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REVISION HISTORY

A record of revisions and amendments to this document is given below:

Rev.	Date	Reason for amendments	Section changes from previous version
DRAFT	29-03-2023	DRAFT Document Issued	

List of abbreviations

Abbreviation	Description
ALARP	As Low As Reasonably Practicable
BS	British Standard
EMEA	Europe, Middle East, Africa
ESD	Emergency Shut Down
FC	Fuel Cell
H2	Hydrogen
HAZID	Hazard Identification
HMI	Human Machine Interface
HSE	Health and Safety Executive
HX	Heat Exchanger
IGF	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMO	International Marine Organisation
ISO	International Standards Organisation
LR	Lloyd's Register
N2	Nitrogen
O2	Oxygen
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
PRV	Pressure Relief Valve
SCE	Safety Critical Equipment
SME	Subject Matter Expert
SOV	Solenoid Valve
UPS	Uninterruptible Power Supply

Contents

1. Introduction

The shipping industry currently emits 3% of all the greenhouse gases in the world. Therefore, it is more than relevant that the shipping industry and the port authorities start to invest in decarbonisation, searching for the implementation of zero emission technologies. Today, there are quite a lot of obstacles in order to realise a full-scale use of zero emissions fuels on board of the ships and vessels. In order to tackle some of these obstacles, the ISHY project will investigate the following working fields:

- testing of the effectiveness of the low carbon propulsion technologies
- demonstrating the feasibility of H2 bunkering-facilities in a port
- prepare tools to support the transition to low-carbon propulsion systems for both retrofitting and building of new ships

To support the initiatives on alternative, low and zero-carbon fuels for the maritime industry, Work Activity A1.9 a Hazard & Operability (HAZOP) Study was completed on the zepp.X150 Fuel Cell System designed by zepp.solutions on 10 March 2023.

Prior to the workshop commencing, Lloyd's Register issued a Terms of Reference (ToR) document [1].

1.1 Objective

The objective of this report is to summarise the HAZOP Study methodology and provide details of outcome of the workshop.

1.2 Scope

The HAZOP solely assessed the Fuel Cell Systems and as such Fuel Storage and Conditioning Systems were considered outside the Scope of this Work Package.

1.3 Design information

Reference should be made to the Terms of Reference (ToR) document [1] and where additional information has been made available prior to, or post, the HAZID workshop this should be clarified.

2. HAZOP

2.1 Objectives

The objectives of the HAZOP study were:

- to identify any operability hazards associated with the system
- to understand how the system could operate outside of its intended design parameters
- to review existing design safeguards
- to make recommendations where necessary

2.2 Methodology

A HAZOP study is a methodical technique used to identify hazards and operational issues associated with a process or the integration of a design into another system. It was completed in line with IEC 61882:2001, Hazard and operability studies (HAZOP studies) [2]. The process is summarised in the flowchart shown in Figure 1.

The system was divided into nodes, with guide words (e.g. High, Low, No) applied to parameters (e.g. Flow, Temperature, Pressure) to produce a comprehensive list of how it could operate outside of its intended design. The consequences were determined and assessed with consideration given to any safeguards included within the systems design.

The process was as follows:

Deviation – The deviation was determined by the application of the guideword and parameter to the elements within the node. The team discussed whether the deviation was possible, and only assessed it, if deemed so.

Causes – The team established possible causes for the deviation, if the consequences of the deviation were insignificant the process was terminated at this point (this was recorded in the worksheet).

Consequences – The team considered largely considered consequences that resulted in harm to persons and / or the environment.

Safeguards – Existing safeguards in the design, Cause & Effect drawing, operating manuals were discussed, in particular the robustness of them and their suitability. A HAZOP is not a forum to engineer / re-engineer safeguards, any addition or modification to these were captured under 'follow-up' Actions.

Recommendations – Were suggested if any further information or supporting studies on the design / safeguards were required.

Actions – A list of actions and persons responsible for them was collected throughout the HAZOP.

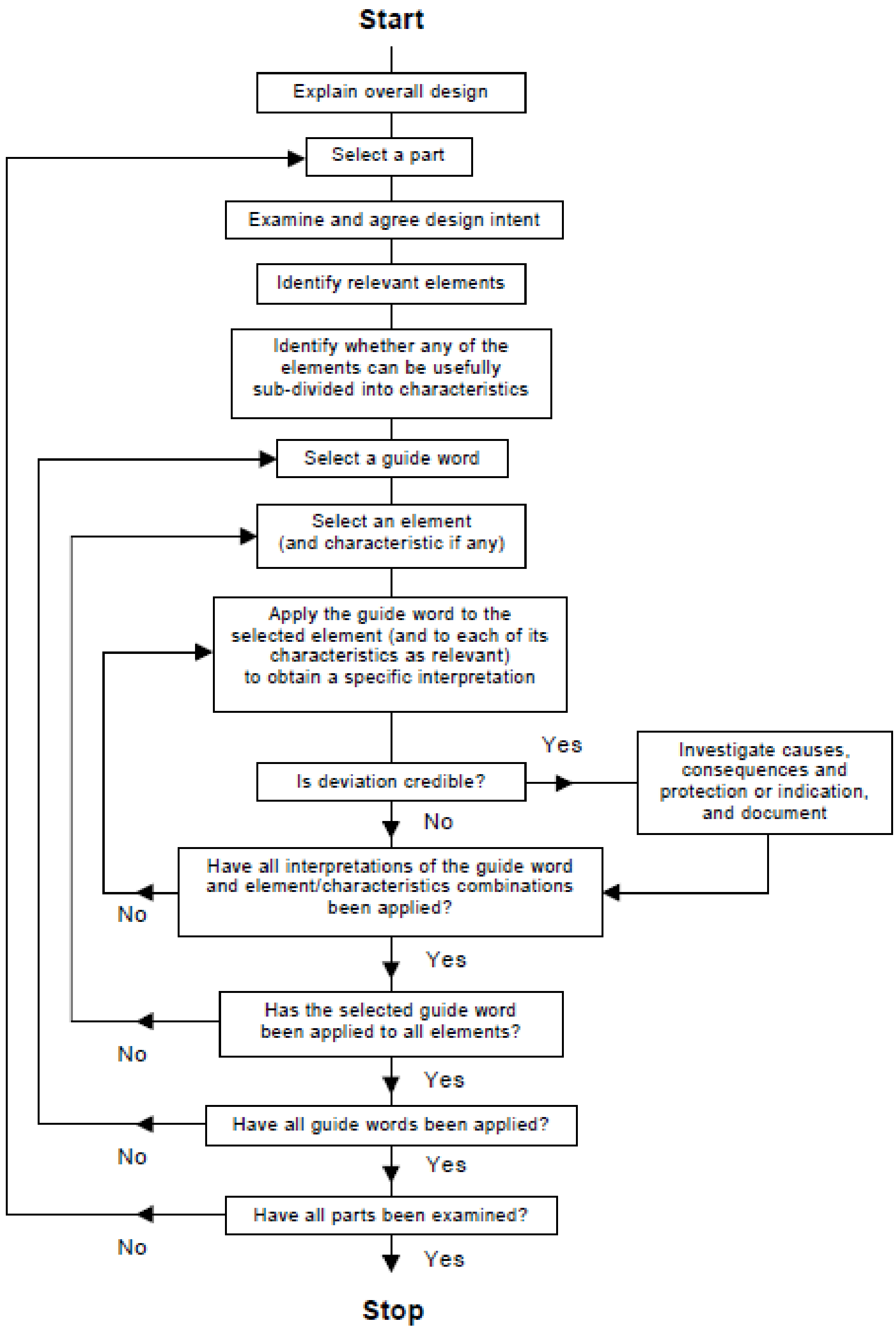

Figure 1 Flow Chart of the HAZOP Procedure (IEC 61882)

2.2.1 Assumptions

The HAZOP study assumed the following:

- The systems, equipment and layout was per the information shared prior to the workshop
- The systems shall be installed, operated and maintained in accordance with the manufacturers recommendations
- Only single failures / events were considered, i.e. multiple failures were not be considered credible, unless they could go undetected (hidden failures)
- The safeguards, including operational procedures discussed and included within the HAZOP Worksheet were in place and functioned as outlined
- The FC is providing the ship with a supplementary source of power
- If the FC system is to be installed onboard a ship it would undergo Type Approval

2.2.2 Node Definitions

The system was divided into the following nodes, as shown in Table 1 for effective review during the workshop. The Node mark up on flow diagram is included in Appendix 4.

Node No.	Description	Remark
1	Anode	
2	Cathode	
3	Coolant	
4	General Cabinet Design	

Table 1, Nodes for HAZOP Workshop

2.3 Attendance

The HAZOP workshop sessions attendance has been recorded in Table 2.

Name	Company/Department	Role
Alex Pedgrift	Lloyd's Register	Facilitator & Scribe
HRR Manager, Mechanical Engineer with more than 15 years' experience working in aviation, power generation, offshore oil & gas and marine sectors. Facilitator / scribe for a number of risk assessments on alternative fuels and to support AD&As.		
Jonas Brendelberger	zepp.solutions	SME
Co-Founder and Product Expert for zepp.solutions		
Aditi Ahuja	zepp.solutions	Engineer
Technical Engineer for zepp.solutions		

Table 2: HAZOP workshop attendance record

1.1 Sessions and Timings

Sesion	Date	Topic / Subject	Duration (hours:minutes)
1	10/03/2023	Introductions	00:10
2	10/03/2023	HAZOP Methodology Introduction	00:10
3	10/03/2023	zepp.X150 System Introduction	00:20
4	10/03/2023	HAZOP Node 1, Anode	01:20
5	10/03/2023	HAZOP Node 2, Cathode	01:10
6	10/03/2023	HAZOP Node 3, Coolant	00:35
7	10/03/2023	HAZOP Node 4, General Cabinet Design	00:20
8	10/03/2023	'Wash-up'	00:10

2.4 Actions register

The HAZOP team made the recommendations listed in Table 3 below:

Action	Place(s) Used	Responsibility	Comments
1. Consider installing differential pressure monitoring for the FC cabinet to ensure that it maintains a lower pressure to its adjacent / external space. There could be a two tier control logic: 1st alarm level start the second fan unit 2nd level controlled shutdown of the FC.	Consequences: 1.4.1.1, 4.1.1.1, 4.4.1.1	zepp.solutions	
2. Consider installing 100 % duty / standby ventilation fan arrangement, with automatic changeover upon detection of a functional failure with the duty unit.	Consequences: 1.4.1.1, 4.1.1.1	zepp.solutions	
3. Consider the installation of an H2 detector within the coolant system expansion pot, that will shutdown the FC upon detection of H2.	Consequences: 1.4.2.1	zepp.solutions	
4. Consideration should be given to duplicating the gas detectors in the exhaust duct, with an appropriate voting philosophy 1oo2 or 2oo3.	Consequences: 1.4.4.1, 1.4.5.1	zepp.solutions	
5. Assess the impact of residual heat energy in the system and what the pressure increase could be expected in the anode, and whether this could lead to a loss of containment incident.	Consequences: 1.9.2.1	zepp.solutions	
6. Review the cathode separator design to ensure carryover of liquids damaging the cathode pump turbine is suitably mitigated	Consequences: 2.5.1.1	zepp.solutions	
7. Complete a similar assessment to the smaller (50 kW) FC unit to confirm that the H2 concentrations in the event of low flow through the stack housing ventilation line while the FC is shutdown remain below LEL.	Consequences: 2.1.6.1	zepp.solutions	
8. Assess the systems heat / mass balance for the loss of cooling system event to understand the consequences on the FC membrane	Consequences: 3.9.1.2	zepp.solutions	

Table 3: HAZOP - Actions register

3. Discussion[1]

A comprehensive HAZOP was completed on the proposed fuel cell system. The system designer engaged fully throughout the workshop, providing technical input into the system design and operational philosophy. They demonstrated an excellent understanding of the system, which did have some similarities to a smaller unit with which they have previous operating experience with.

Based on the proposed mitigation measures and safeguards no significant safety risks were identified that could not be mitigated by further design enhancements. To support this, eight recommendations were made. These were related to:

- Design enhancements that could be made to the ventilation systems through additional control and monitoring systems and the introduction of redundancy in the critical equipment.
- Installation of additional gas detectors at locations were H2 crossover could occur and duplication of instrumentation to avoid spurious alarms / system responses.
- Completion of further assessments on the system (many of which had already been completed on zepp.solution's smaller unit)

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4. References

[1] LR, 1904-0040, Terms of Reference - zepp.X150, March 2023

[2] British Standards Publication - *Hazard and operability studies (HAZOP studies)* - BS IEC 61882-2016 - 2016

Appendix 1 HAZOP Worksheet

Node: 1. Anode

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
1. No/Less Flow	1. No / Low Flow Through Valve ANS V, ANHX, ANFILT, SUPPV	1. Lower power output from the FC	1. The control and monitoring systems compares H2 mass flow to the FC stack power. If this deviates outside of a defined allowable threshold, an alarm would be generated and the system would try and control the cathode flow to a desired FC power output. If the control and monitoring system is unable to react to the deviations there would be a controlled shutdown of the FC.			
	2. No / Low Flow Through Valve DRAINV	1. There would be water carryover into the stack in the lower cells	1. There is monitoring of the solenoid valve coil to detect the valve position. There would be an alarm and controlled shutdown if this deviated from the valves expected position.			
			2. The control and monitoring systems monitor cell voltages. These would differ between the upper and lower cells (as there would be water in the lower ones). If the control and monitoring system detects a deviation of the cell voltage spread from the defined threshold there would be a controlled shutdown of the FC.			

<table>
<thead>
<tr><th rowspan="2">Deviations</th><th rowspan="2">Causes</th><th rowspan="2">Consequences</th><th rowspan="2">Safeguards</th><th colspan="2">Recommendations</th><th rowspan="2">Remarks</th></tr>
<tr><th>Action</th><th>By</th></tr>
</thead>
<tbody>
<tr><td rowspan="2"></td><td rowspan="2">3. No / Low Flow Through Valve PURGEV</td><td rowspan="2">1. There would be the accumulation of other gases (N2)</td><td>1. There is monitoring of the solenoid valve coil to detect the valve position.

There would be an alarm and controlled shutdown if this deviated from the valves expected position.</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>2. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to the reduction in H2 supplied to the cells.

If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.</td></tr>
<tr><td rowspan="3">2. More Flow</td><td>1. More Flow Through Valve SUPPV</td><td>1. There would be a pressure rise in the stack, resulting in damage to the stack</td><td>1. Pressure transmitter, PT-005 (performance level C/D), will detect a high pressure and close valves ANSV and SUPPV</td><td></td><td></td><td></td></tr>
<tr><td>2. More Flow Through Valve DRAINV</td><td>1. There would be a pressure drop in the stack</td><td>1. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2.

If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.</td><td></td><td></td><td></td></tr>
<tr><td>3. More Flow Through Valve PURGEV</td><td>1. There would be a pressure drop in the stack</td><td>1. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2.</td><td></td><td></td><td></td></tr>
</tbody>
</table>

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
3. Reverse Flow	1. No credible hazardous scenarios were identified.					
4. Elsewhere Flow	1. External Leak	1. Increased H2 concentration in the H2 FC Cabinet Fire / Explosion risk Flammable between 5% and 75% (Volume)	1. There are two H2 Detectors installed in the FC cabinet. They will give an alarm signal at 10% LEL and emergency shutdown at 20% LEL.	1. Consider installing differential pressure monitoring for the FC cabinet to ensure that it maintains a lower pressure to its adjacent / external space. There could be a two tier control logic: 1st alarm level start the second fan unit 2nd level controlled shutdown of the FC.	zepp.solutions	
			2. There is an extraction type forced ventilation system, which is continuously running to provide 10 AC/hr. Upon detection of H2 concentration > 10% LEL it will ramp up to 40 AC/hr.	2. Consider installing 100 % duty / standby ventilation fan arrangement, with automatic changeover upon detection of a functional failure with the duty unit.	zepp.solutions	
			3. There are two heat detectors fitted in the cabinet that will complete an emergency shutdown of the system upon detection of a fire.			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			4. A hazardous area classification assessment has been completed for the FC cabinet. The space shall follow an ESD protected philosophy.			
	2. Crossover into ANHX	1. H2 crossover into the coolant side Fire / Explosion risk in the expansion pot Flammable between 5% and 75% (Volume)	1. Large leaks are likely to be detected by the control and monitoring system as a H2 pressure drop, and a rise in the coolant pressure.	3. Consider the installation of an H2 detector within the coolant system expansion pot, that will shutdown the FC upon detection of H2.	zepp.solutions	
			2. There is an extraction type forced ventilation system, which is continuously running to provide 10 AC/hr. Upon detection of H2 concentration > 10% LEL it will ramp up to 40 AC/hr.			
			3. It was discussed that there would not be an ignition source in the expansion pot.			
			4. There is a pressure relief valve on the expansion pot, this would vent H2 into the FC cabinet space and the external leak scenario safeguards would be applicable.			
			5. There are two H2 Detectors installed in the FC cabinet. They will give an alarm signal at 10% LEL and emergency shutdown at 20% LEL.			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			6. There are two heat detectors fitted in the cabinet that will complete an emergency shutdown of the system upon detection of a fire.			
			7. A hazardous area classification assessment has been completed for the FC cabinet. The space shall follow an ESD protected philosophy.			
	3. Crossover into Stack, due to membrane rupture	1. There could be a flame / fire event in the stack	1. There are limited ignition sources in the area			
			2. Cell voltage measurement would detect a drop in the cells performance and the system would be shutdown on low voltage.			
			3. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
	4. Through Valve DRAINV	1. There could be a fire / explosion in the exhaust Flammable between 5% and 75% (Volume)	1. There are limited ignition sources in the area	4. Consideration should be given to duplicating the gas detectors in the exhaust duct, with an appropriate voting philosophy 1oo2 or 2oo3.	zepp.solutions	
			2. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
			3. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2. If the control and monitoring system detects a drop in the cell voltages outside of a defined			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
	5. Through Valve PURGEV	1. There could be a fire / explosion in the exhaust Flammable between 5% and 75% (Volume)	1. There are limited ignition sources in the area	4. Consideration should be given to duplicating the gas detectors in the exhaust duct, with an appropriate voting philosophy 1oo2 or 2oo3.	zepp.solutions	
			2. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
			3. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
	6. Crossover into ANPUMP	1. No credible hazardous scenarios were identified.				
5. High Level	1. Water Separator	1. Already covered above in the worksheet				
6. Low Level	1. No credible hazardous scenarios were identified.					
7. High Temperature	1. High H2 Supply Temperature	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
	2. High Temperature in the Stack Due to loss of cooling	1. Damage to the fuel cell membrane	1. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
			2. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
			3. The control and monitoring systems monitor multiple parameters that would identify an issue with the cooling water system, including: FCPUMP, FLT301, PT311, TT301, TT302. If these deviated from defined thresholds for normal operating conditions, there would be a controlled shutdown of the FC.			
	3. High Temperature in the ANPMP Due to loss of cooling	1. Damage to the pump	1. This would be detected by the pump self monitoring system, which would automatically derate. If this could not be managed within defined thresholds for normal operating conditions, there would be a controlled shutdown of the FC.			
8. Low Temperature	1. Low H2 Supply Temperature	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
		outside of the scope of the HAZOP				
	2. Low Temperature in the Stack Due to increased cooling prior to start-up	1. Damage to the fuel cell membrane (considered extremely unlikely if the system was installed in a machinery room)	1. In cold ambient conditions, the coolant is pre-heated coolant and circulated prior to the unit starting-up, this is a start permissive and if the system failed of the heating cycle was not complete the FC would not be started			
	3. Low Temperature in the ANPMP Due to increased cooling	1. No credible hazardous scenarios were identified.				
9. High Pressure	1. Considered largely covered by the flow discussions. No high pressures can be generated by the anode pump, due to its design.					
	2. High pressures due to residual heat in the system during system shutdown / ESD	1. Release of H_2 and a fire / explosion event Flammable between 5% and 75% (Volume)	1. The system has been designed with consideration to the expected pressures that could be seen during normal and abnormal operating conditions, with a factor of safety applied	5. Assess the impact of residual heat energy in the system and what the pressure increase could be expected in the anode, and whether this could lead to a loss of containment incident.	zepp.solutions	
10. Low Pressure	1. Already covered above in the worksheet (low flow)					
11. Composition	1. Poor quality H_2 sent to the FC	1. No safety consequences were identified, it could result in poisoning of the stack, which will impact the operation of the system, however this was				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
		considered outside of the scope of the HAZOP				

Node: 2. Cathode

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
1. No/Less Flow	1. No / Low Flow Through CAFILT, CAPMP, CAHX, CAHUM-1, CAHUM-2, Valve CAUSV	1. It wouldn't be possible to get the right operational conditions for the FC, therefore there would be lower power output from it	1. For the filter, differential Pressure Transmitter, DPT211 would detect a high dP and alarm / shutdown of the system			
			2. For the Cathode Pump, Mass Flow, MFT 201 and Pressure Transmitter PT221 would alarm if the system deviated from expected parameters, the control system would try and make changes to reach desired outputs. If the control and monitoring system is unable to react to the deviations there would be a controlled shutdown of the FC.			
			3. For the Cathode Heat exchanger Pressure Transmitters PT203 & PT201 would alarm if the system deviated from expected parameters, the control system would try and make changes to reach desired outputs. If the control and monitoring system is unable to react to the deviations there would be a controlled shutdown of the FC.			
			4. The control and monitoring systems monitor cell voltages. There would be a drop in cell voltages due to reduced partial pressure of H2. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
	2. No / Low Flow Through Valve CADSV, CAHUM-1, CAHUM-2, CASEP	1. There could be an increased pressure on the stack, resulting in damage to the membrane	1. Mass Flow, MFT 201 would be controlling the cathode air pump to deliver the required output. If the control and monitoring system is unable to reach the required output there would be a controlled shutdown of the FC.			
			2. A high pressure at Pressure Transmitters, PT203 / PT221 would result in the derating of the cathode air pump and opening of the bypass valve CASBV. If the control and monitoring system is unable to reach the required output there would be a controlled shutdown of the FC.			
			3. Upon damage to the FC membrane, there would be a drop in the measured cell voltage. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
			4. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
	3. No / Low Flow Through Turbine, due to bypass valve	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
		outside of the scope of the HAZOP				
	4. No / Low Flow Through valve CATBV	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP The discharge from the turbine is upstream of the H2 connections and dilution is unaffected as there would be the same mass flow through the Cathode exhaust line.				
	5. No / Low Flow Through TUNE-2	1. There would be reduced flow to the Cathode Pump Vent Housing, resulting in higher operational temperatures. There could be a slight impact on system performance,	1. If the system deviated from expected parameters, the control system would try and make changes to reach desired outputs. If the control and monitoring system is unable to react to the deviations there would be a controlled shutdown of the FC.			
	6. Low flow through the Stack Housing Ventilation Line (during FC shutdown)	1. Under a 'dead-ship' scenario. If there is a leak there could be a flammable atmosphere generated	1. The H2 and air supply valves are normally closed by design and expected to limit the inventory 2. Under this condition there would be no ignition sources	7. Complete a similar assessment to the smaller (50 kW) FC unit to confirm that the H2 concentrations in the event of low flow through the stack housing ventilation line while	zepp.solutions	50 kW a leakage assessment was completed an showed that concentrations remained below LEL

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			3. There is likely to be some consumption of the H2 with the O2 4. There is a sealing arrangement to prevent a significant leakage from the stack.	the FC is shutdown remain below LEL.		
2. More Flow	1. More Flow Through CAFILT, CAPMP, CAHX, CAHUM-1, CAHUM-2, Valve CAUSV	1. Not considered credible, set-points would be derived during design and tested at factory and upon installation / commissioning				
	2. More Flow Through Valve CADSV, CAHUM-1, CAHUM-2, CASEP	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				
	3. More Flow Through CAPMP Vent Outlet, CASIL	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				
	4. More Flow Through TUNE-2	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
3. Reverse Flow	1. No credible hazardous scenarios were identified.					
4. Elsewhere Flow	1. External Leak	1. Before the pump, there could be unfiltered air into the stack, which could result in damage / degradation of it	1. Inspection and maintenance tasks shall be completed to ensure the equipment is working correctly			
			2. Mass Flow, MFT 201 would be controlling the cathode air pump to deliver the required output, it is likely that an external leakage would result in the FC performance being affected			
			3. For the filter, differential Pressure Transmitter, DPT211 would detect an issue			
		2. After the pump, the consequences were considered to be similar to those assessed under low flow				
		3. After mixing with anode purge, a leak of diluted H2 into the cabinet. A fire / explosion event Flammable between 5% and 75% (Volume)	1. This would be detected by H2 detectors			
			2. Gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			
	2. Crossover into CAHX	1. Small leak No safety consequences were identified, there could be a slight impact on system performance,	1. A low pressure at PT203, less that what was measured at the mass flow meter (with pressure losses considered)and would shutdown the system			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
		however this was considered outside of the scope of the HAZOP				
		2. Large leak There would be air into the coolant, detected by overheating of the stack (as already covered by Node 1, high temperature)				
	3. Crossover into CAHUM-1 / -2	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				
	4. Crossover into Stack	1. Already covered under Node 1				
	5. Leak through Valve CASBV	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				
	6. Leak through Valve CATBV	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered				

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
		outside of the scope of the HAZOP				
5. High Level	1. High Level in CASEP	1. There could be the water 'carried over' into the turbine resulting in damage to it	1. By its design it is expected that the separator shall prevent liquid 'carry-over'	6. Review the cathode separator design to ensure carryover of liquids damaging the cathode pump turbine is suitably mitigated	zepp.solutions	
6. Low Level	1. Low Level in CASEP	1. No safety consequences were identified				
7. High Temperature	1. Failure of the CAHX, there could be drying of the membrane	1. Damage to the fuel cell membrane	1. Temperature Transmitter, TT224 would detect a high temperature and shutdown the system			
			2. Temperature Transmitter, TT204 would detect a high temperature and shutdown the system			
			3. Humidity sensors HT211 / HT212 would detect lack of humidity and shutdown the system			
			4. Upon damage to the FC membrane, there would be a drop in the measured cell voltage. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
			5. Upon damage to the membrane, gas detector, H2T203 would detect a high H2 concentration in the stack exhaust and initiate a shutdown of the system			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
8. Low Temperature	1. Low ambient temperatures	1. No safety consequences were identified, there could be a slight impact on system performance, however this was considered outside of the scope of the HAZOP				
9. High Pressure	1. This would result in damage to the FC membrane, the consequence and safeguards would be similar to Elsewhere Flow, Node 1					
10. Low Pressure	1. Already covered by Low Flow					
11. Composition	1. Poor quality air sent to the FC1.	1. It could result in damaging of the stack.	1. There is an activated carbon filter installed in the system to remove any damaging contaminants. Differential Pressure Transmitter, DPT211 would detect an issue with its operation			

Node: 3. Coolant

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
1. No/Less Flow	1. Loss of coolant	1. Overheating of liquid cooled equipment, resulting in damage to them. Potential fire risk	1. The liquid cooled equipment (Converter, Motor, Pump and Motor Controller) all have internal temperature monitoring to derate them at high temp and shutdown if temperatures continue to increase to a defined shutdown limit			
	2. FC Circuit, already covered under Node 1					
2. More Flow	1. No credible hazardous scenarios were identified.					
3. Reverse Flow	1. No credible hazardous scenarios were identified.					
4. Elsewhere Flow	1. External leakage - LT System	1. There could be dry-running of the pump, resulting in damage to it.	1. Pressure transmitter, PT-411 would detect dry-running of the pump.			
	2. External leakage - HT System	1. There could be dry-running of the pump, resulting in damage to it.	1. There shall be a drip tray installed under the equipment, with level detection monitoring, that will generate an alarm / shutdown			
			2. The control and monitoring systems monitor multiple parameters that would identify an issue with the cooling circuit including: TT301, TT302, TT304, TT224, FLT301. If these deviated from defined thresholds for normal operating conditions, there would be a controlled shutdown of the FC.			

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
5. High Level	1. Overfilling of both cooling systems	1. During operational temperature changes there could be the discharge of coolant out of the expansion pot relief valves to the cabinet	1. There shall be a drip tray installed under the equipment, with level detection monitoring, that will generate an alarm / shutdown			
6. Low Level	1. Considered already covered by leakage					
7. High Temperature	1. Heater control failure resulting in it remaining on	1. High coolant temperature	1. The control and monitoring systems monitor TT301 and TT302. If these deviated from defined thresholds for normal operating conditions, there would be a controlled shutdown of the FC.			
8. Low Temperature	1. Heater control failure resulting in it not running	1. Low coolant temperature, was considered an operational issue, rather than a safety related one	1. Pre-heated coolant is circulated prior to start-up in extreme cold temperatures, if this failed the FC would not be started			
9. High Pressure	1. Coolant pump failure, and residual heat in the system	1. 'Boiling' of the coolant and overpressurisation of the system	1. The expansion pot is fitted with a relief valve			
			2. There shall be a drip tray installed under the equipment, with level detection monitoring, that will generate an alarm / shutdown			
		2. Damage to the fuel cell membrane due to high temperature	1. The control and monitoring systems monitor multiple parameters that would identify an issue with the cooling circuit including: TT301, TT302, TT304, TT224. If these deviated from defined thresholds for normal operating conditions, there would be a controlled shutdown of the FC.	8. Assess the systems heat / mass balance for the loss of cooling system event to understand the consequences on the FC membrane	zepp.solutions	

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
			2. It was discussed that the membrane would start to 'dry' out, there would be a drop in the measured cell voltage. If the control and monitoring system detects a drop in the cell voltages outside of a defined threshold for normal operating conditions, there would be a controlled shutdown of the FC.			
10. Low Pressure	1. Considered already covered by low flow					
11. Composition	1. FC coolant should remain under a defined conductivity threshold	1. There would be a ground fault in the FC, resulting in damage to the FC	1. There is insulation monitoring of the HV & ground, this will result in a shutdown of the system if it drops below a defined threshold			
			2. There is an ion polisher system installed, DI Filter			

Node: 4. Cabinet

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
1. No/Less Flow	1. Loss of ventilation	1. Loss of a layer or protection in the event of a hydrogen leakage	1. PT201 is monitoring pressure	1. Consider installing differential pressure monitoring for the FC cabinet to ensure that it maintains a lower pressure to its adjacent / external space. There could be a two tier control logic: 1st alarm level start the second fan unit 2nd level controlled shutdown of the FC.	zepp.solutions	
			2. Pressure transmitter, PT-201 is monitoring the pressure in the space and will shutdown the systems, if this deviated from a defined threshold.	2. Consider installing 100 % duty / standby ventilation fan arrangement, with automatic changeover upon detection of a functional failure with the duty unit.	zepp.solutions	
2. More Flow	1. No credible hazardous scenarios were identified.					
3. Reverse Flow	1. No credible hazardous scenarios were identified.					
4. Elsewhere Flow	1. External leak from the FC Cabinet	1. Unable to maintain the DP from the extraction ventilation	1. Pressure transmitter, PT-201 is monitoring the pressure in the space and will shutdown the systems, if this deviated from a defined threshold.	1. Consider installing differential pressure monitoring for the FC cabinet to ensure that it maintains a lower pressure to its adjacent / external space.	zepp.solutions	

Deviations	Causes	Consequences	Safeguards	Recommendations		Remarks
				Action	By	
				There could be a two tier control logic: 1st alarm level start the second fan unit 2nd level controlled shutdown of the FC.		
5. High Level	1. No credible hazardous scenarios were identified.					
6. Low Level	1. No credible hazardous scenarios were identified.					
7. High Temperature	1. High air temperature from the ventilation system,	1. Overheating of equipment, resulting in damage to them. Potential fire risk	1. The main equipment (Converter, Motor, Pump and Motor Controller) are liquid cooled equipment and have internal temperature monitoring			
8. Low Temperature	1. No credible hazardous scenarios were identified.					
9. High Pressure	1. No credible hazardous scenarios were identified.					
10. Low Pressure	1. Considered already covered by low flow					
11. Composition	1. No safety related issues were identified, there is the ships ventilation filtration systems. It is expected as part of the design specification the ventilation system requirements would be defined					

Appendix 2 Tables

Appendix 3 Figures

Appendix 4 Design Drawings & Documentation.

Drawings have been removed due to their confidential nature.