below the yield strength of the material	Applied stress, temperature and duration.	Deformation -->Delamination-->Voids/Fracture
3	**Fatigue**	Progressive and localized structural damage that occurs when a material is subjected to cyclic thermal or mechanical loading	Mechanical/thermal cycles	Micro cracks --> Voids/Fracture
4	**H2 embrittlement**	H2 atoms in a metal cavaties in metal matrix cause cracks to propigate	H2 exposure	cracks --> Voids/Fracture
5	**Stress corrosion cracking**	Growth of cracks in a corrosive environment. It can lead to unexpected sudden failure of normally ductile metals subjected to a tensile stress, especially at elevated temperature in the case of metals.	cordder exposure	cracks --> Voids/Fracture
6	**Tensile fracture**	Different parts of an object expand by different amounts indiucing stresses along the material	Thermal gradients	cracks --> Voids/Fracture
7	**Wear**	Material displacement from its "derivative" and original position a consequence of friction.	Thermal expansion/vibration	errosion --> voids
8	**yielding**	Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible (sudden failure)	excessive forces	deformation -->Delamination
9	**Phase change/oxidation etc**	Exotic failure modes that lead to mechanical damage		

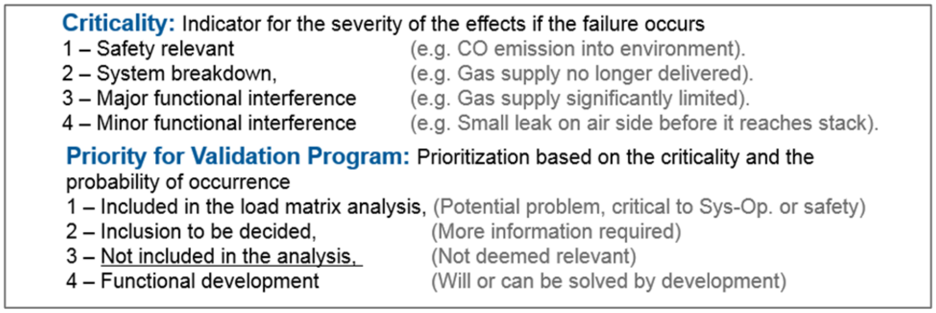
1.2.4 Results from the FP sheet analysis

From the FP sheet fill out workshops, which were attended by members of the consortium a total of 36 mechanical type failure modes were identified for the SOFC stacks. The following components were scrutinized, as seen in Table 2. It should be noted that from the onset mechanical type failure modes were targeted for the analysis.

Table 2: Components scrutinized in PROSOFC and priority allocation

Component	Priority 1	Priority 2	Priority 3	Priority 4
Interconnector	3	1	4	1
Sealing	1	1	7	0
Anode support	1	6	0	1
Anode functional	0	1	0	0
Electrolyte	0	0	1	3
Cathode	2	0	0	0
Cathode contact	0	1	0	0

The prioritization (1-4) as seen in Table 2 is defined below in Figure 2.



Criticality: Indicator for the severity of the effects if the failure occurs

1 – Safety relevant (e.g. CO emission into environment).
2 – System breakdown, (e.g. Gas supply no longer delivered).
3 – Major functional interference (e.g. Gas supply significantly limited).
4 – Minor functional interference (e.g. Small leak on air side before it reaches stack).

Priority for Validation Program: Prioritization based on the criticality and the probability of occurrence

1 – Included in the load matrix analysis, (Potential problem, critical to Sys-Op. or safety)
2 – Inclusion to be decided, (More information required)
3 – Not included in the analysis, (Not deemed relevant)
4 – Functional development (Will or can be solved by development)

Figure 8: AVL's rating system in order to determine the inclusion of a failure mode in a validation test program.

Table 3: Results for the priority 1 failure modes identified in PROSOFC. Table 3 the priority 1 failure modes and details about them are listed according to the load matrix FP-Sheets. Since there are 36 failure modes only the 7 priority 1s have been show. A deeper analysis follows hereafter. These failure modes were deemed relevant for scrutiny during and after testing within the PROSOFC project.

Table 3: Results for the priority 1 failure modes identified in PROSOFC.

Subsystem / component	Failure mode	Failure Location	Cause of failure	Effect	Criticality	Priority for Validation Program	Explanation Priority	Damaging Operating Conditions	Additional harmful conditions	Measurable parameters (Sub-System parameter)
Inter connector	Creeping	Whole interconnector	Under normal operation, thermal & mechanical load	Leads to creeping of the interconnector which leads to delamination from the anode/cathode. leads to a chain effect facilitating further failure mechanisims.	3	**1**	This is one of the prime suspects for loss of contact in the stack.	stationary & transient operating conditions (normal operation)	Inevatible cell degredation leads to temperature increase in certain zones	Pizo sensor measuring compressive stress on interconnector. Temperature measurement.
Inter connector	Interconnector phase change	interconnector in contact with Ni	Phase change where the IC and Ni are in contact. This causes Austenite formation region near the contact has different CTE the stresses may cause interconnector delamination or cracking of the anode and electrolyte	leads to higher fuel consumption on zones on anode which must compensate for zones covered by damaged interconnector/anode interfaces which leads to anode oxidation & cracks and possible crack in electrolyte	2	**1**	A known & observed problem with Ni based anodes or Ni current collectors	stationary & transient operating conditions (normal operation)	Empty	(1) Contact resistance ? (2) Temperature
Interconnector	Scale growth	Interconnector in contact with glass	oxide scale on metal induces a tensile condition in the glass	delamination of the glass from the interconnector or cracking of the glass during cooldown. can lead to leaks and leads to a chain effect facilitating further failure mechanisims.	4	**1**	When the stack is disassembled after testing, the scale between interconnect and glass is the weakest point in the sealing area. Although we have not tested for it we fear that thermocycles after operating for a long time will provoke delamination in the scale.	stationary & transient operating conditions (normal operation)	stresses caused by thermal gradients	If a scale growth means additional volume could be measured with force sensor.
Sealing	Fatigue	whole glass sealing	thermal profiles & mechanical load, thermo cycles	Cracks lead to leaks and a chain effect of dregading events.	4	**1**	When crystallized the glass contains hard crystals and a softer residual glass.	all changes in the temperature profile, start-up, cool down, emergency shutoff,	Inevatible cell aging leads to temperature gradient increase in certain zones (crystalisation of glass over time 1000-2000 hrs can also be considered)	(1) leak rate (2) Temperature (3) resistance ?
Anode support	Tensile fracture	Whole anode support	temperature profile --> thermo mechanical stress--> cell failure	crack propagation --> breaking of the electrolyte/support --> cell failure	2	**1**	Plastic deformation of cell deserves inclusion	stationary & transient operating conditions (normal operation)	Inevatible cell aging leads to temperature increase in certain zones	(1) Cell temperature profile), (2) in- output temperature, (3) mean stack
Cathode(LSCF+CGO)	buckling * (due to compressive forces)	whole cathode	thermo cycles and/or change of temperature profile and/or creep may cause the cathode to buckle.	Cathode delaminates from the electrolyte. leads to a chain effect facilitating further failure mechanisims.	3	**1**	compex connection to operation condition, performance related, likely to happen if not treated	cold start / shutdown, emergency shutdown (rapid changes in supply chain)	Empty	(1) Cathode temperature profile (2) Cell voltage (3) Cathode deactivation (4) Ohmic
Cathode(LSCF+CGO)	Phase change	whole cathode	At the cathode/electrolyte interface departure from stoichiometry within ceramic materials	Leads to a phase change and cathode delamination or deactivation. leads to a chain effect facilitating further failure mechanisims.	2	**1**	Departure from stoichiometry can occur for many reasons.	Low P(O2) caused by high cathode overpotential/high current density	Inevatible cell aging leads to temperature increase in certain zones	(1) Gas concentrations (2) Cathode temp profile (3) Cathode deactivation (4) ohmic resistance

As displayed in Figure 9 the failure modes rated with apriority 1 account for 19% of the all the failure modes scrutinized. This is a typical result and the number of 7, fits to the work package resources.

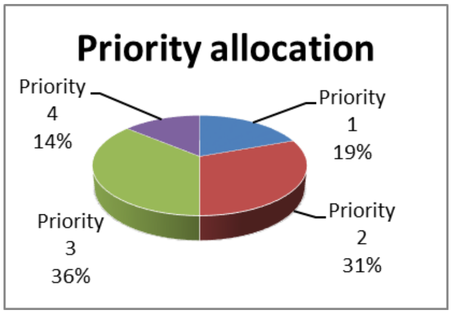


Figure 9: Priority allocation of all 36 the failure modes determined in the PROSOFC project.

In Figure 10 the locations of the various priority 1 allocations are shown. The highest number of failure modes (3) were linked to the interconnectors, while (2) were allocated to the Cathode and (1) each to the Anode support and glass seal.

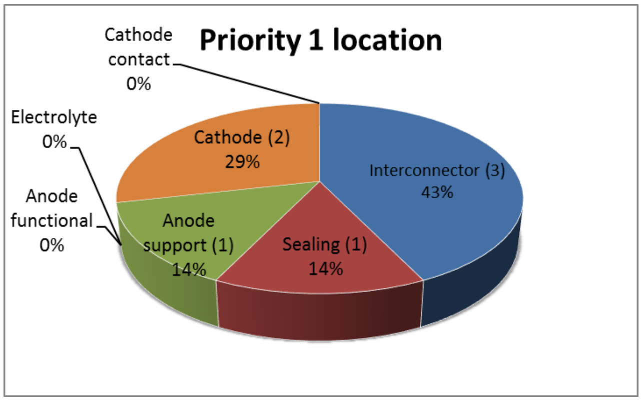


Figure 10: Location of the failure modes deemed relevant for scrutiny in the PROSOFC project.

In Figure 11 the distribution of failure modes that were allocated with a priority 1 is shown.

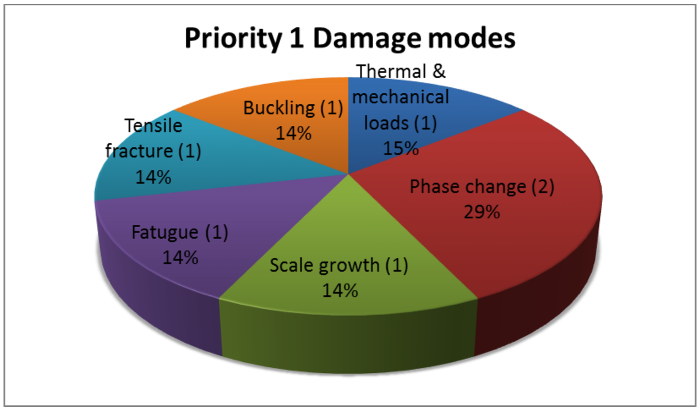


Figure 11: Names of the Priority 1 failure modes and

Final the damaging operating conditions that facilitate the failure modes allocated with a Priority 1 is shown in Figure 12.

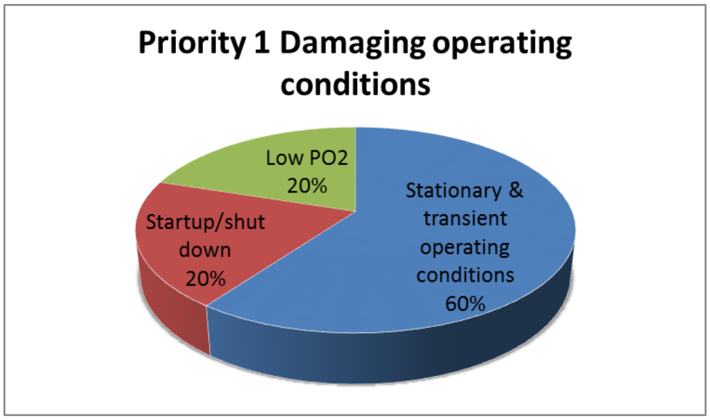


Figure 12: Breakdown of the damaging operating conditions that result in the failures allocated with a Priority 1 rating.

1.2.5 Conclusion

For the PROSOFC project, mechanical type failure modes were identified for the cell and interconnects and the failure modes were prioritized according to the load matrix Failure Prioritization methodology. In total 36 failure modes were identified and 7 of these were deemed relevant for a reliability and durability validation test program. In the PROSOFC project it is planned that these failure modes should be analyzed by simulation and monitored during the stack and cell tests.

2 Reliability targets and reference load

2.1 Introduction

It is necessary to define a **reference application** and some basic operating parameters, which will represent the load on cells and stacks in real life use. The choice of the reference application will also be influenced by the **orientation of the project towards fracture mechanics**. The definition will be carried out by AVL and TOFC, representing the know-how for system integration in the consortium. Also the **stack boundary conditions** need to be **defined** to allow for stack modelling and testing. Based on the decisions above, TOFC as stack manufacturer decides which boundary conditions are realistic. Furthermore, In order to assess the robustness of the cells and stacks, **target values** need to be **defined**. To make a suitable comparison to the usage of cells and stacks in the field a **realistic reference load cycle** needs to be selected. These tasks will be performed by AVL and TOFC

2.2 Methodology

In the PROSOFC project it was decided that the stacks should be tested to specification that are defined by TOFC. It was intended that these **specifications** should be the **maximum recommendable values** in order to **accelerate the failure modes** in as described in D5.2. Thus, for example, the maximum stack temperature was defined according to the limits that the stack manufacturer recommended. Since the model work that was planned to be performed by AVL in order to predict damage acceleration factors for the priority 1 failure modes, these definitions from TOFC are required. **When the models are completed** and validated then **acceleration factors** for the completed tests can be **defined**.

It was also decided from an early stage that the stacks would be tested for a stationary application. AVL knows from experience that testing for stationary systems presents a real challenge, since the lifetime of the system should be greater than 30k hrs. Please see Section 2.3.3 for more information regarding the reliability targets

2.3 Results

2.3.1 Reference Application and reference cycle

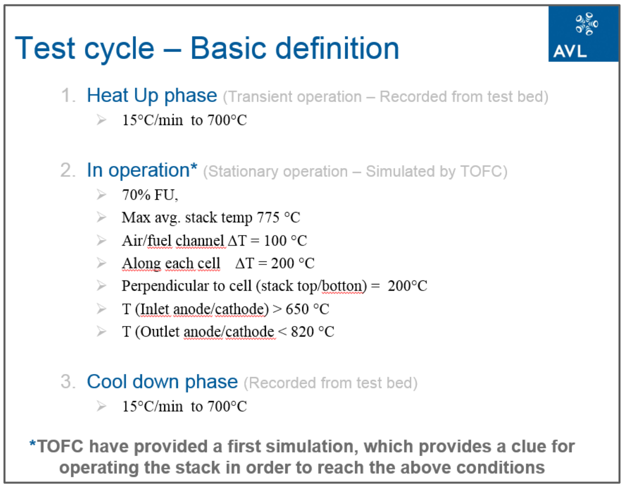
For a stationary system a typical operating strategy is defined as in Table 4 below. This strategy was defined based on discussion between TOFC and AVL and it is against this cycle that that all test cycles will be compared to in order to calculate the acceleration factors, according to the AVL Load Matrix™ approach. It was decided that the data required in order to load the models developed for the load matrix analysis should be recorded at some stage from the test bed since accurate transient simulation would be too resource intensive. Furthermore, this approach increases the degree of realism, since the required data would come directly from the test object.

Table 4: Definition of the reference cycle

Step		Value
1	Turn on fuel	2.0 NL/min 5%H_2 and 23.1 NL/min
2	Turn on oxidant	450 Nl/min
3	Wait	300 seconds
4	Apply heat	7°C/min to Calibrtated temp
5	Switch fuel to reformate	Enough for 70% FU
6	Oxidant regulated	Calibrtated OU
7	Switch to 25 A	-
8	Run at 25 A	125 hours
9	Switch to 0 A	-
10	Wait	300 seconds
11	Regulate cathode flow	134 NL/min air
12	Cool stack to 200°C (maintinance safe tem	7°C/min to Calibrtated temp
-	Repeat	32 times (2X 250 s.d. /30K hr)

2.3.2 Operating boundary conditions for test cycles

For the three tests that will be performed in PROSOFC in WP7 it was decided that all the test cycles should be identical in order to facilitate direct comparisons between the cell generations tested in each test. The test cycle that was defined based on the maximum allowable values from TOFC are shown below in Figure 13. Some simulation results were used in order to provide an indication of maximum values, but it was agreed that these values should be double checked from measurements on the test beds. In Figure 14 a plot of the temperature profile and current drawn from the stack is shown with labels. This cycle should be repeated 32 times in order to meet the 4000 hrs. test program time.



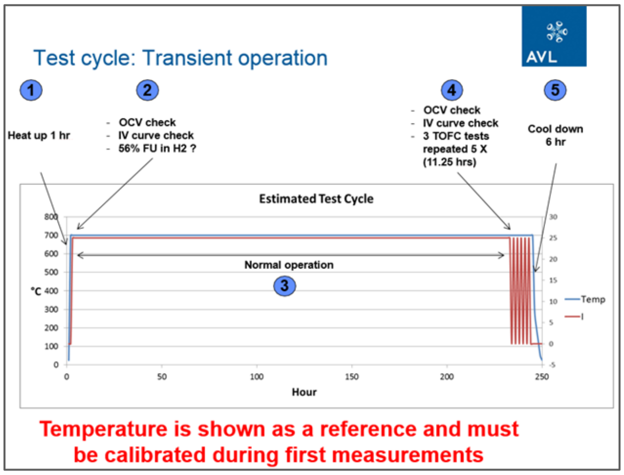
Test cycle – Basic definition

AVL

1. Heat Up phase (Transient operation – Recorded from test bed)
   - 15°C/min to 700°C
2. In operation* (Stationary operation – Simulated by TOFC)
   - 70% FU,
   - Max avg. stack temp 775 °C
   - Air/fuel channel ΔT = 100 °C
   - Along each cell ΔT = 200 °C
   - Perpendicular to cell (stack top/botton) = 200°C
   - T (Inlet anode/cathode) > 650 °C
   - T (Outlet anode/cathode < 820 °C
3. Cool down phase (Recorded from test bed)
   - 15°C/min to 700°C

*TOFC have provided a first simulation, which provides a clue for operating the stack in order to reach the above conditions

Figure 13: Basic definition of the test cycle to be implemented on all 3 tests in WP7.



Test cycle: Transient operation

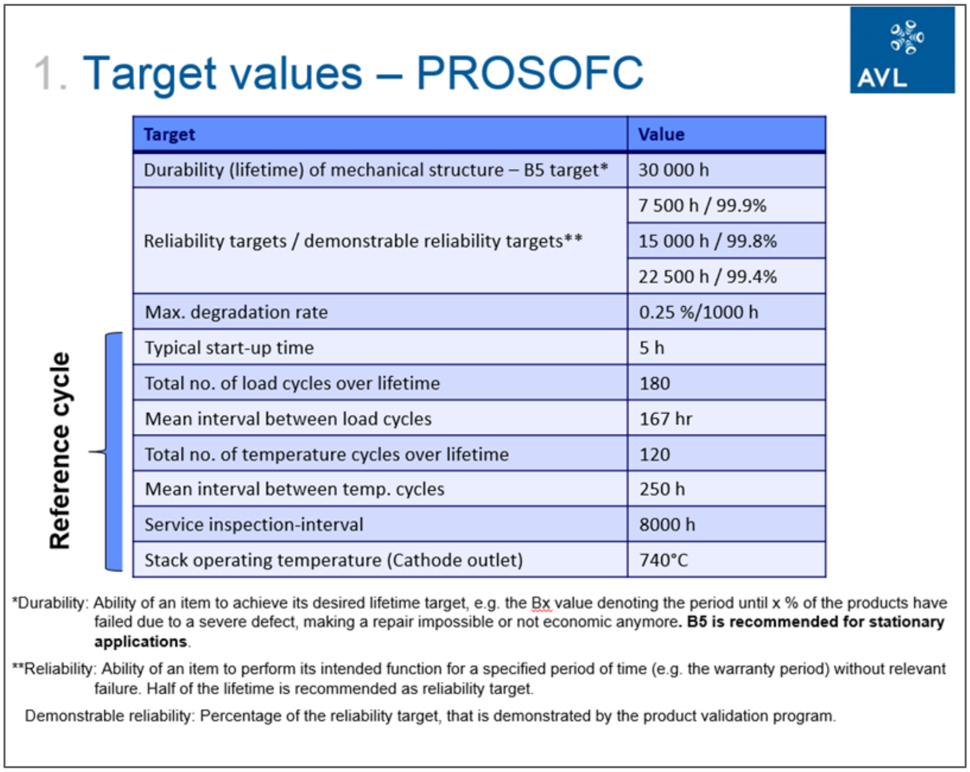
AVL

Temperature is shown as a reference and must be calibrated during first measurements

Figure 14: Plot of the temperature and current for the test cycle as defined by TOFC & AVL

2.3.3 Target Values

The target vales for the load matrix™ analysis are provided below in Figure 15. TOFC defined that the lifetime of a stack should be 30k hrs. with a maximum degradation rate of 0.25% per 1000 hrs. Other parameters including information for the definition of a reference cycle are also provided in Figure 15.



1. Target values – PROSOFC

Target	Value
Durability (lifetime) of mechanical structure – B5 target*	30 000 h
Reliability targets / demonstrable reliability targets**	7 500 h / 99.9%
	15 000 h / 99.8%
	22 500 h / 99.4%
Max. degradation rate	0.25 %/1000 h
Typical start-up time	5 h
Total no. of load cycles over lifetime	180
Mean interval between load cycles	167 hr
Total no. of temperature cycles over lifetime	120
Mean interval between temp. cycles	250 h
Service inspection-interval	8000 h
Stack operating temperature (Cathode outlet)	740°C

*Durability: Ability of an item to achieve its desired lifetime target, e.g. the Bx value denoting the period until x % of the products have failed due to a severe defect, making a repair impossible or not economic anymore. **B5 is recommended for stationary applications**.

**Reliability: Ability of an item to perform its intended function for a specified period of time (e.g. the warranty period) without relevant failure. Half of the lifetime is recommended as reliability target.

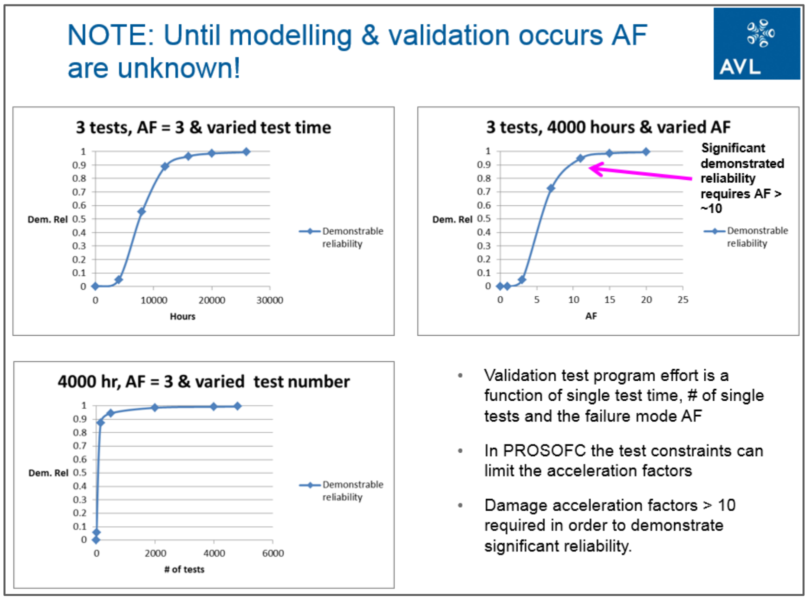
Demonstrable reliability: Percentage of the reliability target, that is demonstrated by the product validation program.

Figure 15: The life time target values for the stacks produced in PROSOFC.

The B5 target was defined to 30K hrs meaning that after 30k hrs 95% of the stacks should not have failed. In order to perform the load matrix analysis AVL has defined some additional reliability targets 99.9% after 7.5k hrs 99.8 after 15k hrs and 99.4 after 22.5k hrs., implying that this % of stacks should still be operational after the defined amount of hours. These values come from a statistical analysis that shows in order for 95% of the stacks to still be operational, following normal failure rates, the pre-defined rates must be met.

2.3.4 Conclusion

For a stationary SOFC system because of the long lifetime requirement there are some points worth noting. Typically using statistical methods based on validated relative type models that account for the physics of failure modes, test programs are designed base on (1) the acceleration factor achieved in a test, (2) the test duration and (3) the number of tests performed. The plots in Figure 16 show that in order to reach a B5 at 30K hrs the key features of a test program will be few test numbers, long testing durations and the acceleration factor should be about 10. Typically an acceleration factor of 10 is extremely high, meaning that the operating conditions would be substantially different to the reference cycle. Since SOFC systems are so sensitive it is unlikely that such a high acceleration factor will be achieved for any failure mode. A typical high value would be 3 and this means that substantial testing that will not be accounted for in PROSOFC will be required at a later date in order to prove demonstrated reliability according to the load matrix methodology. PROSOFC provides an excellent opportunity to validate the models developed and analyze the system operation up to 4k hrs. According to the load matrix it would be better to test 1 stack for 12K then 3K each. Nonetheless the tests performed in PROSOFC are still valid and count towards the overall demonstrated reliability evaluation.

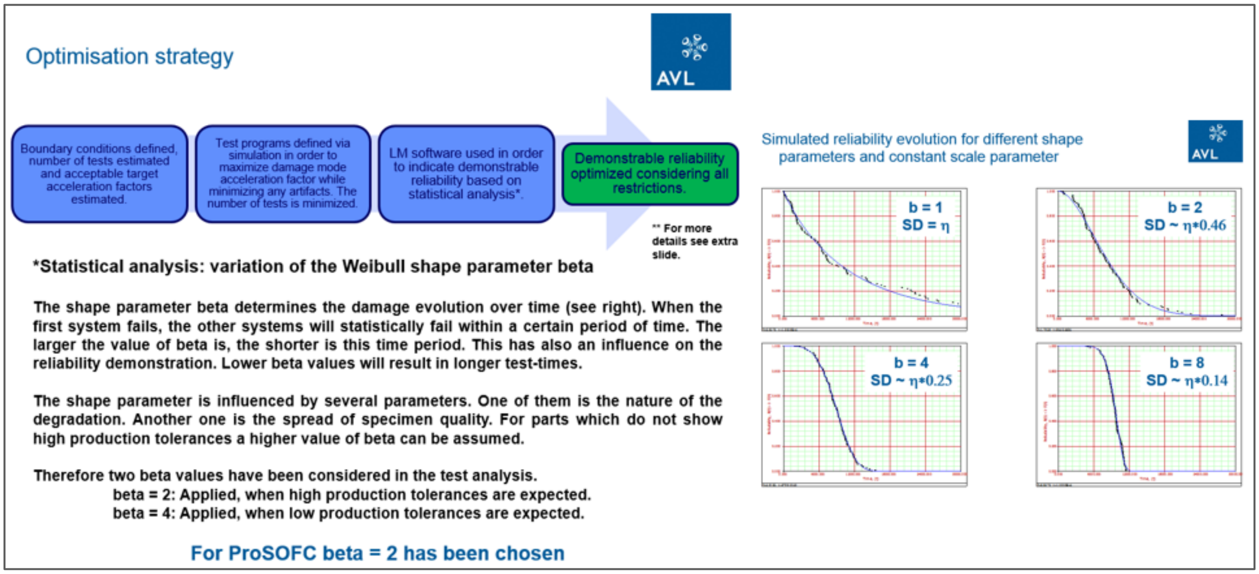


NOTE: Until modelling & validation occurs AF are unknown!

- Validation test program effort is a function of single test time, # of single tests and the failure mode AF
- In PROSOFC the test constraints can limit the acceleration factors
- Damage acceleration factors > 10 required in order to demonstrate significant reliability.

Figure 16: Comparison of (1) acceleration factor, (2) test duration and (3) number of tests on the demonstrated reliability valuation of a system based on statistical analysis.

The steps in order to optimize a validation test program design are shown in Figure 17. Typically in a load matrix project the second step is the design of the test program whereby, features of the test cycle are defines in order to maximize the acceleration factors while minimizing test artifacts, or unrealistic events that effect a test result in a way that would not occur in reality. In PROSOFC these artifacts will be minimized by the test program definition prescribed by TOFC. On the other hand it is expected that the acceleration factors from these test will be quite low. As a consequence the demonstrated reliability towards the B5 at 30k hrs is expected to be quite low. The Weibull beta value can be used in order to benefit the situation. The beta value accounts for the spread of failures as can be seen in the right of Figure 17. With a Beta = 1 the failure distribution of a prototype can be quite varied due to high tolerances, while an in series product should have a failure spread over time much more concentrated, so a beta value of 8 could be more appropriate. A beta value of 2 has been assumed for the TOFC system. In order to proof this several tests would be required.



Optimisation strategy

Boundary conditions defined, number of tests estimated and acceptable target acceleration factors estimated.

Test programs defined via simulation in order to maximize damage mode acceleration factor while minimizing any artifacts. The number of tests is minimized.

LM software used in order to indicate demonstrable reliability based on statistical analysis*.

Demonstrable reliability optimized considering all restrictions.

** For more details see extra slide.

*Statistical analysis: variation of the Weibull shape parameter beta

The shape parameter beta determines the damage evolution over time (see right). When the first system fails, the other systems will statistically fail within a certain period of time. The larger the value of beta is, the shorter is this time period. This has also an influence on the reliability demonstration. Lower beta values will result in longer test-times.

The shape parameter is influenced by several parameters. One of them is the nature of the degradation. Another one is the spread of specimen quality. For parts which do not show high production tolerances a higher value of beta can be assumed.

Therefore two beta values have been considered in the test analysis.
beta = 2: Applied, when high production tolerances are expected.
beta = 4: Applied, when low production tolerances are expected.

For ProSOFC beta = 2 has been chosen

Simulated reliability evolution for different shape parameters and constant scale parameter

Figure 17: The optimization strategy for a validation test program design and the significance of the Weibull beta value.

Thus the following has been achieved

- A reference application and reference cycle have been defined
- The operating boundary conditions for the test cycles have been defined
- The target values have been defined with some comment regarding the expected impact of the tests performed in PROSOFC and their impact on the overall demonstrated reliability of the developed SOFC system.

3 Conclusions and following steps

To date the work package has run quite smoothly and the following tasks are within the reach of the remaining resources. 3 damage calculation functions have been assigned to 3 of the 7 identified failure modes. For more information please refer to the midterm report.

While the test program has in essence been defined it has been agreed that data from the test bed should be recorded in order to provide realistic loading for the damage calculations. Furthermore, this data, which comes from WP7, will also be used to validate some multi physics simulations in order to generate look up tables for values of characteristics not measured that must be predicted.

The following steps are planned:

(1) Completion of the remaining 4 failure modes damage accumulation functions.

(2) Recording of data to be fed from the test stands to the load matrix for the reference and test cycles.

▪

(3) Deduction of the non-measurable stack characteristics based on full physical model approaches.

(4) Calculation of the acceleration factors produced by the reference and PROSOFC test cycles.

▪

(5) Recommendations for a validation test program that covers all 7 failure modes identified in the PROSOFC project that demonstrates the reliability and durability robustness against these modes and meets the targets defined within the project.

4 References

[1] R. S. Gemmen and C. D. Johnson. Evaluation of fuel cell system efficiency and degradation at development and during commercialization. *Journal of Power Sources*, 159(1):646–655, 2006.

[2] Andrei Fedorov Jianmin Qu and Comas Haynes. An integrated approach to modeling and mitigating sofc failure. Technical Report DE-FC26-02NT41571, Georgia Tech,, 2002.

[3] Lin Liu. *Solid oxide fuel cell reliability and performance modeling and fabrication by spray pyrolysis*. PhD thesis, Iowa State University, 2011.