FLUIDCELL

ADVANCE M-CHP FUEL **CELL** SYSTEM BASED ON A NOVEL BIO-ETHANOL **FLUID**ISED BED MEMBRANE REFORMER

FCH JU GRANT AGREEMENT NUMBER: 621196

Start date of project: 01/04/2014 **Duration: 3 years**

WP9 – LCA and safety analysis

D9.5
Safety assessment of the m-CHP

Application area: SP1-JTI-FCH.3: Stationary Power Generation & CHP
Topic: SP1-JTI-FCH.2013.3.4 Proof of concepts and validation of whole fuel cell systems for stationary power and CHP applications at a representative scale
Funding scheme: Collaborative Project
Call identifier: FCH-JU-2013-1

Due date of deliverable: 31-07-2018	**Actual submission date:** 20-07-2018	**Reference period:** 01-10-2015 - 31-07-2018
Document classification code: FluidCELL-WP9-D95-DLR-HYG-20072018-v11.docx		**Prepared by:** QUA

Version	DATE	Changes	CHECKED	APPROVED
v0.1	26-01-2018	Original Release	HYG	LR
v0.2	04-07-2018	Addition information WP8	ICI	CT
v1.0	19-07-2018	Revised version	QUANTIS	VM
v1.1	20-07-2018	Approved (format)	TECNALIA	J.L. Viviente

Project co-funded by the FCH JU within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
CON	Confidential, only for members of the Consortium	

Acknowledgement: *The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 621196.*
Disclosure: *The present publication reflects only the author's views and the FCH JU and the Union are not liable for any use that may be made of the information contained therein.*

Content

1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

Based on the design of the membrane reactor as well as from the integration of the reformer into the fuel cell CHP-system a safety assessment was performed. This deliverable summarizes the methodology used during the safety assessment of the m-CHP system.

The assessment is separated in two main chapters, one for the fuel processor alone, and one for the integration into the CHP. The document describes the safety standards and directives employed for the assessment and certification of the system. The methodology used during the HAZOP and risk assessment are outlined.

The safety assessment was essential to bring forward a system with safe and robust operation.

1.2 Brief description of the state of the art and the innovation brought

The micro CHP system based on ethanol ATR membrane reforming concept with in-situ hydrogen extraction enhanced by steam sweep gas, has never been developed at relevant scale and operating conditions as implemented in FluidCELL. This makes the membrane reactor based CHP system hereafter described first of its class at pilot scale. The findings of FluidCELL brought promising knowledge to the academic and commercial communities involved in this field.

1.3 Deviation from objectives

There was no deviation from objectives.

2 INTRODUCTION

Based on the design of the membrane reactor as well as from the integration of the reformer into the fuel cell CHP-system, a safety assessment was performed. This deliverable summarizes the results of the safety assessment of the m-CHP system.

The assessment is separated in two main chapters. Chapter 3 focuses on the fuel processor alone, and chapter 4 on the integration into the CHP. The fuel processor was developed in WP6 led by HyGear, and the integration with the fuel cell was done in WP8 led by ICI Caldaie.

The document describes the safety standards and directives employed for the assessment and certification of the system. A summary of the safety precautions is presented in this deliverable.

The methodology used during the HAZOP and risk assessment are outlined. Moreover, an analysis of the potential failure modes and effects is given for the CHP integration.

3 FUEL PROCESSOR

3.1 Safety standards and directives

The fuel processor of FluidCELL was developed in WP6 led by HyGear. The technology here used incorporates several chemical processes at elevated temperatures and pressures, and with both flammable and toxic gasses. Therefore, conventional standards, directives and procedures had to be applied to ensure safe design of the system. HyGear has vast experience in these type of processes, therefore internal procedures are already in line with the required standards. The fuel processor is CE certified. The following chapters describe a summary of the applicable standards and directives, applied procedures, and the main features related to safety.

3.1.1 Machinery Directive (2006/42/EC)

The Directive applies to all machinery and to safety components. A machine is defined as “an assembly … of linked parts or components, at least one of which moves…”. Clearly this definition encompasses a very large range of machines, from simple hand-held power tools through to complete automated industrial production lines. The requirements of the Directive can essentially be split into two sections - the 'essential health and safety requirements' and 'administrative provisions'.

The essential health and safety requirements demand that the machine manufacturers identify the hazards which their products contain and then assess the risks which these hazards present to users. Any risks thus identified must be reduced to as low a level as is reasonably practicable. Annex I of the Directive gives a comprehensive list of the potential hazards which may arise from the design and operation of machinery, and gives general instructions on what hazards must be avoided. Detailed requirements are laid out in a series of safety standards.

The administrative provisions of the Directive (at least so far as manufacturers are concerned) are primarily aimed at forcing manufactures to provide documentary evidence that the machinery complies with the Directive.

Machinery meeting the requirements of the Directive is required to have the CE logo clearly affixed to indicate compliance. It must also show the year of manufacture, some form of serial number, and other ratings as required by the relevant standards. An item of equipment may only display the CE mark when the equipment satisfies all relevant directives; for instance, machines with electrical controls must also comply with the requirements of the EMC Directive (Electromagnetic Compatibility).

Where volume production is envisaged, the Directive requires that control measures must be implemented to ensure that all of the machines manufactured will conform to the provisions of the Directive.

3.1.2 Pressure Equipment Directive (2014/68/EU)

The Pressure Equipment Directive (PED) 2014/68/EU (formerly97/23/EC) of the EU sets out the standards for the design and fabrication of pressure equipment generally over one litre in volume and having a maximum pressure more than 0.5 bar(g). The directive covers a very broad range of products such as vessels, pressurised storage containers, heat exchangers, steam generators, boilers, industrial piping, safety devices and pressure accessories. It also sets the administrative procedures requirements for the "conformity assessment" of pressure equipment, for the free placing on the European market without local legislative barriers. It has been mandatory throughout the EU since 2002, with 2014 revision fully effective as of 19 July 2016. The PED requires third party involvement (Notified Body) in the conformity assessment of products depending on the level of the hazard.

3.1.3 EN 60204-1 Safety of machinery: Electrical equipment of machines: Part 1 General requirements (2006)

In order to conform to standard EN 60204-1 the system need to agree with requirements and recommendations to promote safety of persons and property, consistency of control response, and ease of maintenance.

The standard covers the risks due to electrical equipment as part of the risk assessment of the machine:

- Equipment failure leading to electrical shock
- Control circuit failure leading to malfunction of the machine
- Disturbance/interruption of the power source leading to malfunction of the machine
- Safety related control circuit failure leading to failure of safety functions
- EMC problems leading to malfunction of the machine
- Release of stored energy leading to unexpected movements / electrical shock
- Excessive noise leading to damaged hearing
- High surface temperatures leading to burns

Correct selection of electrical components and devices based upon the:

- Intended use
- Conformity to applicable standards
- Applied according to manufacturer's instructions
- Suitability for purpose
- Ability to withstand the expected influence
- Appropriate for the intended use
- Suitably placed/positioned
- Readily identifiable with physical durable marking of the component or device

3.1.4 EN 60079-10-1 Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres (2015)

This standard is concerned with the classification of areas where flammable gas or vapour hazards may arise. It serves as a basis to support the proper selection and installation of equipment for use in hazardous areas. It is applied where there may be an ignition hazard due to the presence of flammable gas or vapour, mixed with air.

A place where an explosive atmosphere may occur in quantities that require special precautions to protect the health and safety of workers is defined as hazardous. A place where an explosive atmosphere is not expected to occur in quantities that require such special precautions is deemed to be non-hazardous.

Hazardous area classification is used to identify places where, because of the potential for an explosive atmosphere, special precautions over sources of ignition are needed to prevent fires and explosions.

Hazardous places are further classified in Zones which distinguish between places that have a high chance of an explosive atmosphere occurring and those places where an explosive atmosphere may only occur occasionally or in abnormal circumstances. The definitions of the Zones also recognise that the chance of a fire or explosion depends on the likelihood of an explosive atmosphere occurring at the same time as an ignition source becomes active.

3.2 Safety precautions

3.2.1 Flammable gases

The system contains pressurized flammable gases. During maintenance, the electrical power to the system should be switched off. Smoking and open fire in the vicinity of the system are strictly prohibited. The release of flammable gases must be avoided by purging the system with an inert gas prior to maintenance or repair. After maintenance or repair of the system all oxygen must first be removed from the system by purging it with an inert gas. The system must be leak-tested before it is put into operation. After a power loss, the system should be inspected and tested for the presence of flammable gases before power is restored.

3.2.2 Location

At the outlet of the system vent pipe, a potentially explosive mixture can occur. This creates an area where no ignition sources shall be placed (ATEX zone 1).

The cabinet containing the fuel processor should incorporate all the safety regulations needed for use of flammable gasses (e.g. CO and LEL) sensors.

3.2.3 Toxic gases

During the process of converting ethanol to hydrogen, amongst other gases, highly toxic carbon monoxide (CO) is formed. This gas can be present in lethal concentrations in parts of the system. Therefore, the system must be purged with an inert gas prior any work on gas carrying parts of the system. During work on the system, all personnel should wear a personal CO monitor. After maintenance or repair the system must first be leak-tested before it is put into operation.

3.2.4 High temperature

The reformer reactor operates at high temperature. Under no circumstances should the reformer insulation be removed whilst the reactor is hot. The reformer and some of the lines and heat exchangers contain superheated water or steam. Allow the reformer to fully cool down and depressurize the system prior to maintenance or repair. Be extremely careful when accessing the system as parts may be hot.

3.2.5 High pressure

The system operates at elevated pressures up to a pressure equal to the inlet pressure of the natural gas. With a maximum of 12.5 bar(g). It should be confirmed that the system is depressurized before performing maintenance or reparations on the system. Do not bleed off pressure by (partially) disconnecting fittings. Use the appropriate way to depressurize and purge the system.

3.2.6 Freezing

Freezing of this system may result in structural and permanent damage of vessels, pipes or components. As a result, the system should therefore not be exposed to temperatures below 0 °C before nor after installation is complete.

3.3 Hazard and operability study (HAZOP)

A PRIME analysis was carried out to identify the factors that are important with regards to safety. PRIME stands for Process, Resources, Instrumentation, Materials, and Environment. The “P” part of the analysis is analogue to what is typically referred to as HAZOP. In PRIME, the analysed characteristics are related to:

- Process characteristics (pressure, temperature, residence time, flow rate, etc)
- The exposed persons (age, level of knowledge, experience, insight, motivation, etc)
- The installation itself (utilities, sound, moving parts, vibrations, processed materials, accessories, measuring instruments, tooling, etc)
- The physical properties of the (auxiliary) substances to be processed by the installation under pressure (density, toxicity, mass, flammability, etc)
- The environment in which the installation is located (temperature, humidity, light, space, traffic load, etc)

The following method is used for classification of risks. Risk can be described in statistical-like terms. The extent of the risk is determined by parameter ˈKˈ (chance) and ˈEˈ (possible consequence), where the risk is the product of K and E. The chance ˈKˈ is in itself calculated from W (likelihood) and B (exposure) by the product of W and B. Then the overall risk score ˈRˈ is computed as the product of the three separate factors as R = W x B x E. These numerical values, although arbitrarily chosen are self-consistent and together they provide a realistic but relative score for the overall risk.

The factor ˈWˈ indicates the likelihood of occurrence of a hazardous event, and it is related to the mathematical probability that it might occur. For the purpose of the risk analysis, likelihood is expressed in alternative terms of expectations. Likelihoods that may be encountered in practical safety situations range from the completely unexpected and unanticipated, but remotely possible, up to an event that might well be expected at some future time. The risk scenario assumes a dangerous situation, where an undesired initial event arises, which could develop further through intermediate events to a final event with a certain injury or damage.

The exposure factor ˈBˈ indicates how often and how long a person is exposed to a potentially hazardous situation. The number of exposed persons can also be included in the exposure factor. Thus, exposure can be considered as the product of the exposure frequency, exposure duration, and the number of exposed persons.

The possible consequence ˈEˈ can be material damage or physical and psychological injury. In the case of occupational health risks, it only concerns the effects on the health of employees. With regard to this method, however, you can also weigh material damage, environmental effects, financial effects, reputation damage and the like. This way you can use this method for many more aspects than just occupational safety.

The way the factors W, B and E can be ranked is shown in the tables below.

W: Likelihood

Value	Likelihood
0.1	Virtually impossible
0.2	Practically impossible
0.5	Conceivable but very unlikely
1	Only remotely possible
3	Unusual but possible
6	Quite possible
10	Might well be expected

B: Exposure

Value	Exposure
0.5	Very rare (yearly)
1	Rare (a few per year)
2	Unusual (monthly)
3	Occasional (weekly)
6	Frequent (daily)
10	Continuous

E: Possible consequence

Value	Possible consequence
1	Noticeable (minor first aid accident)
3	Important (disability)
7	Serious (serious injury)
15	Very serious (fatality)
40	Disaster (few fatalities)
100	Catastrophe (many fatalities)

Risk scores, defined as the products of three factors, can with some convenience be calculated graphically using the nomograph shown in Figure 1, otherwise can be numerically determined. Depending on the risk score, a corresponding priority is given to the mitigation action (see table below). Specific situations where 'E' or 'W' fall on the highest range (i.e. E 40/100 or W 10) should also be reviewed with special attention even if 'R' were on a low score range.

Risk score	Risk situation
R ≤ 20	Acceptable risk
20 < R ≤ 70	Possible risk; attention indicated
70 < R ≤ 200	Substantial risk; correction needed
200 < R ≤ 400	High risk; immediate correction required
400 < R	Very high risk; consider discontinuing operation

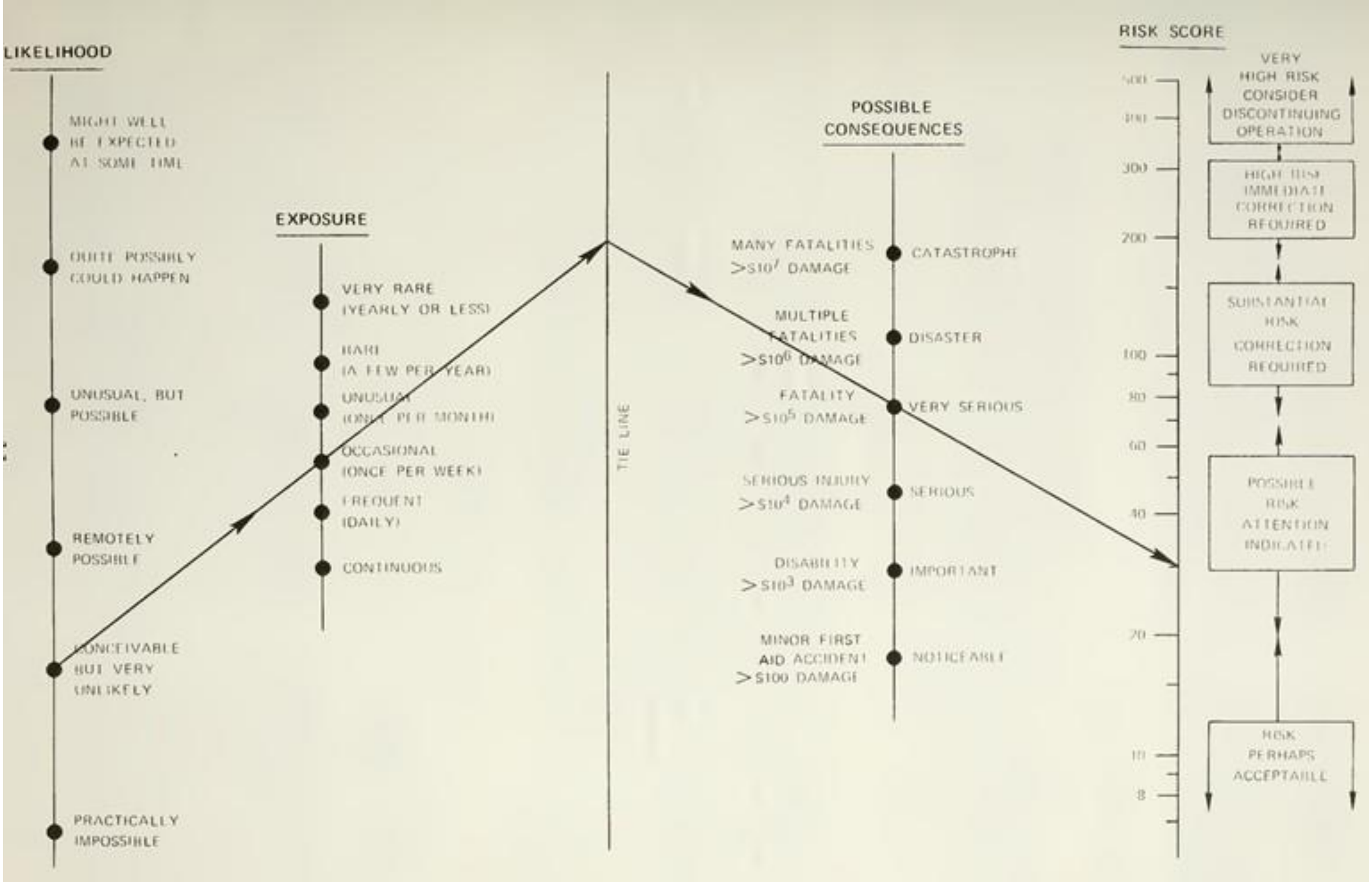

Figure 1. Nomograph risk analysis.

In the development of the fuel processor, the PRIME methodology was performed including the risk analysis as here described. The analysed risks having a score corresponding to substantial risk were subject to risk mitigation measures.

3.3.1 Flammability barrier

Given a predetermined flow rate of fuel and water (steam), the controller restricts flow rate of air so as to ensure that the resulting feed composition falls outside the flammable region at all operating steps (start-up, production, shutdown).

3.3.2 Emergency shutdown

Prior to commissioning all triggers for emergency shutdown were tested (both hardwired or not). The system includes connections for external triggers for emergency shutdown. These are to be connected by the user of the machine. External emergency triggers should include emergency push-button and gas detectors (for instance toxic or flammable gases due to leaks).

Following an emergency shutdown, all feed controllers and equipment are cut off except for the cooling water pump and the nitrogen purge both on reactor and sweep side.

3.4 Conformity assessment and inspection for commissioning

A conformity assessment according to module G of PED directive was carried out for the pressurized assembly. This assessment is verified by an external notified body in order to certify that appropriate safety measures had been implemented. Moreover, an inspection for commissioning (Keuring voor Ingebruikneming) was performed by the NoBo.

3.5 MSDS

When handling or operating with potentially harmful substances as those contained in the FluidCELL system, the corresponding material safety datasheets (MSDS) were supplied. Aspects relevant to safety are addressed in such documents, such as:

- Hazards identification
- First aid measures
- Firefighting measures
- Accidental release measures
- Handling and storage
- Exposure controls & personal protection
- Toxicological information
- Ecological information
- Disposal considerations

4 COMPLETE CHP SYSTEM

4.1 Ranking Criteria

An analysis of Potential Failure Mode and Effects has been carried out. To each item or function a value for Severity, Probability and Detection has been associated and reported in the table below.

Severity			
score	**Description**	**Customer perception**	**Consequences for the company**
1	Without relevant degradation	Does not realise anything	
2	Product working without performance reduction (aesthetics)	Light perception	Customer management
3	Product working without significative performance reduction (aesthetics)	Small degradations perceived.	Service cost. Customer management
4	Product working with some performance reduction Requires maintenance	Performance limitations perceived.	Service cost. Customer management
5	Product working but out of contractual specifications. Requires maintenance and/or replacement of parts	Unsatisfied	Replacement and service cost Customer management
6	Product working but out of general specifications. Requires maintenance and/or replacement of parts	Unsatisfied	Replacement and service cost Customer management
7	Product not working Requires intervention and replacement of parts	Unsatisfied	Replacement and service cost Potential cancellation of contract
8	Product not working within law limits. Requires full substitution	strongly unsatisfied	Full substitution Potential cancellation of contract
9	Has consequences on safety of personnel with advice or causes big discomfort to customer or causes damages to customer goods	strongly unsatisfied	Several costs Civil responsibility
10	Has consequences on safety of personnel without advice	strongly unsatisfied	Several costs Penal responsibility

Probability		
score	**Description**	**1 event out of**
1	Remote probability, unlikely event	< 1/100.000
2	Low probability Event is very rare	< 1/20.000
3		< 1/10.000
4	Medium probability. Occasional Event	< 1/2.000
5		< 1/1.000
6		< 1/200
7	High probability Event is continuously present	< 1/100
8		< 1/20
9	Very high probability Event certainly occurs	< 1/10
10		> 1/10

Detection		
score	**Description**	**Detection probability**
1	VERY HIGH – Controls will certainly reveal the criticality. Predictive control: the potential failure is detected before the failure occurs	>100%
2		>99%
3	HIGH – controls have good probability to detect the criticality. The failure is detected. Sometime, it's possible to detect before the failure occurs	>95%
4		>90%
5	AVERAGE – Control can detect the criticality. Failure is detected after it has occurred	>50%
6		>20%
7	LOW – control have low probability to detect the failure. Failure isn't easily recognizable	>10%
8		>5%
9	VERY LOW – Controls cannot detect the criticality. Failure cannot be recognized.	>1%
10		0

FC ANODE FEEDING		
Items	**Functions**	**Control**
Bypass Valve Syngas V5.3	Deviate the syngas directly to chimney when required	Main
On/Off valve V5.4	Close anode side from syngas supply	Main
P5.1 Pressure sensor	Syngas pressure before anode	Main
TC5.1 thermocouple	Syngas temperature before anode	Main
Anode	Use syngas for electrochemical reaction to produce electric and thermal power	Main
P5.2 Pressure sensor	Syngas pressure after anode	Main
TC5.2 thermocouple	Syngas temperature after anode	Main
Condensate discharge	Discharge condensate coming from syngas line	None
Recirculation Pump	recirculates the exhausted anodic from the cells to the fuel processor	Main
Pressure sensor P5.3	Syngas pressure after recirculation pump	Main
Purge Valve V5.2	performs a purge of 0.5 sec every 90 sec	Main
On/Off valve V5.1	close the anodic output towards fuel processor	Main
Sample gas analysis manual valve	Supply sample gas to external gas analyser	None
Inverter FC	Convert FC power output from DC to AC	Main
Disconnector	Physically disconnect FC inverter from the grid	Main
FC CATODE FEEDING		
Air blower	Supply air to the cathode	Main
P7.1 Pressure sensor	Air pressure before humidifier	Main
TC7.1 thermocouple	Air temperature before humidifier	Main
f7.1 Mass flow controller	Regulate cathode air amount	Main
Humidifier	Humidify dry air from the blower to supply to the cathode	None
P7.2 Pressure sensor	Air pressure before cathode	Main
TC7.2 thermocouple	Air temperature before cathode	Main

Cathode	Use air for electrochemical reaction to produce electric and thermal power	Main
Sample gas analysis manual valve v7.1	Supply sample gas to external gas analyser	None
Condensate discharge	Discharge condensate coming from air line	None
P7.3 Pressure sensor	Air pressure before cathode exhaust	Main
TC7.3 thermocouple	Air temperature before cathode exhaust	Main
Sample gas analysis manual valve	Supply sample gas to external gas analyser	Main
Tc7.4 thermocouple air exhaust	Air temperature after humidifier exhaust	None
FC COOLING CIRCUIT		
P6.3 Pressure sensor	Water pressure after cooling	Main
TC6.2 thermocouple	Water tc after cooling	Main
Cooling pump	circulate water to cooldown FC stack	Main
P6.1 Pressure sensor	Water pressure after pump	Main
manual valve	manual valve after pump	None
Heat exchanger	heat exchanger for cooling circuit temp regulation	None
Three-way valve Twv8.1	Three-way valve for cooling circuit temp regulation	Main
Air cooler	heat exchanger for cooling circuit temp regulation	None
Mf6.1 Mass flow meter	Measure water flow rate trough the stack	Main
Air vent	discharge the air from the heating circuit	None
Hydraulic Head	Set the inlet pressure of the stack cooling circuit to a constant value	None
P6.2 Pressure sensor	Water pressure before stack cooling side	Main
TC6.1 thermocouple	Water temperature before stack cooling side	Main
stack cooling side	Remove heat produced by electrochemical reaction from FC stack	Main

Table 1. Potential Failure Mode and Effects Analysis.

											Action Results				
Item / Function	**Potential Failure Mode(s)**	**Potential Effect(s) of Failure**	**Sev**	**Potential Cause(s)/ Mechanism(s) of Failure**	**Prob**	**Current Design Controls**	**Det**	**RPN**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**New Sev**	**New Occ**	**New Det**	**New RPN**
Bypass Valve Syngas V5.3	Failed open	possible cell poisoning	4	Mechanical damage, rust, dust	2	at service	2	16							0
	Failed closed	None	1	Mechanical damage, rust, dust	2	at service	2	4							0
	Leaks IN to Out	none	1	Mechanical damage, rust, dust	2	at service	10	20							0
	Leaks to the ambient	syngas in the enclosure/ambient	9	Sealing damaged	2	at service	2	36							0
On/Off valve V5.4	Failed open	none	1	Mechanical damage, rust, dust	2	at service	2	4							
	Failed closed	potential system overpressure, FC stacks stops, possible cell poisoning	7	Mechanical damage, rust, dust	2	pressure sensor	2	28							

	Leaks IN to Out	potential system overpressure, FC stacks stops, possible cell poisoning	7	Mechanical damage, rust, dust	2	pressure sensor	2	28							0
	Leaks to the ambient	syngas in the enclosure/ambient	9	Sealing damaged	2	at service	2	36							0
P5.1 Pressure sensor	Measure out of range HIGH	Alarm High pressure, fuel cell stack stops	7	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	FC stack does not work	2	28							0
	Measure out of range LOW	Fuel cell stack does not stop if a High pressure occurs	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0

	Measure in scale but wrong	Fuel cell stack does not stop if a High pressure occurs, Alarm High pressure, fuel cell stack stops	6	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	5	60							0
TC5.1 thermocouple	Measure out of range HIGH	Alarm High temperature, FC stack stops	2	Failure of wires, Contamination of junction. Failure of control	2	other temperature sensor	2	8							0
	Measure out of range LOW	Fuel cell stack does not stop if a High temperature occurs	8	Failure of wires, Contamination of junction. Failure of control	2	other temperature sensor	2	32							0
	Measure in scale but wrong	Alarm High temperature, FC stack stops. Fuel cell stack does not stop if a High temperature occurs	8	Drift of measure in time, contamination, mechanical damage to wires. Failure of control	3	other temperature sensor	4	96							0

Anode	Leaks of syngas to the ambient	FC performances loss, potential anode starvation, potential anode electrode carbon corrosion	9	overpressure	2	FC stack performances (voltage)	4	72							0
	Catalyst poisoning	FC performances loss, FC stack stops	5	High CO content into the syngas	5	FC stack performances (voltage)	3	75							0
P5.2 Pressure sensor	Measure out of range HIGH	Alarm High pressure, fuel cell stack stops	5	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	FC stack does not work	2	20							0
	Measure out of range LOW	Fuel cell stack does not stop if a High pressure occurs	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							

	Measure in scale but wrong	Fuel cell stack does not stop if a High pressure occurs, Alarm High pressure, fuel cell stack stops	6	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	5	60							0
TC5.2 thermocouple	Measure out of range HIGH	Alarm High temperature, FC stack stops	3	Failure of wires, Contamination of junction. Failure of control	2	other temperature sensor	2	12							
	Measure out of range LOW	Fuel cell stack does not stop if a High temperature occurs	3	Open circuit, contamination. Failure of control	2	other temperature sensor	2	12							0
	Measure in scale but wrong	Alarm High temperature, FC stack stops. Fuel cell stack does not stop if a High temperature occurs	3	Drift of measure in time, contamination, mechanical damage to wires. Failure of control	3	other temperature sensor	3	27							0

Condensate discharge	Failed closed	System reduced performance till system stops	9	Float stuck, Exit line obstructed, Seal stuck	3	System stops	8	216							0
	Failed open	Syngas discharged in the recirculation pump	5	Float stuck, Exit line obstructed, Seal stuck	3	Recirculation pump working with performance reduction	3	45							0
Recirculation Pump	Always turn ON	potential anode underpressure	6	Failure of control	2	Pressure sensor	3	36							
	Always turn OFF	No syngas circulation through the anode	7	Failure of control, mechanical damage, wires damage	3	Pressure sensor	3	63							
Pressure sensor P5.3	Measure out of range HIGH	Alarm High pressure, fuel cell stack stops	7	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	FC stack does not work	2	28							

	Measure out of range LOW	Alarm Low pressure, fuel cell stack stops	7	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	2	28							
	Measure in scale but wrong	Fuel cell stack does not stop if a High pressure occurs, Alarm High pressure, fuel cell stack stops	6	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	2	24							
Purge Valve V5.2	Failed open	FC stacks stops, possible cell poisoning	7	Mechanical damage, rust, dust	2	at service	2	28							
	Failed closed	potential system downpressure, FC stacks stops	7	Mechanical damage, rust, dust	2	at service	2	28							

	Leaks IN to Out	potential system downpressure, FC stacks stops	7	Mechanical damage, rust, dust	2	at service	2	28							
	Leaks to the ambient	syngas in the enclosure/ambient	9	Sealing damaged	2	at service	2	36							
On/Off valve V5.1	Failed open	none	1	Mechanical damage, rust, dust	2	at service	2	4							
	Failed closed	potential system overpressure, FC stacks stops, possible cell poisoning	7	Mechanical damage, rust, dust	2	pressure sensor	2	28							
	Leaks IN to Out	potential system overpressure, FC stacks stops, possible cell poisoning	7	Mechanical damage, rust, dust	2	pressure sensor	2	28							
	Leaks to the ambient	syngas in the enclosure/ambient	9	Sealing damaged	2	at service	2	36							
Sample gas analysis manual valve	Failed open	impossible to analyse anode exhausted gas	1	Mechanical damage, rust, dust	1	None	1	1							

	Failed closed	syngas in the ambient	9	Mechanical damage, rust, dust	2	at service	1	18							
	Leaks IN to Out	potential leak of anode exhausted gas in ambient	9	Proper choose of material	2	at service	1	18							
	Leaks to the ambient	potential leak of anode exhausted gas in ambient	9	Sealing damaged	2	at service	1	18							
Inverter FC	Supply electric power	none	1	none	1	FC stack performances (voltage)	2	2							0
	Does not supply electric power	FC stack does not work	5	Mechanical damage or electrical failure	2	Inverter alarm	2	20							0
Disconnector	contact to grid stays open	FC stack does not work	5	Electronics, lifetime degradation, EOL of component	2	FC stack does not work	2	20	This Item out of FMEA evaluation as component full certified as safety device						0
	contact to grid stays closed	supply electric power to the grid when should not do it	10	over temperature, stuck contact	1	none	10	100							0

Air blower	Supply maximum flow	air manifold overpressure, potential difficulties in air management, system stops	4	Electronics, lifetime degradation, EOL of component	2	pressure sensor	2	16							0
	Does not supply air	no air flow for devices, system stops,	5	Electronics, lifetime degradation, EOL of component, failure of control, cable failure	3	system not works	2	30							0
f7.1 Mass flow controller	Supply air but wrong flow rate	air manifold overpressure, scarse air flow for devices, system stops	5	Electronics, lifetime degradation, EOL of component, failure of control	3	different sensors and devices (pressure, CO, temperature, voltage, MF)	2	30							0
	Measure out of range HIGH	FC performances loss, potential cathode starvation, Fuel cell stack stops due to lack of air	8	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	FC stack performances (voltage), pressure sensor	2	32							0

	Measure out of range LOW	FC performances loss, air flow higher than allowed, potential fuel cell stack cathode dehydration, FC stack stops	4	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	FC stack performances (voltage), pressure sensor	4	32							0
Humidifier	Measure in scale but wrong	FC performances loss, air flow out of control, potential cathode starvation, potential fuel cell stack cathode dehydration, potential system stop	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	FC stack performances (voltage), pressure sensor	4	64							0
	Leaks from dry side to wet side	FC performances loss, potential scarse air flow to cathode, FC performances loss	4	lifetime degradation, overpressure, extreme dehydration	3	FC stack performances (voltage)	3	36							0

P7.2 Pressure sensor	Leaks of air to the ambient	FC performances loss, potential scarse air flow to cathode	4	lifetime degradation, overpressure, extreme dehydration	3	FC stack performances (voltage)	3	36							0
	Measure out of range HIGH	Alarm High pressure, FC stack stops	5	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	other pressure sensor	3	30							0
	Measure out of range LOW	FC stack does not stop if a High pressure occurs	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0
TC7.2 thermocouple	Measure in scale but wrong	FC stack does not stop if a High pressure occurs. Alarm High pressure, FC stack stops	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0

	Measure out of range HIGH	Alarm High temperature, FC stack stops	5	Failure of wires, high temp for long time. Contamination of junction. Failure of control	3	other temperature sensor	2	30							0
	Measure out of range LOW	FC stack does not stop if a High temperature occurs	7	Open circuit, contamination. Failure of control	3	other temperature sensor	2	42							0
Cathode	Measure in scale but wrong	FC stack does not stop if a High temperature occurs. Alarm High temperature, FC stack stops	7	Drift of measure in time, contamination, mechanical damage to wires. Failure of control	5	other temperature sensor	2	70							0
	Leaks of air to the ambient	Potential cathode starvation, potential cathode electrode carbon corrosion	7	overpressure	2	FC stack performances (voltage)	3	42							0

Condensate discharge	Electrode dehydration	FC performances loss, FC stack stops	5	Low water content into the air	4	FC stack performances (voltage)	3	60							0
	Failed closed	FC reduced performance till system stops	6	Float stuck, Exit line obstructed, Seal stuck	3	System stops	2	36							0
Tc7.4 thermocouple air exhaust	Failed open	Air discharged in collector cond. Disch	3	Float stuck, Exit line obstructed, Seal stuck	3	Collector cond disch	2	18							0
	Measure out of range HIGH	Alarm High temperature, FC stack stops	5	Failure of wires, high temp for long time. Contamination of junction. Failure of control	3	other temperature sensor	2	30							
	Measure out of range LOW	FC stack does not stop if a High temperature occurs	7	Open circuit, contamination. Failure of control	3	other temperature sensor	2	42							

	Measure in scale but wrong	FC stack does not stop if a High temperature occurs. Alarm High temperature, FC stack stops	7	Drift of measure in time, contamination, mechanical damage to wires. Failure of control	5	other temperature sensor	2	70							
P6.3 Pressure sensor	Measure out of range HIGH	Alarm High pressure, FC stack stops	5	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	other pressure sensor	3	30							
	Measure out of range LOW	FC stack does not stop if a High pressure occurs	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0

P6.1 Pressure sensor	Measure in scale but wrong	FC stack does not stop if a High pressure occurs. Alarm High pressure, FC stack stops	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0
	Measure out of range HIGH	none	1	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	none	10	20							0
	Measure out of range LOW	Alarm Low pressure, fuel cell stack stops	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0

Mf6.1 Mass flow meter	Measure in scale but wrong	Fuel cell stack does not stop if a Low pressure occurs	8	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	3	48							0
	Measure out of range HIGH	none	1	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	at service	2	4							0
	Measure out of range LOW	none	1	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	at service	2	4							0

Hydraulic Head	Measure in scale but wrong	none	1	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	at service	2	4							0
	clogging of pipe	When water heat up cannot expand, overpressure	5	dust or something similar	2	pressure sensors	2	20							
P6.2 Pressure sensor	connection break off	Water level decrease, FC stack inlet pressure decrease, potential Low pressure alarm, FC stack stops	5	lifetime degradation	1	pressure sensor, at service	3	15							0
	Measure out of range HIGH	Alarm High pressure, fuel cell stack stops	5	Electronics, lifetime degradation, EOL of component, Short circuit in the connecting cable	2	other pressure sensor	1	10							0

	Measure out of range LOW	Alarm Low pressure, fuel cell stack stops	5	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	1	10							0
TC6.1 thermocouple	Measure in scale but wrong	Fuel cell stack does not stop if a High or Low pressure occurs	6	Electronics, lifetime degradation, EOL of component, Open circuit in the connecting cable	2	other pressure sensor	1	12							0
	Measure out of range HIGH	Alarm High temperature, fuel cell stack stops	5	Failure of wires, . Contamination of junction. Failure of control	3	other temperature sensor	2	30							0
	Measure out of range LOW	Fuel cell stack does not stop if a High temperature occurs	7	Open circuit, contamination. Failure of control	3	other temperature sensor	2	42							0

stack cooling side	Measure in scale but wrong	Fuel cell stack does not stop if a High temperature occurs. Alarm High temperature, fuel cell stack stops	7	Drift of measure in time, contamination, mechanical damage to wires. Failure of control	5	other temperature sensor	2	70							0
	Leaks of water to the ambient	Emptying of cooling circuit, over temperature of stack, over temperature of PROX, potential system stop	7	overpressure	2	Pressure and temperature sensors	2	28							0
	Leaks of water to cathode or anode	Emptying of cooling circuit, over temperature of stack, over temperature of PROX, flooding of cathode or anode, potential system stop	7	overpressure, carbon corrosion	2	Pressure and temperature sensors	2	28							

	Clogging of stack water cooling channel	increase of pressure into cooling side, hot spot into the FC stack, potential system stop	7	dust or something similar	3	pressure sensors	2	42							0
FMEA SUMMARY															
MAX			**Sev**		**Prob**		**Det**	**RPN**				**New Sev**	**New Occ**	**New Det**	**New RPN**
MAX			**10**		**5**		**10**	**216**							
AVERAGE			**5,8**		**2,4**		**2,5**	**34,8**							

Based on the average values of Severity, Probability and detection can be seen that the probability of failure of the stack part is low and even if something happens it does not have a high severity.

5 CONCLUSIONS

A safety assessment for the FluidCELL system was carried out. For the fuel processor, the main directives applied were the Machinery Directive (2006/42/EC), the Pressure Equipment Directive (2014/68/EU), the EN 60204-1 Safety of machinery, and the EN 60079-10-1 Explosive atmospheres.

A risk analysis was done. Adequate mitigation measures were taken where needed. The safety assessment was essential to bring forward a system with safe and robust operation.