PEMBeyond

PEMFC system and low-grade bioethanol processor unit development for back-up and off-grid power applications

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HAZOP report

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Summary

This deliverable reports the **Haz**ard and **Op**erability study (HAZOP) of the integrated PEMFC based power system operating on low-grade (crude) bioethanol that is developed in PEMBeyond project.

The HAZOP study was carried out in the beginning of year 2017 as a part of the integration of the individual subsystems into a functioning overall system and related development and design work at VTT. The objective of the HAZOP study was to identify and analyse hazards and operability problems related to the integrated PEMFC based power system and its operation, and thus provide feedback to the ongoing integration and development work, e.g. by suggesting possible improvements to the design or operation of the system.

The first section of this report gives an introduction, followed by the second section describing the system under study. The implementation of the HAZOP study is reported in section three, followed by results.

Moreover, the piping and instrumentation diagram and HAZOP worksheets are included as appendices.

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Contents

1. Introduction and study objective

This Deliverable deals with the **Haz**ard and **Op**erability study (HAZOP) of the integrated PEMFC based power system operating on low-grade (crude) bioethanol that is developed in PEMBeyond project. The system is intended for back-up and off-grid power generation and it uses crude bioethanol as primary fuel to produce electricity (see Fig.1). The system consists of the following four main subsystems (Koski et al. 2016):

- Bioethanol fuel processor (later FP)
- Pressure swing adsorption unit for H_2 purification (PSA)
- PEMFC system (FCS)
- Higher level control system.

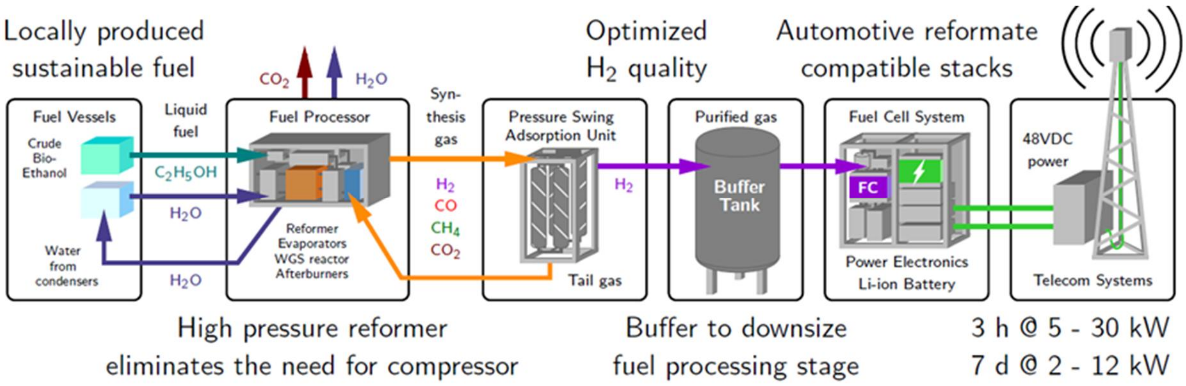

Fig. 1. The system concept showing the flow of fuel (bioethanol & water) through fuel processing and purification, finally entering the fuel cell system. (Koski et al. 2016)

As a part of the integration of the individual subsystems into a functioning overall system and related development and design work VTT Technical Research Centre of Finland Ltd (later VTT) carried out a HAZOP study for the system in the beginning of year 2017. The objective of the HAZOP study was to identify and analyse hazards and operability problems related to the integrated PEMFC based power system and its operation, and thus provide feedback to the ongoing integration and development work, e.g. by suggesting possible improvements to the design or operation of the system.

2. Description of the studied system

The following description of the studied system is based on Koski et al. (2016) article and the system piping and instrumentation diagram given in Appendix B. The description is focused on the steady state operation of the system as this was the studied operation mode in the HAZOP study carried out (see 3.2). In addition to Koski et al. (2016) article there exist also more detailed system descriptions but these are not public, so that's why the article in question has been used as a reference here.

Bioethanol fuel processor

The fuel processor (FP) includes a steam reformer reactor (SRR) and a water gas shift reactor (WGSR) integrated together with in an elaborate configuration of afterburners (AFBs) and heat exchangers (HXs). At steady state operation, most of the heat required in fuel processor is produced from the PSA tail gas. In addition, small amounts of ethanol may be dosed to AFB1 and AFB2 to sustain stable operation temperature.

For on-site H_2 generation the fuel processor is fed with a mixture of H_2O and EtOH, so that the steam to carbon (S/C) ratio is 4:1. The feed is divided into two evaporators (EVA1 & 2) heated by afterburners (AFB1 & 2). The gaseous ethanol steam mixture proceeds to the steam reformer, operated at about 730 °C and 8,5 bar(g).

The produced reformate gas is cooled to 400 °C before entering the WGS reactor (260–400 °C), where CO is converted to CO_2, reducing the CO content of 7 vol-% at SRR outlet to 0,3 vol-% at WGSR outlet (based on simulation). The gas is finally cooled down in COND1 to 20 °C, condensing the steam.

The high pressure of the fuel processor feeds (H_2O and EtOH) allows the FP to feed the PSA directly without a compressor. By volume, the gas feed to PSA should contain 70,7 % H_2, 24,4 % CO_2, 3,5 % CH_4, 0,5 % CO and 0,9 % H_2O.

Pressure swing adsorption unit

The pressure swing adsorption (PSA) unit separates the H_2 from reformate gas produced by the fuel processor. PSA unit employs multi-bed processes with complex valving between the feed stream, the beds and the product stream. The target is to reach CO content < 20 ppm in the purified H_2, with 70 % H_2 recovery.

From the PSA unit the purified H_2 flows through a buffer tank (H_2 tank in P&ID in Appendix B) to the fuel cell system (FCS). Before entering the FCS H_2 pressure is reduced by pressure reducer (PR1) to 0.7–4.0 bar(g). Tail gas from the PSA unit contains combustible components and is used for heat production in fuel processor (in AFB1 and AFB2).

Fuel cell system with power electronics

The fuel cell system (FCS) comprises of a PEMFC stack, balance of plant (BoP) components handling H_2, air and coolant delivery to the stack, power electronics including the Li-ion battery pack and the FCS control system. The 100-cell stack in the FCS features automotive type steel bipolar plates and reformate MEAs. The nominal operation point is at 0,6 A/cm^2 with the estimated power production around 7-9 kW depending on the final H_2 quality.

3. Implementation of the HAZOP study

3.1 Description of the HAZOP method

According to the standard IEC 61882[1] HAZOP is a structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment, or prevent efficient operation. A suitably experienced multidisciplinary team (HAZOP team) normally carries it out during a set of meetings.

1 IEC 61882 Hazard and operability studies (HAZOP studies) – Application guide (2001).

HAZOP deals with the identification of potential deviations from the design intent, examination of their possible causes and assessment of their consequences. The objectives of a HAZOP study are:

- to identify potential hazards in the system,
- to identify potential operability problems and in particular the causes of operational disturbances with the system.

HAZOP is based on the use of guidewords, which question how the design intention might not be achieved at each part[2] of the system.

The primary strength of HAZOP is that it presents a systematic, disciplined and documented approach. To achieve full benefits from a HAZOP study, it has to be properly documented and followed up. An important benefit of HAZOP studies is that the resulting knowledge, obtained by identifying potential hazards and operability problems in a structured and systematic manner, is of great assistance in determining appropriate remedial measures.

Detailed description of the HAZOP is available in the standard IEC 61882:2001 *Hazard and operability studies (HAZOP studies) – Application guide*[3]. Shorter description of the method can be found e.g. in the standard EN 31010:2010 *Risk management. Risk assessment techniques.*

3.2 Basis of the study and study limitations

In the focus of the study were both aspects of HAZOP methodology i.e. hazards that can endanger safety or health of persons (either system operation personnel or external people) and deviations that can cause operational problems or equipment failures.

The study carried out focused on hazards and operability problems of the integrated system, and mostly did not enter deep into details of individual subsystems like PSA for example. This was because partners responsible for development and design of individual subsystems (FP, PSA and FCS) were responsible carrying out in the project separate safety studies for their own subsystems. Integrated system as a focus of the HAZOP study was important also from the point of view of the higher level control system that was still further developed partly parallel with the HAZOP study.

As the main system description (HAZOP standard: design representation) and basis for the HAZOP study served piping and instrumentation diagrams (P&ID) of the integrated system that were available at the time of the study. In addition to these the expertise of analysis team members as well as the experience gained by them e.g. during system integration and by that time carried out test runs as well as other technical documentation of the system served as an important basis for the study.

In the study actually two PI&D versions were used. These were Main P&ID 20161230 rev. 1.0 and Main P&ID 20170207 rev. 1.0. The latter one of these was not drawn until the HAZOP study had already started. As the differences between these two PI&Ds were in the so-called Tail gas system (see chapter 2 and later in this chapter), and rest of the PI&Ds were identical, only this latter PI&D version is presented in Appendix B.[4]

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2 Expression used later for the part = “examination point”, see e.g. 3.2.
3 Note! There is available a newer version of the HAZOP standard (IEC 61882:2016), but this was not used in this work.
4 In the same way also in the HAZOP worksheets (see Appendix A) a reference only to P&ID version Main P&ID 20170207 rev. 1.0 is used.

The analyzed system was at the time of the HAZOP study in its integration phase and this was taking place inside of a laboratory at VTT premises. In this phase, the system elements/sub-systems were not yet installed into system's final installation environment i.e. a 10 ft. ISO container. However, in the HAZOP study carried out, the focus was in the system, that has been installed inside of a container. In this form the system will be tested later in the project e.g. in a task related to field trial period.

HAZOP study carried out covered only steady state operation of the system. This was because start-up and shutdown procedures were still in development phase at the time of the study. System was also assumed to be in full load operation mode in the study. This was because the parts of the system on which the study focused i.e. system parts preceding FCS, work in this way. Fuel cell system (FCS) is the only part, that operates in a load-following operation mode and the rest of the system i.e. FP and PSA for example operate at full load operation mode. This is due to the H_2 tank between PSA and the FCS (see PI&D in Appendix B).

Operation in winter conditions i.e. in temperatures below 0 °C and possibly resulting freezing problems were not taken into consideration in the study. This exclusion was done because the integrated system to be built and tested during the project, is not designed to be operated in sub-zero temperatures. Thus, during winter conditions the system shelter and heating should ensure that temperature stays above 0 °C. HAZOP study focused mainly on hazards arising from the properties of substances (e.g. ethanol, hydrogen and other flammable gases) and from process conditions (e.g. pressures, temperatures). Issues related to electrical safety were mainly excluded from the study.

The HAZOP study carried out was a qualitative study from its nature as HAZOP technique from its origin is (see standard IEC 61882:2001). In other words risk ranking or estimation was not carried out in this study.

The entire object of the HAZOP study was divided for the purposes of the actual analysis work in the following sections:

- Fuel processor (FP) including fuel feed to fuel processor
- FP product gas feed to PSA
- Tail gas/heating system including air feed
- PSA product gas feed to FCS
- FCS air-side exhaust gas water condensing & feed to H_20 tank
- Whole system - Conditions inside container and leaks inside container or outside of it

All these sections except the last one can be interpreted as physical entities of the entire system. The last HAZOP section was not a physical system, but instead it was formed partly for example on the basis of "hazard type" (leak). Each of the first five sections was further divided into the actual "examination points" for which the actual deviations - characteristic for a HAZOP study - were generated. In the HAZOP worksheets (see Appendix A), each of these analysis sections forms its own part with corresponding table heading. Respectively the examination points are presented in the worksheets as table wide subheadings. In the used PI&D (see Appendix B) examination points are marked with a red circle. From the PI&D it can be seen that there were altogether 18 examination points in the study.

3.3 Time of study, meetings organised, participants of study group

The HAZOP study was carried out in January–February 2017. Altogether 6 study meetings were organised and each of them lasted approximately between 3 and 5 hours.

The participants of the HAZOP study meetings were all from VTT. Study group members were Pauli Koski and Johan Tallgren from Fuel cell solutions team, Noora Kaisalo from Catalyst technologies team, and Janne Sarsama and Minna Nissilä from Risk and asset management team.

4. Results

All the identified deviations, their causes and consequences, measures to detect hazardous events or events leading to operability problems and existing safeguards are presented in the HAZOP worksheets in Appendix A. In addition to these, required or suggested actions that came up during the study in order to improve the safety or the operability of the system as well comment type records, have also been recorded in the worksheets. All these categories of information have been written down in the worksheets in corresponding columns. The most right hand column in the worksheets "Action allocated to" was systematically left blank in this study. This was because all the actions were directed to VTT's project team, which is compact and works closely together, and as a team is responsible for the integration of the subsystems into a functioning total system. So person level allocation of actions was not found necessary in this HAZOP study.

In the study altogether some 120 hazards or operability problems were identified. As one deviation can have multiple causes, the total number of individual undesirable scenarios is clearly higher than the number of deviations. However it should be noted that all the scenarios are not entirely different when compared with one another. Instead a part of the scenarios are quite close to each other. This is not by any means an exception but merely a normal outcome of a HAZOP study.

Among the identified hazards and operability problems were for example following types of deviations and their causes and consequences:

Leaks from the system to its surroundings
(Leak typically was a cause for example for a deviation "low flow" or "no flow")
As the basic nature of the system is to process its input substances, i.e. ethanol and water, through various pressurized process stages to a purified H_2 to be directed through a buffer tank to the fuel cell system (FCS), there is quite naturally in the system possibilities for different leak situations.

Leaks can be caused e.g. by pipeline and reactor or heat exchanger failures or because of pipeline fitting is broken etc. The composition of the leaking substance naturally varies depending on the location of the leak, but often there is a possibility for a formation of explosive atmosphere somewhere inside the container. However for example in case of air leak from the subsystem feeding air to afterburners or in case of water leak there is no risk of explosion.

In most cases identified leak possibilities were in gaseous form, but if the leak is for example in the front end of the system i.e. before EVAs, the leak is in liquid form. Container H_2 detectors, and in the study suggested ethanol detector, and related control or shutdown sequences are as the main safeguard for this hazard together with good system operation and maintenance practices. An identified action proposal *"Carry out pressure tests at least after any modification to the system"* can be given as an example of these good practices.

High or low temperatures of process flows in various process stages

High or low temperature of some process flow was quite a typical deviation in the HAZOP. This is because system includes many process stages where temperatures must be in the right temperature window in order to assure that chemical reactions happen correctly and on the other hand that e.g. reactor catalysts are not damaged. This is important particularly for the SRR and WGSR. If the temperature in a reactor is wrong chemical reactions may not occur as planned and as a consequence the output composition might be wrong.

Flow temperatures were not important process parameters only because of chemical reactions and avoiding equipment failures, but for example also because of water condensing from the process stream (as in COND1). Control of temperatures is much more important and challenging in the front end of the system i.e. in FP side, than in the tail end of the system. In COND1 FP product gas is cooled down to about 20 °C (and water condensed) after which there is no much change of flow temperatures in the rest of the system. All the changes in main process flow temperatures after COND1 are mainly due to spontaneous heat exchange between the part under consideration and the rest of the system, not because of intended heat exchange.

Causes for wrong temperatures in different process stages were often related to the incorrect operation of the related heating or cooling stage. Consequences of wrong temperatures in different process flows varied naturally according to the deviation (high or low temperature) and a process stage, where the deviation occurs. Temperature measurements and related control circuits, including also the automatic and emergency shut-downs, were typically as main safeguards (or as suggested or required actions) in respect to this deviation type.

Wrong composition of process flows in various process stages

One several times occurred deviation type in the study was a wrong composition of a substance flow e.g. before SRR, WGSR, PSA or FCS. Partly this deviation type was closely linked to the previous one i.e. temperature related deviation type but the deviation was also caused by other types of causes.

For example, wrong composition in SRR feed i.e. high or low H_2O/C -ratio ("steam-to-carbon ratio", deviations 10 and 11 in worksheets) can be caused by problems in water or ethanol feed systems. Tank is empty, pump is not operating, there is a leak or blockage in pipeline, flow control operates incorrectly etc. Respectively high CO concentration after PSA can be caused by PSA operating not as expected (e.g. adsorbent performance is decreased).

The specific consequences of wrong composition of course vary depending on that where in the system wrong composition takes place, but in general a consequence of a wrong composition is system or at least subsystem non-optimal operation or shut down. Measures related to detect the situation and to safeguard the system typically are not related to the measurement of substance concentrations, but instead are based on some other measurements, flow meters, level indicators, reactor temperature measurements, cell voltage monitoring etc.

The above given examples of the identified scenarios form just a very small subset of all the hazards or operability problems that were identified during the study. As already mentioned, all the scenarios are presented in detail in the form of worksheets in Appendix A.

When concerning required or suggested actions that were written down on worksheets, the number of these was very high - being totally more than 220. This figure is however far too big when the number of individual action proposals is considered. This is because a certain required or suggested action typically was relevant in connection with multiple scenarios. So action proposals were repeated in the worksheets in order to make analysis worksheets as complete as possible, and thus enable worksheets reader to explore them also one scenario at a time.

When considering required or suggested actions, of which the latter ones typically started with phrasing *"Consider…"*, the major part of these were as required actions[5]. From among the identified required or suggested actions for example following types of action proposals can be identified[6]:

Required or suggested actions related to the physical structure of the system

- Vent pipe should be located so that, it is not hazardous to people or property even in case of gas ignition. (25.5)
- Ground all components in pipeline properly to avoid build-up of static electricity. (44.1)
- Check if separate ventilation blower(s) is needed at the floor level of the container (for possible ethanol vapours). (60.2)
- Restrict unauthorized access to system with a fence. (95.1)

Required or suggested actions related to control system

- Add (to the control system) emergency shut down triggered by high temperature after EVA1. (1.1)
- Change control of DP1 from TI-FP5 to EVA1 outlet temperature. (1.2)
- Consider controlling TGP1 speed by PI-10. (43.1)
- Add ethanol detector inside container. (60.2)

Required or suggested actions related to the operation or maintenance

- Use deionized water in the system. (2.4)
- Carry out pressure tests with nitrogen at least after any modification to the system. (6.1)
- Personnel entering container should carry portable CO detectors and container doors should be open for CO ventilation. (114.1)
- Reason for high pressure should be investigated and pressure relief valve checked before system is operated again. (119.1)

Required or suggested actions to be taken into account when putting the whole system ready for test runs

- Analyse the composition of condensed water during system initial testing at VTT laboratories. (10.6) → To check if water tank contains traces of ethanol (or some alike reaction intermediate).
- Internal insulation of FP casing should be checked for leaks after moving casing or container. (63.1)
- Take care of possibility of flooding in placement of container. (110.1)

The conducted HAZOP study is assumed to be quite a comprehensive and it generated many action proposals i.e. either required or suggested actions to be taken into account in the next steps of the system integration and development. After the system integration is finalized and before test runs of the whole system are started, it would be advisable to check the latest design of the system (= P&ID) against the one used in this study and update the HAZOP worksheets at least on some level.

In case this system to be developed in PEMBeyond project is further developed after the project and even tried to commercialize, it is important that all the legal safety requirements (based

[5] This is not to the very end confirmed distribution of action proposals to the required and suggested actions, because it is based on the total number of recorded action proposals (being totally more than 220). However about 40 of the above mentioned 220 recorded action proposals were as suggested actions starting with *"Consider…"*.

[6] Note! Action proposals are presented here - for the reason of clarity - in some cases in a bit longer form than in the worksheets.

on for example various EU Directives) are known and taken properly into account. In the possible commercialization phase more detailed safety analyses for the system need to be carried out.

References

Koski, P., Pulkkinen, V., Auvinen, S., Ihonen, J., Karimäki, H., Keränen, T., Rydén, A., Tineglöf, T., Limonta, S., Croci, D., Fracas, P., Wichert, M., Kolb, G., Magalhaes, R., Relvas, F., Boaventura, M., Mendes, A. (2016). Development of reformed ethanol fuel cell system for backup and off-grid applications -System design and integration. 38th IEEE International Telecommunications Energy Conference, INTELEC 2016, 23–27 October 2016, Austin, TX, USA Proceedings (2016), Article number 7749097.

HAZOP worksheets

HAZOP	System: Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			Date: 4. & 18.1.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Fuel flow out of EVA1 [T ≈ 300-550 °C, p ≈ 8.0-8.5 bar(g)]					
1. High temperature after EVA1	1.1 Tail gas flow to AFB2 too high	No harmful consequences in fuel side downstream. Failures of AFB2/EVA1 are possible (to be covered in connection with tail gas/heating system).	• EVA1 temperature indicators (8 + 1 in outlet line)	• Add EM-SD triggered by high temperature after EVA1.	
	1.2 EtOH-1 flow to AFB2 too high	No harmful consequences in fuel side downstream. Failures of AFB2/EVA1 are possible (to be covered in connection with tail gas/heating system).	• EVA1 temperature indicators (8 + 1 in outlet line)	• Change control of DP1 from TI-FP5 to EVA1 outlet temperature.	
	1.3 Fuel flow to EVA1 too low	No harmful consequences in fuel side downstream.	• EVA1 temperature indicators (8 + 1 in outlet line). • AFB2 outlet temperature indicator (TI-FP5).		
2. Low temperature after EVA1	2.1 Tail gas flow to AFB2 too low (to be covered in connection with tail gas/heating system).	No complete vaporization in EVA1 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA1 temperature indicators (8 + 1 in outlet line)	• Add EM-SD triggered by low temperature after EVA1.	
	2.2 No EtOH-1 to AFB2 when needed or amount of EtOH-1 too low (to be covered in connection with tail gas/heating system).	No complete vaporization in EVA1 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA1 temperature indicators (8 + 1 in outlet line)		

HAZOP	System: Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 4. & 18.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 2. Low temperature after EVA1	2.3 Fuel flow to EVA1 too high	No complete vaporization in EVA1 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA1 temperature indicators (8 + 1 in outlet line)		
	2.4 Fouling of EVA1 heat exchange surfaces, because of impurities in water or in EtOH.	No complete vaporization in EVA1 → problems in SRR, no reforming because of low temperature. Serious problems downstream. Doesn´t happen immediately, slow process.	• EVA1 temperature indicators (8 + 1 in outlet line)	• Use of deionized water. • EtOH must not contain sediment.	
Fuel flow out of EVA2 [T ≈ 300-550 °C, p ≈ 8.0-8.5 bar(g)]					
3. High temperature after EVA2	3.1 Tail gas flow to AFB1 too high (to be covered in connection with tail gas/heating system).	No harmful consequences in fuel side downstream. No serious consequences to HX3/EVA2.	• EVA2 temperature indicators (6 + 1 in outlet line)	• Add EM-SD triggered by high temperature after EVA2.	
	3.2 SU-EtOH-3 flow to AFB1 too high (to be covered in connection with tail gas/heating system).	No harmful consequences in fuel side downstream. No serious consequences to HX3/EVA2.	• EVA2 temperature indicators (6 + 1 in outlet line)	Comment: SU-EtOH-3 designed not to be used in steady state.	
	3.3 Fuel flow to EVA2 too low	No harmful consequences in fuel side downstream.	• EVA2 temperature indicators (6 + 1 in outlet line) • HX3 outlet temperature indicator.		

HAZOP	System: Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf	**Date:** 4. & 18.1.2017

Deviation	Causes	Consequences	Detection and safeguards	Suggested/required actions, comments	Action allocated to
4. Low temperature after EVA2	4.1 Tail gas flow to AFB1 too low (to be covered in connection with tail gas/heating system).	No complete vaporization in EVA2 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA2 temperature indicators (6 + 1 in outlet line)	• Add EM-SD triggered by low temperature after EVA2.	
	4.2 No SU-EtOH-3 to AFB1 when needed or amount of SU-EtOH-3 too low (to be covered in connection with tail gas/heating system).	No complete vaporization in EVA2 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA2 temperature indicators (6 + 1 in outlet line)		
	4.3 Fuel flow to EVA2 too high	No complete vaporization in EVA2 → problems in SRR, no reforming because of low temperature. Serious problems downstream.	• EVA2 temperature indicators (6 + 1 in outlet line)		
	4.4 Fouling of EVA2 heat exchange surfaces, because of impurities in water or in EtOH	No complete vaporization in EVA2 → problems in SRR, no reforming because of low temperature. Serious problems downstream. Doesn´t happen immediately, slow process.	• EVA2 temperature indicators (6 + 1 in outlet line)	• Use of deionized water. • EtOH must not contain sediment.	
Fuel feed flow to SRR [$\dot{m}$ ≈ 3.7 kg/h, T ≈ 300-500 °C, p ≈ 8.0-8.5 bar(g), H_2O/C-ratio ≈ 4:1]					
5. High fuel flow to SRR (correct composition)				• Comment: Not very probable because dosing of both H_2O and EtOH should be simultaneously wrong.	

HAZOP	**System:** Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 4. & 18.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
6. Low fuel flow to SRR (correct composition)	6.1 Small leakage after the mixer	No serious consequences. Contact of fuel with electronic equipment can cause harm. Consequences and related detection and safeguards of ethanol leakage to be covered later more detail in section *Leaks from system inside container*.	• Container ventilation.	• Carry out pressure tests with nitrogen at least after any modification to the system. • Add EtOH detector inside the container, because small leakage can be difficult to detect.	
	6.2 Leakage in EVA1 or EVA2	Fuel flows to AFB2 (leakage in EVA1) or to HX3 (leakage in EVA2) and possibly burns in AFB2. Possible "extra flue gas" generated by fuel burning in AFB2 or non-burned fuel flows with other flue gases to exhaust gas vent line. Possibly explosive gas mixture at the top of vent line.	• PI-01 • EVA1 temperature indicators (8 + 1 in outlet line) • EVA2 temperature indicators (6 + 1 in outlet line) • SRR temperature indicators (7 separate indicators).	• Verify if the fuel can burn in AFB2.	
	6.3 Blockage in filter F1 or F2 because of impurities in H2O or in EtOH.	Pressure before the filter increases. Product gas output decreases. If only one of the filters is blocked, the fuel flow goes through the other one causing changes in EVA1 and EVA 2 temperatures.	• Pressure indicator PI-01. • EVA1 temperature indicators (8 + 1 in outlet line) • EVA2 temperature indicators (6 + 1 in outlet line)		

HAZOP	System: Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 4. & 18.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
7. No fuel flow to SRR	7.1 Broken pipeline or fitting	Both fuel and product gas start to escape from the system. Temperature increase in SRR.	• Pressure indicator PI-01 • SRR temperature indicators (7 separate indicators).	• Add EM-SD triggered by PI-01 low pressure (6 bar(g)) • Add after the tail gas tank a shut-off valve that closes if the system pressure goes too low. SV5 should open simultaneously.	
	7.2 Both feed pumps FFP1 and FFP2 inoperable	System stops.	• Pressure indicator PI-01	• Comment: Not very likely that both feed pumps fail simultaneously.	
8. High pressure of SRR fuel flow	8.1 Blockage in SRR or equipment after it due to catalyst flaking.	Equipment design pressure can be exceeded. Pumps are able to generate 16 bar(g). Design pressure for components (in FP) is 10 bar(g).	• Pressure indicator PI-01	• Add emergency shut down triggered by PI-01 high pressure (9 bar(g)).	
9. Low pressure of SRR fuel flow	9.1 Big leakage	Both fuel and product gas start to escape from the system. Temperature increase in SRR.	• Pressure indicators PI-01, PI-04	• Add emergency shut down triggered by PI-01 low pressure (< 6 bar(g)), • Add after the tail gas tank a shut-off valve that closes if the system pressure goes too low. SV5 should open simultaneously.	

HAZOP	**System:** Fuel processor (FP) including fuel feed to fuel processor, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 4. & 18.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
10. H2O/C -ratio too low (below 4)	10.1 Water tank empty	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA.	• Water tank level indicator LI-03 triggers AUTO-SD • FI-02	• Locate the low level indicator in water tank so that enough water is still available for normal shut down.	
	10.2 Water pump FFP2 not operating due to air bubbles component failure.	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA.	• FI-02	• Add H_2O/C ratio calculation which triggers EM-SD, if ratio goes below 3. • Consider adding alarm related to limits of FFP2 control voltage (RPM control) using on lookup table or formula based on normal operation data.	
	10.3 Leakage in water line	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA. Consequences and related detection and safeguards of water leakage to be covered later in section *Leaks from system inside container*.	• FI-02 (relevant if leakage point is before FI-02). • PI-01	• Consider carrying out pressure test before start up, if possible.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 10. H2O/C -ratio too low (below 4)	10.4 Blockage in water line due to impurities in H2O tank.	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA.	• FI-02		
	10.5 EtOH feed too high due to failure of FI-01	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA.	• FFP1 control voltage	• Consider adding alarm related to limits of FFP1 control voltage (RPM control) using on lookup table or formula based on normal operation data.	
	10.6 Water tank contains traces of ethanol (or some alike reaction intermediate) originating from product gas line vapour-liquid separator (VLS1) due to incomplete reformation in SRR.	Coking in SRR. WGS reaction conditions not optimal, too high CO concentration for PSA.	• SRR temperature indicators (7 separate indicators).	• If needed, samples of condensed water should be taken from VLS1. • Analyse the composition of condensed water during system initial testing at VTT laboratories. • Comment: Ethanol traces may start to accumulate in long term if SRR catalyst performance decreases.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
11. H2O/C -ratio too high (above 4)	11.1 Ethanol tank empty	No product gas flow to PSA, temporary increase in EVA1&2 and SRR temperatures. AUTO-SD takes place.	• Both LI-01 and FI-01 trigger AUTO-SD.	• Configure in the automation system appropriate scripts for automatic shut down (AUTO-SD) and for emergency shut down (EM-SD).	
	11.2 Air in ethanol pump inlet due to leakage in pipe fittings e.g.	Temporary or permanent decrease/stop of ethanol feed. AUTO-SD takes place.	• FI-01 (see suggested actions)	• Configure following functionalities in the automation system: Short-term decrease of ethanol flow (FI-01) triggers alarm for operator, longer-lasting decrease triggers AUTO-SD. • Carry out leakage tests for ethanol pump suction side piping, fittings etc.	
	11.3 Ethanol pump FFP1 not operating due to diaphragm rupture e.g.	No product gas flow to PSA, temporary increase in EVA1&2 and SRR temperatures. AUTO-SD takes place.	• FI-01 (see suggested actions)	• Configure following functionalities in the automation system: Short-term decrease of ethanol flow (FI-01) triggers alarm for operator, longer-lasting decrease triggers AUTO-SD.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 11. H2O/C -ratio too high (above 4)	11.4 Leakage in ethanol line (after pump)	Too little or no product gas flow, increase in EVA1&2 and SRR temperatures. Consequences and related detection and safeguards of ethanol leakage to be covered later in section *Leaks from system inside container*.	• FI-01 (relevant if leakage point is before FI-01). • Pressure indicator PI-01	• Configure following functionalities in the automation system: Short-term decrease of ethanol flow (FI-01) triggers alarm for operator, longer-lasting decrease triggers AUTO-SD. • Carry out pressure test before start up, if possible.	
	11.5 Blockage in ethanol line due to impurities in ethanol tank.	Too little or no product gas flow, increase in EVA1&2 and SRR temperatures.	• FI-01 (see suggested actions)	• Configure following functionalities in the automation system: Short-term decrease of ethanol flow (FI-01) triggers alarm for operator, longer-lasting decrease triggers AUTO-SD. • EtOH must not contain sediment.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 11. H2O/C -ratio too high (above 4)	11.6 Water feed too high due to failure of FI-02	Decrease in EVA1&2 and SRR temperatures, product gas composition may change. Higher water feed not a problem, lower temperatures in reactors might cause problems.	• Output signal of FFP2 PID controller is abnormally high.	• Consider adding in the automation system automatic monitoring of feed pump control signals or limiting pump controller output signals to certain value, e.g. 30 %.	
12. Liquid phase impurities in SRR fuel flow	12.1 Ethanol tank contains in addition to ethanol small amounts of higher alcohols or other heavier organic impurities.	SRR catalyst deactivation and later WGSR catalyst deactivation.	• SRR temperature gradient changes over time.	• Ethanol should be purchased from reliable supplier or analysed in detail.	
Feed flow out from SRR [$\dot{m}$ ≈ 3.7 kg/h, T ≈ 600-700 °C, p ≈ 8.0-8.5 bar(g)]					
13. High temperature after SRR	13.1 Heat generation in AFB1 too high	SRR catalyst damage and further equipment damage possible.	• SRR temperature indicators (7 separate indicators). • High temperature in first SRR temperature indicator triggers AUTO-SD.		
14. Low temperature after SRR	14.1 Heat generation in AFB1 too low	Product gas composition wrong.	• SRR temperature indicators (7 separate indicators). • Low temperature in first SRR temperature indicator triggers AUTO-SD.		

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Feed flow to WGSR [$\dot{m}$ ≈ 3.7 kg/h, T ≈ 350-475 °C, p ≈ 8.0-8.5 bar(g)]					
15. High feed gas flow to WGSR (correct composition)				• Comment: Not very probable because dosing of both H_2O and EtOH should be simultaneously wrong. If deviation occurs in WGSR, same deviations would also occur in the previous process stages i.e. in EVAs and SRR.	
16. Low feed gas flow to WGSR (correct composition)	16.1 Leakage in SRR or HX1	Less product gas to PSA, WGSR temperatures possibly decrease. Gas burns in both cases in AFB1 causing temperature increase in AFB1/SRR, possible equipment damage.	• Large leakage: PI-01 and PI-04. • WGSR temperature indicators (7 separate indicators) • SRR temperature indicators (7 separate indicators)	• Carry out pressure tests at least after any modification to the system.	
	16.2 Leakage in pipeline between SRR and WGSR	Less product gas, WGSR temperatures possibly decrease. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• Large leakage: PI-01 and PI-04. • WGSR temperature indicators (7 separate indicators)	• Carry out pressure tests at least after any modification to the system.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
17. No feed gas flow to WGSR	17.1 Blockage in SRR or HX1 due to coking in SRR or SRR catalyst flaking.	No product gas.	• Pressure indicator PI-01	• Add EM-SD triggered by PI-01 high pressure (9 bar(g))	
	17.2 Major pipe failure between SRR and WGSR.	No product gas. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• Pressure indicator PI-01	• Add emergency shut down triggered by PI-01 low pressure (6 bar(g))	
18. High temperature of WGSR feed gas	18.1 Too low air flow through HX1, fouling of heat exchanger surfaces	Change in the behaviour of WGRS, product gas contains too much CO. Possible damage to WGSR catalyst.	• TI-FP3 (main detection measure) • WGSR temperature indicators (7 separate indicators)	• Add AUTO-SD down triggered by high WGSR inlet temperature (inside reactor).	
19. Low temperature of WGSR feed gas	19.1 Too high air flow through HX1	Product gas contains too much CO. Possible damage to WGSR catalyst.	• TI-FP3 (main detection measure) • WGSR temperature indicators (7 separate indicators)	• Add AUTO-SD triggered by low WGSR inlet temperature	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
20. High pressure of WGSR feed gas	20.1 Blockage in WGSR or equipment after it due to SRR or WGSR catalyst flaking.	Equipment design pressure might be exceeded. Product gas composition changes (methane increases).	• Pressure indicator PI-01	• Add emergency shut down triggered by PI-01 high pressure (> 9 bar(g)). • Consider adding pressure relief valve to the inlet side of the fuel processor (in the part of the process where the flowing media is still in liquid phase).	
21. Low pressure of WGSR feed gas	21.1 Big leakage	Product gas escapes from system. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• Pressure indicators PI-01 and PI-04	• Add EM-SD triggered by PI-01 low pressure (< 6 barg). • Add after the tail gas tank a shut-off valve that closes if the system pressure goes too low. SV5 should open simultaneously.	
22. Wrong composition in WGSR feed gas	22.1 SRR catalyst deactivation/damage due to too high SRR temperature, higher alcohols etc. in fuel processor feed mixture	WGSR feed contains too high amount of CO, causing CO in excess of 1-vol % to flow to PSA. WGSR feed contains too much CH_4. Complete system efficiency is decreased with lower H_2 yield.	• FCS cell voltages • SRR temperature indicators. Temperature gradient changes over time. (When SRR functions normally, temperature is in inlet higher than in outlet.)		

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
23. Impurities in WGSR feed gas	23.1 SRR catalyst deactivation (see above) leading to unreacted impurities flowing to WGSR (ethanol and other organic compounds)	Ethanol and possibly other residues in WGSR feed gas. Deactivation/possible damage to WGSR catalyst. Change in the behaviour of WGRS: Possibly reforming of ethanol or coke formation. Wrong FP product gas composition (contains e.g. too much CO).	• SRR temperature indicators. Temperature gradient changes over time. (When SRR functions normally, temperature is in inlet higher than in outlet.) • WGSR temperature indicators.		

HAZOP	System: FP product gas feed to PSA, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
PSA feed flow [T ≈ 25 °C, p ≈ 8.0-8.5 bar(g)]					
24. High PSA feed flow (correct composition)				• Comment: Not very probable because dosing of both H_2O and EtOH should be simultaneously wrong. • Comment: Coolant pressure level in COND1 few bar(g) at maximum, thus leak from coolant side to process gas unlikely.	

HAZOP	**System:** FP product gas feed to PSA, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
25. Low PSA feed flow (correct composition)	25.1 Small leakage in WGSR	Less product gas. Increase of combustible gas to AFB2. H_2 concentration in AFB2 increases. If leak large enough, flame front may proceed upstream up to HX2.	• Temperature indicators inside EVA1 • AFB2 outlet temperature indicator (TI-FP5). • Temperature measurement in pipeline before AFB2 inside FP. (Not shown in PI diagram.)	• Add AUTO-SD triggered by high temperature at AFB2 inlet (> 750 °C). • Add AUTO-SD triggered by high temperature at AFB2 outlet (> 300 °C). • Comment: HX2 temperature below H_2 autoignition temperature (536 °C), so combustion takes place in AFB2. • Comment: Product gas H_2 concentration 65-70 %, tail gas 35-45 %.	
	25.2 Small leakage in COND1.			• Comment: Unlikely because condenser can withstand pressure difference up to 100 bar.	

HAZOP	**System:** FP product gas feed to PSA, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 25. Low PSA feed flow (correct composition)	25.3 Small leakage in DV1 due to malfunctioning	Combustible gas may flow to H_2O tank. Gas vented from tank into container. Less product gas. Consequences and related detection and safeguards of combustible gas leakage to be covered later more detail in section *Leaks from system inside container*.	• H_2 detector in container	• Comment: Malfunctioning of DV1 very unlikely, because liquid does not contain objects above 1 mm size that could block the valve open.	
	25.4 Small leakage in pipeline between WGSR and PSA feed inlet	Less product gas. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.		• Carry out pressure tests at least after any modification to the system.	
	25.5 Small leakage through PRV1 due to triggered relief valve not resealing properly.	Less product gas. Combustible gas flows through vent line out of container.		• Vent pipe should be located so that, it is not hazardous to people or property even in case of gas ignition.	

HAZOP	System: FP product gas feed to PSA, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			**Date:** 27.1.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
26. No PSA feed flow	26.1 Big leakage	Product gas escapes from system. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• Pressure indicators PI-01, PI-04 and PI-05.	• Add EM-SD triggered by PI-04 and PI-05 low pressure (6 barg).	
	26.2 Malfunctioning of SV2, valve opens.	Combustible gas flows through vent line out of container	• Pressure indicators PI-01, PI-04 and PI-05.	• Add EM-SD triggered by PI-04 and PI-05 low pressure (6 barg). • Vent pipe should be located so that, it is not hazardous to people or property even in case of gas ignition.	
27. High temperature of PSA feed				• Comment: Heat up of gas not possible after the condenser and VLS1.	
28. Low temperature of PSA feed				• Comment: Low temperature not detrimental for PSA. • Comment: Sub-zero temperatures not considered in study.	

HAZOP	**System:** FP product gas feed to PSA, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
29. High pressure of PSA feed	29.1 PSA gas consumption stops due to malfunction in PSA cycle.	Pressure increase in system upstream PSA.	• Pressure indicators PI-04 and PI-05. • SV2 triggers open at 10 bar(g) at PI-04. • PRV1 opens at 11 bar(g).	• Add EM-SD triggered by PI-04 and PI-05 high pressure (10 barg) • Add AUTO-SD when PSA stops running.	
30. Low pressure of PSA feed	30.1 Big leakage	Product gas escapes from system. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• Pressure indicators PI-01, PI-04 and PI-05.	• Add EM-SD triggered by PI-04 and PI-05 low pressure (6 barg)	
	30.2 Malfunctioning of SV2, valve opens.	Combustible gas flows through vent line out of container	• Pressure indicators PI-01, PI-04 and PI-05.	• Add EM-SD triggered by PI-04 and PI-05 low pressure (6 barg). • Vent pipe should be located so that, it is not hazardous to people or property even in case of gas ignition.	

HAZOP	System: FP product gas feed to PSA, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 30. Low pressure of PSA feed	30.3 SV1 closes due to malfunction.	Pressure downstream SV1 decreases slowly due to feed tank volume. (Pressure in system upstream SV1 increases much faster.)	• Pressure indicator PI-05.	• Add EM-SD triggered by PI-05 low pressure (6 barg)	
31. High pressure fluctuation in FP product gas upstream feed tank	31.1 Feed tank hand valve MV6 unintentionally closed.	Fluctuations in FP pressure. Small temperature and/or gas composition fluctuations. Feed pump control signals fluctuating under PID control.	• Pressure indicators PI-01, PI-04 and PI-05.	• Check feed tank hand valve MV6 position (= open) before start-up. • Comment: Point of examination in this deviation is between SV1 and feed tank pipe branch.	
32. High CO concentration of PSA feed	32.1 WGSR reaction conditions wrong, too high temperature. WGSR catalyst deactivation.	Too high CO concentration in hydrogen fed to H_2 tank. Reduced efficiency of FCS due to anode catalyst poisoning.	• WGSR temperature indicators (7 separate indicators) • FCS cell voltage monitoring • FCS shuts down when voltage drops too low, triggers AUTO-SD.	• Add AUTO-SD triggered by high WGSR outlet temperature (> 350 °C)	
33. High water vapour concentration of PSA feed	33.1 No/low coolant flow to COND1. Coolant circuit/pipeline failure. Coolant temperature too high. Cooling system not functioning.	Steam enters PSA and causes water condensation in adsorbent columns. High temperature gas may damage components downstream.	• Temperature indicator TI-05 • Temperature indicator TI-06	• Add EM-SD triggered by TI-05 high temperature (> 30 °C). • Add AUTO-SD triggered by TI-06 high temperature (> 15 °C).	

HAZOP	System: FP product gas feed to PSA, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 27.1.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
34. Low H2 concentration (= high viscosity) of PSA feed				• Comment: PSA malfunctions if H_2 concentration in PSA feed gas < 50 %, due to valves not designed for high viscosity gas. • Comment: Under SRR normal operation, < 50 % H_2 not likely. • Comment: High CO content is observed before low H_2 content.	
35. Wrong phase in PSA feed (water droplets in PSA feed)	35.1 Malfunctioning of VLS1.	Droplets enter PSA. PSA adsorbents start flooding. More CO in gas feed to H_2 tank.	• FCS cell voltages	• Add a water coalescing filter upstream PSA inlet. Droplets detected from filter inspection port.	

HAZOP	**System:** FP product gas feed to PSA, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			**Date:** 27.1.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 35. Wrong phase in PSA feed (water droplets in PSA feed)	35.2 COND1 not cooling enough.	Condensing taking place downstream VLS1. Droplets enter PSA. PSA adsorbents start flooding. More CO in gas feed to H_2 tank.	• Temperature indicators TI-05 and TI-07. • FCS cell voltages	• Add warning triggered by TI-05 and TI-07 high temperature (> 25 °C). • Add EM-SD triggered by TI-05 high temperature (> 30 °C). • Add AUTO-SD triggered by TI-07 high temperature (> 40 °C).	
36. Other impurities in PSA feed	36.1 Impurities in FP product gas flow due to SRR or WGSR catalyst flaking e.g.	Components downstream WGSR are not likely to block due to large channel dimensions, but WGSR operation is disturbed. Particle impurities washed away in VLS1, and may accumulate to H_2O tank or proceed to F1 and F2. Small particle impurities may accumulate to PSA adsorbent beds without considerable effect to functionality.	• WGSR temperature indicators (7 separate indicators) • Visual inspection of H_2O tank	• Add a coalescing filter upstream PSA inlet. Droplets are detected from filter inspection port during shutdown period.	

HAZOP	System: Tail gas/heating system including air feed, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 17. & 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Tail gas flow from PSA [T ≈ 25 °C, p ≈ -400 – +600 mbar(g)]					
37. High pressure of tail gas flow at end of PSA desorption phase	37.1 Malfunctioning of valve CV1 (does not open or opens limitedly) and vacuum pump VP1 not running.	PSA adsorbent not fully regenerated, because too high pressure, > 0.5 bar(a), at end of desorption phase. Too high CO content in product H_2. PSA shuts automatically down if pressure inside vessel > 100 mbar(g) at end of desorption phase. No reformate intake and tail gas production. System shuts down.	• PI-07 • FCS cell voltage monitoring • FP AUTO-SD triggered by PSA shutdown.	• Consider adding pressure sensor for absolute ambient pressure.	
	37.2 Malfunctioning of valve CV1, permitting flow in opposite direction.	VP1 not able to generate vacuum. PSA adsorbent not fully regenerated, because too high pressure, > 0.5 bar(a), at end of desorption phase. Too high CO content in product H_2. PSA shuts automatically down if pressure inside vessel > 100 mbar(g) at end of desorption phase. No reformate intake and tail gas production. System shuts down.	• PI-07 • FCS cell voltage monitoring (in long term)	• Consider eliminating CV1 and running only with VP1. • Check if VP1 can pass enough flow through in case of CV1 malfunction.	

HAZOP	System: Tail gas/heating system including air feed, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 17. & 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
38. High temperature of tail gas	38.1 Can be caused only by high ambient temperature in container. To be covered later in section Conditions inside container.			• Comment: PSA operation isothermal. Tail gas temperature does not deviate from PSA inlet.	
39. Impurities in tail gas	39.1 Adsorbent released from PSA.	Particles possibly getting in tail gas tank are not very harmful. Filter may be clogged over long period of time.	• Filter F8 • Tail gas gets in tail gas tank at bottom and exits from top. • PI-11	• Comment: Adsorbent particles not large enough to cause e.g. pipeline blockages. Would possibly be harmful to MFM4 and MFM5.	
Tail gas flow to tail gas tank [T ≈ 25 °C, p ≈ 200-300 mbar(g)]					
40. High flow of tail gas				• Comment: Not relevant deviation. VP1 cannot extract much flow from vacuum.	
41. Low flow of tail gas	41.1 Pump VP1 malfunctioning.	Pressure in PSA tail gas outlet increases > 100 mbar(g), and causes PSA to stop. System shuts down.	• PI-07 • FP AUTO-SD triggered by PSA shutdown.		

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 41. Low flow of tail gas	41.2 Leakage after VP1 and before tank.	Tail gas tank pressure starts to decrease. Less tail gas for combustion in FP. Temperatures decrease in FP reactors. Consequences and related detection and safeguards of combustible gas discharge into the system surroundings to be covered later in section *Leaks from system inside container*.	• PI-10 • Container H_2 detectors • SRR temperatures	• Perform leak test for tail gas line when components changed or fittings opened.	
42. High pressure of tail gas	42.1 Pump TGP1 not functioning	No tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• PI-10 • FI-04 • PRV2 opens at 450 mbar(g) • SRR temperatures	• Consider adding following safety function: Opening of SV5 triggered by P-10 high pressure, > 400 mbar(g), to preserve PRV2 gaskets.	
	42.2 Valve SV6 closed	No tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• PI-11, PI-10 • FI-04 • PRV2 opens at 450 mbar(g) • SRR temperatures	• Consider adding following safety function: Opening of SV5 triggered by P-10 high pressure, > 400 mbar(g), to preserve PRV2 gaskets.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 42. High pressure of tail gas	42.3 Filter F8 clogged	No tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• PI-11, PI-10 • FI-04 • PRV2 opens at 450 mbar(g) • SRR temperatures	• Comment: Filter may be clogged over long period of time.	
43. Low pressure of tail gas	43.1 Flow through pump TGP1 higher than PSA tail gas production.	Temporarily too much tail gas for combustion in FP. Temperatures increase in FP reactors. Vacuum generated in tail gas tank. Air may leak inside the tank.	• PI-10 • FI-04 • SRR temperatures	• Consider controlling TGP1 speed by PI-10.	
	43.2 Valve SV5 open due to malfunction or power loss.	Very low amount of tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• PI-10 low pressure • FI-04 • SRR temperatures		

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Deviation	Causes	Consequences	Detection and safeguards	Suggested/required actions, comments	Action allocated to
continued… 43. Low pressure of tail gas	43.3 Small leakage outside between pumps VP1 and TGP1.	Less tail gas for combustion in FP. More EtOH needed to keep up FP temperatures. Lower efficiency of the system. Consequences and related detection and safeguards of combustible gas discharge into the system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-10 low pressure, however hard to detect small decrease • Container H_2 detectors	• Perform leak test for tail gas line when components changed or fittings opened.	
44. Air among tail gas	44.1 Leak in pipeline upstream VP1 causing VP1 to suck air into tail gas line.	Combustible and possibly explosive mixture created inside piping and tail gas tank.	• PI-07	• Ground all components in pipeline properly to avoid build-up of static electricity. • Add AUTO-SD triggered by PI-07 if it stays > -400 mbar(g) for one minute. • Perform leak test for tail gas line when components changed or fittings opened.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Tail gas flow downstream MFM4 before flow splitting [T ≈ 25 °C, p ≈ 700-1000 mbar(g)]					
45. High flow of tail gas	45.1 Pump TGP1 malfunctioning, gas throughput too high.	Temporarily too much tail gas for combustion in FP. Temperatures increase in FP reactors. Vacuum generated in tail gas tank. Air may leak inside the tank.	• FI-04 • PI-10 low pressure • PI-11 high pressure • SRR temperatures	• Consider controlling TGP1 speed by PI-10.	
46. Low flow of tail gas	46.1 Pump TGP1 malfunctioning, gas throughput too low.	Too little tail gas for combustion in FP. Temperatures decrease in FP reactors. Pressure increase in tail gas tank.	• FI-04 • PI-10 high pressure • SRR temperatures • PRV2 opens at 450 mbar(g)	• Consider adding following safety function: Opening of SV5 triggered by P-10 high pressure, > 400 mbar(g), to preserve PRV2 gaskets.	
	46.2 Small leakage outside downstream pump TGP1.	Too little tail gas for combustion in FP. Temperatures decrease in FP reactors. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• FI-04 • SRR temperatures • PI-11 • Container H_2 detectors	• Perform leak test for tail gas line when components changed or fittings opened.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
47. No flow of tail gas	47.1 Valve SV6 closed due to malfunction or power loss.	No tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• FI-04, FI-05 • PI-11 and PI-10 high pressure • SRR temperatures	• Comment: TGP1 max. pressure increase 1.38 bar above inlet level, not detrimental to other components. • Add AUTO-SD triggered by PI-11 pressure > 1 bar(g).	
	47.2 Filter F8 clogged	No tail gas for combustion in FP. Temperatures decrease in FP reactors. System AUTO-SD triggered by SRR temperatures.	• FI-04, FI-05 • PI-11 and PI-10 high pressure • SRR temperatures	• Comment: Filter may be clogged over long period of time. • Comment: TGP1 max. pressure increase 1.38 bar above inlet level, not detrimental to other components. • Add AUTO-SD triggered by PI-11 pressure > 1 bar(g).	
48. High pressure of tail gas			• PI-11	• Comment: Both tail gas pipelines (TG1 and TG2) or afterburner pipelines should be blocked, which is not likely. • Add AUTO-SD triggered by PI-11 pressure > 1 bar(g).	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
49. Low pressure of tail gas	49.1 Pump TGP1 malfunctioning, gas throughput too low.	Too little tail gas for combustion in FP. Temperatures decrease in FP reactors. Pressure increase in tail gas tank.	• FI-04 • PI-10 high pressure • SRR temperatures • PRV2 opens at 450 mbar(g)	• Consider adding following safety function: Opening of SV5 triggered by P-10 high pressure, > 400 mbar(g), to preserve PRV2 gaskets.	
	49.2 Leak outside between pump TGP1 and valve CV3 and/or CV4.	Too little tail gas for combustion in FP. Temperatures decrease in FP reactors. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-11 • Container H_2 detectors • SRR temperatures • FI-04	• Perform leak test for tail gas line when components changed or fittings opened.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
50. Air among tail gas	50.1 Leak in pipeline/system between pump VP1 / valve CV1 and pump TGP1.	First tail gas leaks out from system into container. Once pressure in tail gas tank / in system (PI-10) below atmospheric, air starts to be sucked from system surroundings to gas flow. Formation of explosive gas mixture first inside container then in tail gas tank / in tail gas system. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-10 (pressure decreases) • CI-02 (H_2 concentration decreases) • Container H_2 detectors	• Consider adding AUTO-SD triggered by PI-10 < 50 mbar(g).	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 50. Air among tail gas	50.2 Leak to vent line due to SV5 malfunction.	First tail gas leaks out from system through vent line. Once pressure in tail gas tank / in system (PI-10) below atmospheric, air starts to be sucked from vent line to gas flow. Formation of explosive gas mixture in tail gas tank / in tail gas system.	• PI-10 (pressure decreases) • CI-02 (H_2 concentration decreases)	• Consider adding AUTO-SD triggered by PI-10 < 50 mbar(g).	
51. High H2 content in tail gas				• Comment: Should not be possible assuming FP and PSA functioning normally. In case of simulated tail gas (H_2 + N_2) during system development this was possible.	
52. Impurities in tail gas				• Comment: Not likely because of filter F8	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Air flow after HX1 [T ≈ 500-700 °C, p ≈ 700 mbar(g)]					
53. High temperature of air	53.1 Too low air flow rate due to blower AB1 malfunctioning.	WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst.	• WGSR inlet temperature • TI-FP3	• Comment: WGSR inlet 400-430 °C. • Add air flow meter between PI-03 and airline branch. • Add AUTO-SD triggered by high WGSR inlet temperature (450 °C.	
	53.2 Too low air flow rate due to PV2 unintentionally open.	WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst.	• WGSR inlet temperature • TI-FP3	• Add air flow meter between airline branch and PV2. • Add AUTO-SD triggered by high WGSR inlet temperature (450 °C).	
	53.3 Leak outside between blower AB1 and HX1 or from HX1.	WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst.	• PI-03 • WGSR inlet temperature • TI-FP3	• Leak checking.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
54. Low temperature of air	54.1 Too high air flow rate due to blower AB1 malfunctioning.	WGSR inlet temperature decreases, kinetics of WGS reactions slowed down and FP product gas may contain more CO. CO concertation of PSA product gas increases, FCS efficiency decreases.	• TI-FP3 • WGSR inlet temperature	• Add air flow meter between PI-03 and airline branch. • Add air flow meter between airline branch and PV2. • Add AUTO-SD triggered by low WGSR inlet temperature (380 °C)	
	54.2 Too high air flow rate due to PV2 unintentionally closed.	WGSR inlet temperature decreases, kinetics of WGS reactions slowed down and FP product gas may contain more CO. CO concertation of PSA product gas increases, FCS efficiency decreases.	• TI-FP3 • WGSR inlet temperature	• Add air flow meter between PI-03 and airline branch. • Add air flow meter between airline branch and PV2. • Add AUTO-SD triggered by low WGSR inlet temperature (380 °C)	
	54.3 Low air temperature at blower AB1 intake.			• Comment: Not likely because container interior heated by waste heat from FP.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
55. High flow of air	55.1 Malfunctioning of blower AB1.	WGSR inlet temperature decreases, kinetics of WGS reactions slowed down and FP product gas may contain more CO. CO concertation of PSA product gas increases, FCS efficiency decreases.	• TI-FP3 • WGSR inlet temperature	• Add air flow meter between PI-03 and airline branch. • Add AUTO-SD triggered by low WGSR inlet temperature (380 °C)	
	55.2 PV2 unintentionally closed.	WGSR inlet temperature decreases, kinetics of WGS reactions slowed down and FP product gas may contain more CO. CO concertation of PSA product gas increases, FCS efficiency decreases.	• TI-FP3 • WGSR inlet temperature	• Add air flow meter between PI-03 and airline branch. • Add air flow meter between airline branch and PV2. • Add AUTO-SD triggered by low WGSR inlet temperature (380 °C)	
56. Low flow of air	56.1 Malfunctioning of blower AB1.	WGSR inlet temperature increases, may affect FP product composition after WGSR. Possible damage to WGSR catalyst.	• WGSR inlet temperature • TI-FP3	• Add air flow meter between PI-03 and airline branch. • Add AUTO-SD triggered by low WGSR inlet temperature (380 °C)	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 56. Low flow of air	56.2 PV2 unintentionally open.	WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst	• WGSR inlet temperature • TI-FP3	• Add air flow meter between airline branch and PV2. • Add AUTO-SD triggered by high WGSR inlet temperature (450 °C).	
	56.3 Leak outside between AB1 and HX1 or from HX1.	WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst.	• WGSR inlet temperature • TI-FP3 • PI-03	• Leak checking	
57. No flow of air	57.1 Blower AB1 stopped.	No cooling to HX1. WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst. No oxidant to AFB1, to be covered under *Fuel-air ratio (lambda) too rich.*	• PI-03 • TI-FP3 • WGSR inlet temperature	• Add air flow meter between PI-03 and airline branch. • Add AUTO-SD triggered by air flow meter (lambda < 1.5) • Add AUTO-SD triggered by high WGSR inlet temperature (450 °C).	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 57. No flow of air	57.2 Pipeline failure or SUB2 rupture.	No cooling to HX1. WGSR inlet temperature increases, may affect FP product gas composition after WGSR. Possible damage to WGSR catalyst. No oxidant to AFB1, to be covered under *Fuel-air ratio (lambda) too rich.*	• PI-03 • TI-FP3 • WGSR inlet temperature	• Comment: Not very likely. • Comment: Temperature cycling of SUB2 could cause leaks in the long run • Carry out pressure tests at least after any modification to the system. • Add AUTO-SD triggered by high WGSR inlet temperature (450 °C).	
58. High pressure of air	58.1 Blockage in pipeline between HX1 and AFB1.		• PI-03	• Comment: Not very likely. Blower p_{max} ≈ 1 bar(g). • Check pressure tolerance of SUBs.	
59. Low pressure of air	59.1 Leak outside between HX1 and AFB1.	Less air or fuel-air mixture to AFB1. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-12 • Container H_2 detectors • SRR temperature indicators	• Leak testing of tail gas line when components changed or fittings opened.	

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Deviation	Causes	Consequences	Detection and safeguards	Suggested/required actions, comments	Action allocated to
60 Wrong composition	60.1 Reformate gas leak inside HX1.	Possibly explosive gas mixture downstream HX1. Temperature in HX1 close to H_2 autoignition temperature and may ignite. In case of combustion, HX1 not cooling process stream and WGSR inlet temperature increase. Less product gas to PSA.	• HX1 air side outlet temperature • AFB1 inlet temperature indicator • SRR temperature indicators • PI-04 • TI-FP3 • WGSR temperature indicators • PI-12	• Carry out pressure tests of main process line at least after any modification to the system. • Add AUTO-SD triggered by AFB1 high inlet temperature (800 °C).	
	60.2 Air blower AB1 sucks in air and combustible gases due to a leak in system. Container air contains ethanol, reformate or hydrogen.	Possibly explosive gas mixture inside blower AB1 and downstream it. Gas mixture may ignite in SUB2 because of catalyst. Explosive gases/vapours inside container. EtOH vapour stays bottom (46.07 g/mol vs. 28.97 g/mol of air) of container, H_2 rises to upper part of container (2.016 g/mol vs. 28.97 g/mol of air)	• Container H_2 detectors • AUTO-SD and ventilation increase triggered at 25% LEL. • EM-SD triggered at 50% LEL, electricity cut-off from container. • Container ventilation • SUB2 temperature indicators	• Add EtOH detector inside container. • Placement of air blowers vertically at middle in container, or routing air intake by tube to container fresh air intake grille. • Check if separate ventilation blower(s) is needed at the floor level of the container (for possible ethanol vapours).	
61. Impurities	61.1 Dust or particulates from outside or inside of container.	Blockage of AB1, SUB2 and other components downstream.	• PI-03	• Add filters to AB1 (and AB2) intake ports. • Add air flow meter after PI-03.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Fuel-air mixture to AFB1 [T ≈ 500-600 °C, p ≈ 650 mbar(g)]					
62. High temperature of fuel-air mixture				• Comment: No identified causes for high temperature in case the gas composition is correct and HX1 and SRR functioning normally.	
63. Low temperature of fuel-air mixture	63.1 Impaired heat insulation inside FP.	Afterburner AFB1 cools down. All the fuel processor components cool down.		• Internal insulation of FP casing should be checked for leaks after moving casing or container.	
64. High flow of fuel-air mixture				• Comment: No identified causes for high flow in case the gas composition is correct.	
65. Low flow of fuel-air mixture	65.1 Small leakage after TG1 or SU-EtOH-3 mixing point.	Less combustible mixture for afterburner AFB1. AFB1 temperatures decrease. See deviation *Low temperature after SRR*. Consequences and related detection and safeguards of the gas discharge into the system surroundings to be covered later in section *Leaks from system inside container*.	• SRR temperature indicators	• Consider adding small ventilation hole to FP casing to prevent H_2 accumulation inside it. • Leak testing of tail gas lines when components changed or fittings opened. • Add EtOH detector inside container.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
66. No flow of fuel-air mixture	66.1 Broken pipeline between HX1 and AFB1.	Explosive gases inside container. No combustible mixture for AFB1, temperatures decrease. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*	• PI-12, PI-03	• Add EtOH detector inside container. • Consider adding small ventilation hole to FP casing to prevent H_2 accumulation inside it. • Pressure testing of air and tail gas lines during on system commissioning.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
67. Fuel-air ratio (lambda) too rich	67.1 Too high TG1 or SU-EtOH-3 flows.	AFB1 catalyst coking. AFB1 reactions decrease and temperatures decrease. EVA2/HX3 temperatures decrease. Combustible gas mixture proceeds to exhaust line and after that to vent.	• FI-05, FI-04 • FC-06 • SRR temperature indicators • EVA2 temperature indicators	• Add air flow meter between PI-03 and airline branch. • Add lambda calculation in AFB1 using and AUTO-SD triggered by lambda < 1.5. • Top of the vent line should be located high enough to prevent personnel or material damage in case of ignition. • Entry of water/impurities into vent line should be prevented e.g by top cap or by line top bending.	
68. Fuel-air ratio (lambda) too lean	68.1 Too low TG1 or SU-EtOH-3 flows.	AFB1 temperatures decrease, causing problems in SRR and EVA2.	• SRR temperature indicators • EVA2 temperature indicators • FI-05, FI-04 • FC-06	• Add air flow meter between PI-03 and airline branch.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Air flow after HX2 [T ≈ 350-450 °C, p ≈200–300 mbar(g)]					
69. High temperature of air	69.1 Too low air flow rate due to blower AB2 malfunctioning.	WGSR outlet temperature increases slowing down WGS reactions. FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases. Too rich fuel-air mixture fed to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Add air flow meter after PI-02. • Consider adding temperature probe at OFFGAS-1 outlet (not easy to get data that represents HX2 outlet).	
	69.2 Leak outside between blower AB2 and HX2 or from HX2.	WGSR outlet temperature increases, WGS reactions limited by equilibrium and FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases. Too rich fuel-air mixture fed to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Add air flow meter after PI-02. • Consider adding temperature probe at OFFGAS-1 outlet (not easy to get data that represents HX2 outlet)	

HAZOP	**System:** Tail gas/heating system including air feed, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 17. & 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
70. Low temperature of air	70.1 Too high air flow rate due to blower AB2 malfunctioning.	WGSR outlet temperature decrease, kinetics of WGS reactions slowed down. FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases. EtOH-1 not evaporating before AFB2 (not very likely).	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Add air flow meter after PI-02. • Consider adding temperature probe at OFFGAS-1 outlet to detect if EtOH-1 is evaporated.	
	70.2 Low air temperature at blower AB2 intake.			• Comment: Not likely because container interior heated by waste heat from FP.	
71. High flow of air	71.1 Malfunctioning of blower AB2.	WGSR outlet temperature decreases, kinetics of WGS reactions slowed down. FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases.	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Add air flow meter after PI-02.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
72. Low flow of air	72.1 Malfunctioning of blower AB2.	WGSR outlet temperature increases slowing down WGS reactions. FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases. Too rich fuel-air mixture fed to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Add air flow meter after PI-02.	
	72.2 Leak outside between AB2 and HX2 or from HX2.	WGSR outlet temperature increases, WGS reactions limited by equilibrium and FP product gas contains more CO. CO concertation of PSA product gas increases, FCS efficiency decreases. Too rich fuel-air mixture fed to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• WGSR outlet temperature • PI-02	• Comment: WGSR inlet 400-430 °C. • Leak checking.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
73. No flow of air	73.1 Blower AB2 stopped.	No cooling to WGSR. No oxidant to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• PI-02 • WGSR outlet temperature	• Add air flow meter after PI-02. • Add AUTO-SD triggered by air flow meter (lambda < 1.5), or PID not reaching SP. • Consider adding AUTO-SD due to high WGSR outlet temperature (320 °C).	
	73.2 Pipeline failure or SUB1 rupture.	No cooling to WGSR. No oxidant to AFB2. To be covered under *Fuel-air ratio (lambda) too rich.*	• PI-02 • WGSR outlet temperature	• Comment: Not very likely. • Pressure testing of the system during commissioning • Comment: Could temperature cycling of SUB1 be a cause for leaks?	
74. High pressure of air	74.1 Blockage in pipeline between HX2 and AFB2.		• PI-02	• Comment: Not very likely. Blower p_{max} ≈ 1 bar(g). • Check pressure tolerance of SUBs.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
75. Low pressure of air	75.1 Leak outside between HX2 and AFB2.	Less air or fuel-air mixture to AFB1. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*	• PI-13 • Container H_2 detectors	• Leak testing of tail gas line when components changed or fittings opened.	
76. Wrong composition	76.1 WGSR leak to HX2	Less product gas to PSA. Possibly explosive gas mixture already downstream HX2. Temperature low until AFB2, so ignition before AFB2 not probable. However, combustion front may proceed upstream if H_2 concentration in WGSR/tail gas-air mixture is high enough.	• PI-04 • EVA1 temperature indicators • AFB2 inlet temperature indicator • WGSR temperature indicators • PI-13	• Consider adding temperature probe at OFFGAS-1 outlet to detect possible combustion front. • Add AUTO-SD triggered by AFB2 high inlet temperature (800 °C). • Leak testing of main process line after modifications or addition of new components.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 76. Wrong composition	76.2 Air blower AB2 sucks in air and combustible gases due to a leak in system. Container air contains ethanol, reformate or hydrogen.	Possible explosive gas mixture inside blower AB2 and downstream it. Gas mixture may ignite in SUB1 because of catalyst. Explosive gases/vapour inside container. EtOH vapour stays bottom of container, H_2 rises to upper part of container.	• Container H_2 detectors • AUTO-SD and ventilation increase triggered at 25 % LEL. • EM-SD triggered at 50% LEL, electricity cut-off from container. • Container ventilation • SUB1 temperature indicators	• Add EtOH detector inside container. • Placement of air blowers vertically at middle in container, or routing air intake by tube to container fresh air intake grille. • Check if separate ventilation blower(s) is needed at the floor level of the container (for possible ethanol vapours).	
77. Impurities	77.1 Dust or particulates from outside or inside of container.	Blockage of AB2, SUB1 and other components downstream.	• PI-02	• Add filters to air blowers AB2 (and AB1) inlets. • Add air flow meter after PI-02.	
Fuel-air mixture to AFB2 [T ≈ 200-300 °C, p ≈ 200-300 mbar(g)]					
78. High temperature of fuel-air mixture				• Comment: No identified causes for high temperature in case the gas composition is correct and EVA1 functioning normally.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
79. Low temperature of fuel-air mixture	79.1 Impaired heat insulation inside FP.	Afterburner AFB2 cools down. All the fuel processor components cool down.		• Internal insulation of FP casing should be checked for leaks after moving casing or container.	
80. High flow of fuel-air mixture				• Comment: No identified causes for high flow in case the gas composition is correct.	
81. Low flow of fuel-air mixture	81.1 Small leakage after TG2 or EtOH-1 mixing point.	Less combustible mixture for afterburner AFB2. AFB2 temperatures decrease. See deviation *Low temperature after EVA1*. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• EVA1 temperature indicators	• Consider adding small ventilation hole to FP casing to prevent H_2 accumulation inside it. • Leak testing of tail gas lines when components changed or fittings opened. • Add EtOH detector inside container.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
82. No flow of fuel-air mixture	82.1 Broken pipeline between HX2 and AFB2.	Explosive gases inside container. No combustible mixture for AFB2, temperatures decrease. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-13, PI-02	• Add EtOH detector inside container. • Consider adding small ventilation hole to FP casing to prevent H_2 accumulation inside it.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
83. Fuel-air ratio (lambda) too rich	83.1 Too high TG2 and/or EtOH-1 flows.	AFB2 catalyst coking. AFB2 reactions decrease and temperatures decrease. Combustible gas mixture proceeds to exhaust line and after that to vent.	• FI-05 • FC-05 • EVA1 temperature indicators	• Add air flow meter after PI-02. • Add lambda calculation in AFB2 using and AUTO-SD triggered by lambda < 1.5. • Top of the vent line should be located high enough to prevent personnel or material damage in case of ignition. • Entry of water/impurities into vent line should be prevented e.g by top cap or by line top bending.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 83. Fuel-air ratio (lambda) too rich	83.2 Air flow needed for WGSR cooling too low for AFB2.	AFB2 catalyst coking. AFB2 reactions decrease and temperature decreases. Combustible gas mixture proceeds to exhaust line and after that to vent.	• FI-05 • FC-05 • EVA1 temperature indicators	• Add air flow meter after PI-02. • Add lambda calculation in AFB2 using and AUTO-SD triggered by lambda < 1.5. • Top of the vent line should be located high enough to prevent personnel or material damage in case of ignition. • Entry of water/impurities into vent line should be prevented e.g. by top cap or by line top bending.	
84. Fuel-air ratio (lambda) too lean	84.1 Too low TG2 or EtOH-1 flows.	AFB2 temperatures decrease, causing problems in EVA1.	• EVA1 temperature indicators • FI-05 • FC-05	• Add air flow meter after PI-02.	
	84.2 Air flow needed for WGSR cooling too high for AFB2.		• FI-05 • FC-05	• Comment: Not very relevant. Can be compensated by increasing TG2 or EtOH-1flows. • Add air flow meter after PI-02 .	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
AFB exhaust gas after VLS2 [T ≈ 20-50 °C , p ≈ 0-50 mbar(g)]					
85. High temperature of exhaust gas	85.1 Heat conduction and convection from AFB2 and HX3 outlet.	DV2 gaskets may damage. Not enough condensed water, DV2 may dry up and start to leak gas to drain pipe leading outside of container.		• Comment: Temperature at AFB2 and HX3 outlets ≈ 100-200 °C • Pipeline before water separation should be long enough to ensure cooling of the gas. • Pipelines to be located so that condensed water droplets flow to DV2 by gravity. • Drain outlet to be located to container wall inside fence. • To prevent DV2 drying, consider adding a shut-off valve after it, that closes when system not in operation and prevents water leaking through.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
86. Low temperature of exhaust gas				• Comment: Not relevant deviation. Subzero environment temperatures not considered in study.	
87. Wrong composition	87.1 Combustible components in AFB exhaust gas due to incomplete combustion in AFB1 and/or AFB2.	Possibly explosive gas mixture in top of vent line.		• Top of the vent line should be located high enough to prevent personnel or material damage in case of ignition. • Entry of water/impurities into vent line should be prevented e.g. by top cap or by line top bending.	

HAZOP	System: PSA product gas feed to FCS, steady state operation, full load Team: Pauli Koski, Janne Sarsama, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			Date: 2.2.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
PSA product gas flow after pipe branch downstream MV2 [T ≈ 25 °C, p ≈ 1.0-8.5 bar(g)]					
88. High PSA product gas flow (correct composition)				• Comment: Not very probable because dosing of both H_2O and EtOH should be simultaneously wrong.	
89. Low PSA product gas flow (correct composition)	89.1 Small leak outside in PSA or pipeline downstream.	Less product gas. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-06 and PI-08 • Container H2 detectors	• Consider adding AUTO-SD triggered by PI-06, if much lower than PI-08 (<50 mbar lower)	
90. No PSA product gas flow	90.1 Big leakage in PSA or pipeline downstream.	No H_2 feed to FCS. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-06 and PI-08 • Excess flow valves EFV1 & 2 restrict tank from emptying with high gas flow.	• Consider adding shut-off valve inside container to prevent release of whole H_2 tank content into container. Shut-off valve triggered if PI-06 more than 50 mbar lower than PI-08, and in AUTO-SD and EM-SD. • Move PI-08 and TI-10 to the H_2 tank instead of feed pipeline.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
91. PSA product gas flow elsewhere	91.1 Malfunctioning of control system of PSA unit: PSA takes in PSA product gas through H2 purge port in normal steady state run.	No or less H_2 feed to FCS. Possible damage to PSA.	• PSA unit's own control system detects such failures.	• Comment: Not very likely. • Comment: H_2 purge used in shut-down.	
92. High pressure fluctuation in PSA product gas	92.1 Restriction between PSA product gas outlet and H2 tank, e.g. partially closed MV2 and/or MV4. Also H2 bottles (that "form" H2 tank) have their own valves, which can be partially closed.	PSA conditions non-optimal, leading to higher CO concentration in PSA product gas. If control pressure of PSA product gas line is not reached, PSA control system triggers PSA to go to STOP state.	• PI-06 • PSA STOP state triggers system AUTO-SD.	• Comment: Some pressure fluctuation is normal.	
93. High CO concentration of PSA product gas	93.1 PSA not functioning as expected, e.g. adsorbent performance decreased.	Reduced efficiency of FCS due to anode catalyst poisoning.	• FCS cell voltage monitoring • FCS shuts down when voltage drops too low (~ 0,57 V), triggers system AUTO-SD.	• Comment: Cause of low cell voltages investigated afterwards. System operation should not be aborted just because of decreasing cell voltages.	
94. Impurities in PSA product gas	94.1 Adsorbent released from PSA.	Particles possibly getting in H_2 tank are not very harmful.		• Comment: Adsorbent particles not large enough to cause e.g. pipeline blockages.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
PSA product gas flow after H_2 tank (after pipe branch downstream MV3 and MV5, before SV3) [T ≈ 25 °C, p ≈ 1.0-8.0 bar(g)]					
95. No flow of PSA product gas	95.1 Hand valves MV4 or MV5 (or both) are closed unintentionally or deliberately by vandal etc. (Hand valve MV3 normally closed during run.)	No H_2 feed to FCS either immediately or with a delay. FCS shuts down when voltage drops too low (~0.57 V).	• FI-03 • FCS cell voltage monitoring • FCS shut down triggers system AUTO-SD.	• Restrict unauthorized access to system with a fence. • Consider adding locks to MV4 and MV5, and to MV3. • Comment: Hand valve MV3 normally closed during run.	
	95.2 Big leakage, broken pipe etc.	No H_2 feed to FCS. Formation of explosive gas mixture inside or outside of container, at least around leakage point. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container* and *Leaks or gas release from system to outside*	• PI-08 (used also to indicate amount of H_2 currently stored). • PI-09, PI-06 • Flow rate restricted by excess flow valves EFV1 and EFV2. • FI-03 • FCS cell voltage monitoring • FCS triggers shutdown at low pressure and when voltage drops too low. • FCS shutdown triggers system AUTO-SD.	• In placement of indicators PI-08 and TI-10 take into account results of H_2 tank EX-zone classification. • Pipeline outside container should be properly grounded to prevent build-up of static electricity.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 95. No flow of PSA product gas	95.3 Large leakage in H2 tank.	Formation of explosive gas mixture around leakage point.	• PI-08	• Comment: H_2 bottles (2 pcs.) that "form" H_2 tank, specified to hold 200 bar(g), large leakage not probable.	
96. High temperature of PSA product gas	96.1 High ambient temperature.	Pressure increases in H_2 tank and in related pipelines. Max. pressure increase ~ 20 %, when temperature changes from -20 to +35 °C.	• PI-08, PI-06 • TI-10	• Add pressure relief valve to H_2 tank. Opening pressure ca. 11 bar(g). • Comment: No harm to FCS due to increased PSA product gas temperature.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 96. High temperature of PSA product gas	96.2 Fire or other unexpected intense heat source nearby H2 tank.	Pressure increases in H_2 tank and in related pipelines. Possible failure of SV3, SV4, MFM3 (max operating pressure 10bar(g)), PR1 etc. or rupture of H_2 tank.	• PI-08, PI-06 • TI-10	• Add pressure relief valve to H_2 tank. Opening pressure ca. 11 bar(g). • Place MFM3 downstream PR1 (allows usage of 11 bar(g) relief valve). • Consider adding controlled valve in parallel with pressure relief valve that opens if TI-10 or PI-08 measures high temperature (> 50 °C) or pressure (> 10 bar(g)) but is not opened at AUTO-SD.	
97. Low temperature of PSA product gas	97.1 Low ambient temperature.	Cooling capacity needed by FCS decreases. No harm for system.	• TI-10, TI-11	• Comment: In case of low ambient temperature PSA product gas most probably cools down when flowing through H_2 tank.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
98. Impurities in PSA product gas	98.1 Impurities released from H2 tank surfaces at low pressure.	May cause blockage of microporous structures in anode electrodes. Presumably washed away with water droplets. No considerable effects during first 5000 hours of operation. May cause MFM3 malfunction.		• Comment: Under normal operation, pressures < 1 bar(g) at H_2 tank not likely. FCS stops at 1 bar(g) H_2 tank pressure. • Pay attention that when H_2 bottles emptied e.g. for transport/storage, residual gas is not directed into system but is vented into atmosphere e.g. • Comment: Particles not large enough to cause e.g. pipeline blockages. • Consider adding filter before MFM3.	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 98. Impurities in PSA product gas	98.2 Adsorbent released from PSA.	May cause blockage of microporous structures in anode electrodes. Presumably washed away with water droplets. No considerable effects during first 5000 hours of operation. May cause MFM3 malfunction.		• Comment: Adsorbent particles not large enough to cause e.g. pipeline blockages. • Consider adding filter before MFM3.	
PSA product gas flow to FCS (after PR1) [T ≈ 25 °C, p ≈1.0-4.0 bar(g)]					
99. High FCS feed gas flow (correct composition)	99.1 Solenoid valve or valves (SV FCS3 and SV FCS2) unintentionally open inside FCS.	Significant amount or all of H_2 flows to vent through SV FCS3 / SV FCS2, and not through stack. Loss of H_2 in stack, cell voltages decrease. H_2 starvation may cause damage to cathode catalyst.	• FI-03 • Pressure sensors inside FCS • FCS cell voltage monitoring	• Add AUTO-SD triggered by FI-03 if reading very high for extended period (> 100 nlpm for 5-10 s).	

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 99. High FCS feed gas flow (correct composition)	99.2 Big leakage inside FCS.	H_2 released inside FCS and eventually to container. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• FCS and container H_2 detectors. • H_2 detectors inside FCS trigger FCS shutdown.		
100. Low FCS feed gas flow (correct composition)	100.1 Small leakage in pipeline after pipe branch downstream MV3 and MV5 (i.e. after the previous point of examination).	Less H_2 feed to FCS. FCS shuts down if voltage drops too low (~0.57 V) or if inlet pressure is low (<0.7 bar(g)). Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• FI-03 • PI-09	• Consider adding system AUTO-SD triggered by PI 09 low pressure (< 0.7 bar(g)).	
101. No FCS feed gas flow	101.1 SV3 or SV4 unintentionally closed, malfunctioning of PR1.	No H_2 feed to FCS.	• FI-03 • PI-09 • FCS cell voltage monitoring • FCS triggers shutdown at low pressure and when voltage drops too low. • FCS shutdown triggers system AUTO-SD.		

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Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
continued… 101. No FCS feed gas flow	101.2 Big leakage in pipeline after pipe branch downstream MV3 and MV5 (i.e. after the previous point of examination).	No H_2 feed to FCS. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-09 • FI-03 (high reading if leakage downstream of it, in opposite case no flow reading).		
102. High pressure of FCS feed gas	102.1 Malfunctioning of PR1	No harmful consequences because of safeguards.	• PI-09 • FCS controller closes SV FCS1 if pressure too high.	• Comment: Not very likely. • Consider adding system AUTO-SD if PI-09 > 5 bar(g).	
103 Low pressure of FCS feed gas	103.1 Malfunctioning of PR1.	Not enough H_2 feed to FCS.	• PI-09 • FCS shuts down if pressure too low (tank empty)	• Comment: PR FCS1 requires 0,7 bar(g) to function.	
	103.2 Small leakage in pipeline after pipe branch downstream MV3 and MV5 (i.e. after the previous point of examination).	Not enough H_2 feed to FCS. Consequences and related detection and safeguards of combustible gas discharge into system surroundings to be covered later more detail in section *Leaks from system inside container*.	• PI-09 • FCS shuts down if pressure too low (tank empty)	• Consider adding AUTO-SD triggered by PI 09 low pressure (< 0,7 bar(g)).	

HAZOP	**System:** PSA product gas feed to FCS, steady state operation, full load **Team:** Pauli Koski, Janne Sarsama, Johan Tallgren, Minna Nissilä (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			**Date:** 2.2.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
104 High concentration of "inert gas" in FCS feed gas	104.1 PSA not working as specified.	Inert accumulation in FCS. Slightly decreased FCS performance.	• FCS cell voltage monitoring	• Comment: Inert gases from the point of view of FCS e.g. CH_4, CO_2. • Comment: High CO concentration expected before inert gases cause any decrease in performance.	
105. Rapid changes of CO concentration in FCS feed gas	105.1 MV3 open, flow shorts through it.	Gas not mixing properly in H_2 tank. Cell voltages may fluctuate.	• FCS cell voltage monitoring	• Restrict unauthorized access to system with a fence. • Consider adding lock to MV3. • Comment: Problematic mainly immediately after PSA start-up, when PSA steady-state not reached yet and CO concentration > 20 ppm.	

HAZOP	System: FCS air-side exhaust gas water condensing & feed to H_20 tank, steady state operation, full load Team: Pauli Koski, Janne Sarsama (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 2.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Water flow after DV3 [T ≈ 25-30 °C, p ≈ 0-50 mbar(g)]					
106. No flow	106.1 No condensation in COND2 due to low coolant flow or high coolant temperature.	Water not collected, system runtime reduced. Hot and humid exhaust gas goes to vent (70 °C, RH = 100 %). Condensation of water in vent pipe.	• Difference between TI-07 and TI-12 indicate heat transfer. • Low level of water in H_20 tank, LI-03.	• Comment: No detection of low coolant flow. • Comment: Exhaust air cooled to 30 °C. • Consider adding temperature indicator in air exhaust line after COND2.	
	106.2 Malfunctioning of VLS3.	Water not collected, system runtime reduced. Droplets entering vent line.	• Low level of water in H_20 tank, LI-03.	• Comment: Droplets may also back-flow to VLS3 due to gravity.	
107. Impurities	107.1 Wash-out of eroded FCS cathode catalyst carrier. Impurities from air not caught in FCS air intake filter. Fluor traces from FCS membrane or membrane humidifier MH1.	Particle impurities proceed to H_20 tank, and possibly to H_20 feed.	• Filters F1 and F2	• Comment: Chemical contaminants from air intake (e.g. sulphur compounds) very unlikely. • Placement of AFB exhaust vent as far possible from FCS air intake.	

HAZOP	**System:** Whole system - Conditions inside container and leaks inside container or outside of it **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			**Date:** 21.2.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Conditions inside container					
108. High temperature inside container	108.1 High ambient temperature, fire near or inside container, insufficient ventilation.	VP1 diaphragm may be damaged > 60 °C. Electrical equipment inside FCS may overheat.	• TI-13 • Container ventilation.	• Add system EM-SD triggered by TI-13 high temperature (> 80 °C).	
109. Animal(s) inside container (e.g. squirrels, mice, birds, insects…).		Possible damage e.g. to electrical equipment or plastic pipelines.		• Prevent access of animals inside container by appropriate means, installing chicken wire to large openings of container etc.	
110. Water enters inside container	110.1 Heavy rain and related flooding in surroundings of container.	Flooding of container floor, possible damage to electrical equipment.		• Take care of possibility of flooding in placement of container.	
111. External power grid outage		FCS unaffected. Grid outage triggers FP and PSA emergency shutdown.	• UPS for PLC system	• Consider installation of 2nd UPS to enable AUTO-SD for FP and PSA.	
Leaks from system inside container					
112. Liquid EtOH or EtOH/water mixture leakage inside container	112.1 Equipment failure	Liquid spills on container floor or equipment below leakage, possibly causing damage to electrical equipment. EtOH vaporizes and accumulates at the bottom of the container.	• Container ventilation • Splash-proof casing used for electronics. • PLC control system and power supplies located in separate gas proof segment of container.	• Add EtOH detector inside container. • Check if liquid can flow out of container floor.	

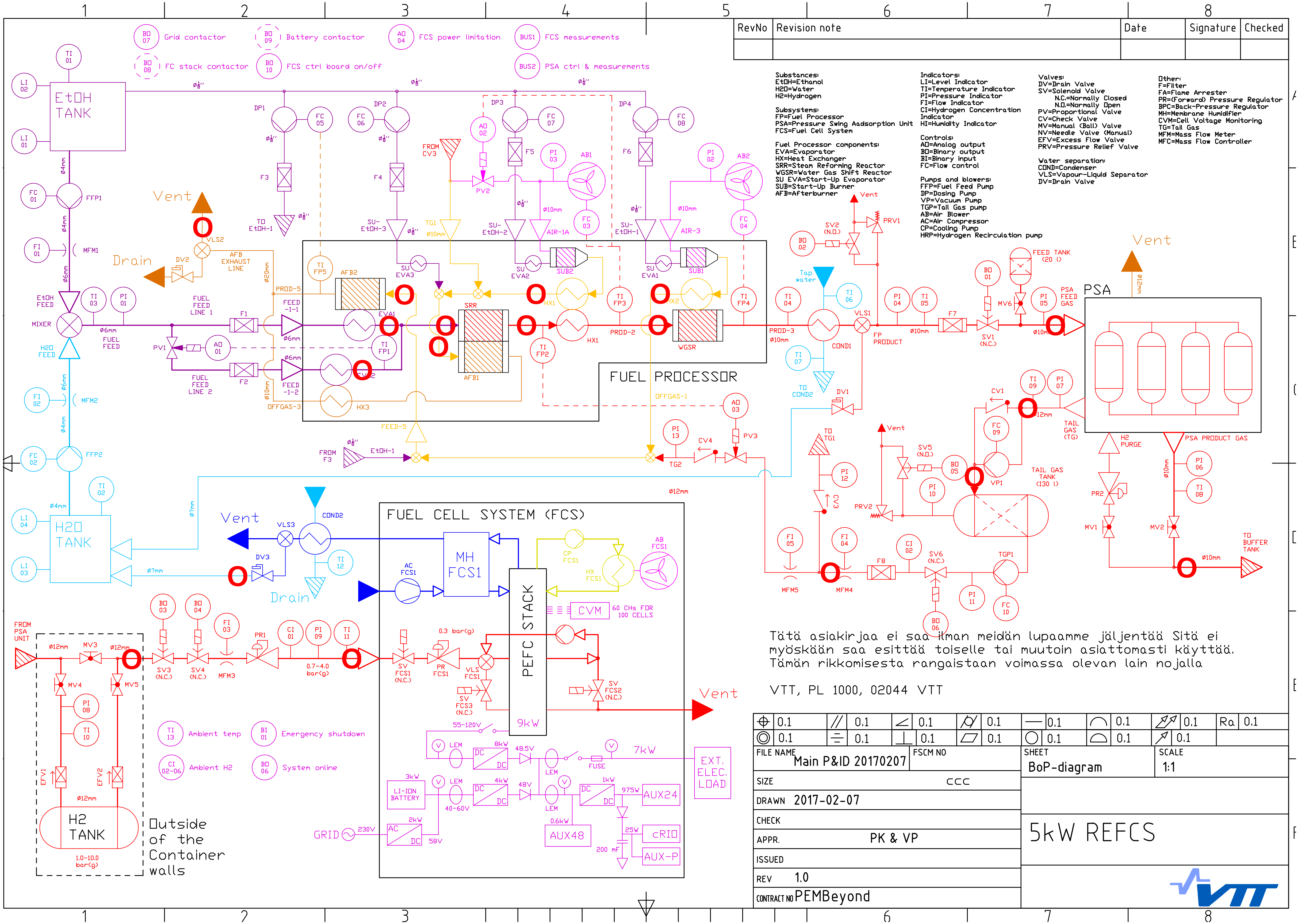
HAZOP	System: Whole system - Conditions inside container and leaks inside container or outside of it Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf			Date: 21.2.2017	
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
113. Liquid water leakage	113.1 Equipment failure	Liquid spills on container floor or equipment below leakage, possibly causing damage to electrical equipment.	• Splash-proof casing used for electronics. • PLC control system and power supplies located in separate gas proof segment of container.	• Check if liquid can flow out of container floor.	
114. Leakage from system inside FP casing (fuel or combustible gas mixture)	114.1 Equipment failure	Depending on leakage location, state of leaking substance may be liquid or gaseous and thus can exit casing as liquid or vapour. In case of fuel leakage and if EtOH vapour separates from H_2O vapour, EtOH vapour may ignite. In case of reformate gas leakage, gas may ignite from hot surfaces.	• Container H_2 detectors • AUTO-SD and ventilation increase triggered at 25 % LEL. • EM-SD triggered at 50 % LEL, electricity cut-off from container. • Container ventilation	• Add EtOH detector inside container. • Consider installing perforation at top of FP casing for ventilation of combustible gases. • Place additional H_2 detector close to perforations. • During H_2 or EtOH alarm, personnel should not enter in container. • Personnel entering container should carry portable CO detectors and container doors should be open for CO ventilation.	

HAZOP	**System:** Whole system - Conditions inside container and leaks inside container or outside of it **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
115. Combustible gas mixture leakage inside container (reformate gas, FP product gas, tail gas)	115.1 Equipment failure	Combustible gas released inside container.	• Container H_2 detectors • AUTO-SD and ventilation increase triggered at 25 % LEL. • EM-SD triggered at 50 % LEL, electricity cut-off from container. • Container ventilation	• During H_2 alarm, personnel should not enter in container. • Personnel entering container should carry portable CO detectors and container doors should be open for CO ventilation.	
116. Hydrogen leakage inside container (PSA product gas)	116.1 Equipment failure	Released hydrogen accumulates near container roof, forming explosive mixture.	• Container H_2 detectors • AUTO-SD and ventilation increase triggered at 25 % LEL. • EM-SD triggered at 50 % LEL, electricity cut-off from container. • Container ventilation	• During H_2 alarm, personnel should not enter in container. • Personnel entering container should keep container doors open for H_2 ventilation.	
117. AFB exhaust gas leakage inside container	117.1 Equipment failure	Water vapour released into container, which may condense on surfaces, possibly causing damage to electrical equipment. Oxygen content inside container decreases.	• Container ventilation • Splash-proof casing used for electronics. • PLC control system and power supplies located in separate gas proof segment of container.		

HAZOP	**System:** Whole system - Conditions inside container and leaks inside container or outside of it **Team:** Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) **PI-diagram:** PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				**Date:** 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
Leaks or gas release from system to outside					
118. Hydrogen leakage from H2 tank or pipeline outside container	118.1 Equipment failure	Released hydrogen forms with air explosive gas mixture near leak source.	• PI-08 • EFV1, EFV2	• Fence around H_2 tank (H_2 bottles) should be large enough to prevent unauthorized access to EX zone. • Use EX certified pressure and temperature probes. • Install appropriate "danger/explosive atmosphere" signs near H_2 tank.	

HAZOP	System: Whole system - Conditions inside container and leaks inside container or outside of it Team: Pauli Koski, Janne Sarsama, Noora Kaisalo (all from VTT Technical Research Centre of Finland Ltd) PI-diagram: PEMBeyond main P_ID, Mech2016_2017-02-07-BoP.pdf				Date: 21.2.2017
Deviation	**Causes**	**Consequences**	**Detection and safeguards**	**Suggested/required actions, comments**	**Action allocated to**
119. Combustible gas mixture release from system pressure relief valves	119.1 Too high pressure in system causing some pressure relief valve to open.	Explosive gas mixture at vent line outlet.		• Vent lines related to pressure relief valves should be located high enough to prevent personnel or material damage in case of ignition. • Entering of water/impurities into vent lines should be prevented e.g by top cap or by line top bending. • Vent lines should be properly grounded • Reason for high pressure should be investigated and PRV checked before system is operated again.	

Piping and instrumentation diagram (P&ID)



RevNo
Revision note
Date
Signature
Checked
BO 07 Grid contactor
BO 09 Battery contactor
BO 08 FC stack contactor
BO 10 FCS ctrl board on/off
AO 04 FCS power limitation
BUS1 FCS measurements
BUS2 PSA ctrl & measurements
Substances:
EtOH=Ethanol
H2O=Water
H2=Hydrogen
Subsystems:
FP=Fuel Processor
PSA=Pressure Swing Aadsorption Unit
FCS=Fuel Cell System
Fuel Processor components:
EVA=Evaporator
HX=Heat Exchanger
SRR=Steam Reforming Reactor
WGSR=Water Gas Shift Reactor
SU EVA=Start-Up Evaporator
SUB=Start-Up Burner
AFB=Afterburner
Indicators:
LI=Level Indicator
TI=Temperature Indicator
PI=Pressure Indicator
FI=Flow Indicator
CI=Hydrogen Concentration Indicator
HI=Humidity Indicator
Controls:
AO=Analog output
BO=Binary output
BI=Binary input
FC=Flow control
Pumps and blowers:
FFP=Fuel Feed Pump
DP=Dosing Pump
VP=Vacuum pump
TGP=Tail Gas pump
AB=Air Blower
AC=Air Compressor
CP=Cooling Pump
HRP=Hydrogen Recirculation pump
Valves:
DV=Drain Valve
SV=Solenoid Valve
N.C.=Normally Closed
N.O.=Normally Open
PV=Proportional Valve
CV=Check Valve
MV=Manual (Ball) Valve
NV=Needle Valve (Manual)
EFV=Excess Flow Valve
PRV=Pressure Relief Valve
Water separation:
COND=Condenser
VLS=Vapour-Liquid Separator
DV=Drain Valve
Other:
F=Filter
FA=Flame Arrester
PR=(Forward) Pressure Regulator
BPC=Back-Pressure Regulator
MH=Membrane Humidifier
CVM=Cell Voltage Monitoring
TG=Tail Gas
MFM=Mass Flow Meter
MFC=Mass Flow Controller
EtOH TANK
H2O TANK
H2 TANK
Vent
Drain
FUEL PROCESSOR
PSA
FUEL CELL SYSTEM (FCS)
PEFC STACK
9kW
CVM
60 CHs FOR 100 CELLS
MH FCS1
EXT. ELEC. LOAD
AUX24
AUX48
cRIO
AUX-P
Li-ION BATTERY
GRID
FEED TANK (20 l)
TAIL GAS TANK (130 l)
TO BUFFER TANK
PSA PRODUCT GAS
Outside of the Container walls
FROM PSA UNIT
Tätä asiakirjaa ei saa ilman meidän lupaamme jäljentää. Sitä ei myöskään saa esittää toiselle tai muutoin asiattomasti käyttää. Tämän rikkomisesta rangaistaan voimassa olevan lain nojalla
VTT, PL 1000, 02044 VTT
FILE NAME Main P&ID 20170207
FSCM NO
SHEET BoP-diagram
SCALE 1:1
SIZE ccc
DRAWN 2017-02-07
CHECK
APPR. PK & VP
ISSUED
REV 1.0
CONTRACT NO PEMBeyond
5kW REFCS
VTT