MULTISTAGE RISK ANALYSIS AND SAFETY STUDY OF A HYDROGEN ENERGY STATION

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ABSTRACT

China has plenty of renewable energy like wind power and solar energy especially in the northwest part of the country. Due to the volatile and intermittent characters of the green powers, high penetration level of renewable resources could arise grid stabilization problem. Therefore electricity storage is considered as a solution and hydrogen energy storage is proposed. Instead of storing the electricity directly, it converts electricity into hydrogen and the energy in hydrogen will be released as needed from gas to electricity and heat. The transformed green power can be fed to the power grid and heat supply network. State Grid Corporation of China carried out its first hydrogen demonstration project. In the demonstration project, an alkaline electrolyzer and a PEM hydrogen fuel cell stack are decided as the hydrogen producer and consumer, respectively. Hydrogen safety issue is always of significant importance to secure the property. In order to develop a dedicated safety analysis method for hydrogen energy storage system in power industry, the risk analysis for the power-to-gas-to-power&heat facility was made. The hazard and operability (HAZOP) study and the failure mode and effects analysis (FMEA) are performed sequentially to the installation, to identify the most problematic parts of the system in view of hydrogen safety and possible failure modes and consequences. At the third step, the typical hydrogen leak accident scenarios are simulated by using computational fluid dynamics (CFD) computer code. The resulted pressure loads of the possibly ignited hydrogen-air mixture in the facility container are estimated conservatively. Important safeguards and mitigation measures are proposed based on the three-stage risk and safety studies.

1.0 INTRODUCTION

Due to the carbon-free nature of hydrogen gas, hydrogen has been considered as future energy in replacement of hydrocarbon resources [1, 2]. As a type of energy, hydrogen contains more than three times combustion energy than gasoline by weight [2]. Hydrogen could be produced by varies means including water electrolysis, reforming, thermocatalytic cracking, thermolysis, biotechnology, photonic and etc. [3]. To utilize the energy in hydrogen, one clean way is to generate electricity by fuel cell technology which converts hydrogen and oxygen to water, electricity and heat.

By combining hydrogen production and utilization processes mentioned above, there is one attractive cycle, hydrogen production with water electrolysis and hydrogen consumption by fuel cell, in which there is no carbon included and hydrogen could act as electricity storage media. Based on this idea, hydrogen energy storage system is developed and many demonstration projects have been employed to prove the feasibility of the idea [4]. One of the successful projects is MYRTE project which was commissioned at Corsica, France. According to [5], in MYRET project, hydrogen energy storage system is integrated into the local PV station to generate hydrogen and oxygen through water electrolysis by excess solar power. Both hydrogen and oxygen are stored in high pressure vessels. Whenever the PV generation could not cover the load, a PEM fuel cell power generation system will generate power by stored hydrogen and oxygen.

Despite the advantages of using hydrogen as energy storage media, a major concern of the technology is safety issue which could also be an obstacle to expand its commercial implementation. To prevent potential hazard from hydrogen system, lots of studies were carried out and different safety analysis methods were developed [1, 2, 6].

Recently, the authors were involved in a pilot hydrogen energy storage demonstration platform in China, which is the first hydrogen project in China power industry. Regarding the hydrogen hazard management, a collaboration between global energy interconnection research institute (GEIRI) and Karlsruhe Institute of Technology (KIT) was established to take care of the safety issue. A multistage risk analysis methodology, which combines three different safety analysis methods (HAZOP, FMEA and CFD), was applied in the project. In this paper, the platform configuration, the methodology, and the results from safety study are presented.

2.0 POWER TO GAS TO POWER & HEAT FACILITY

The platform is container based and consists of PV simulator, alkaline electrolyzer, hydride hydrogen storage, fuel cell and heat recycle system. As the first hydrogen project in China power grid. the scale of this platform was decided to be 10kW level so the research team could gain basic experience from it and build larger system by multiple 10kW modules in next phase. Eventually, considering the equipment availability, the system was set to 11kW electrolyzer (hydrogen production rate: 2Nm^3/h) and 10kW fuel cell stack (FCS). The hydride storage tank was supposed to store the hydrogen produced from the 11kW electrolyte system for 8 hours. Hence, the storage capability was originally designed to be 16Nm^3 and finally, it became 20Nm^3 for redundancy. A PEM electrolyzer with 1Nm^3/h production rate is also equipped in the platform for future research. Fig. 1 presents the on-site overview of the platform.

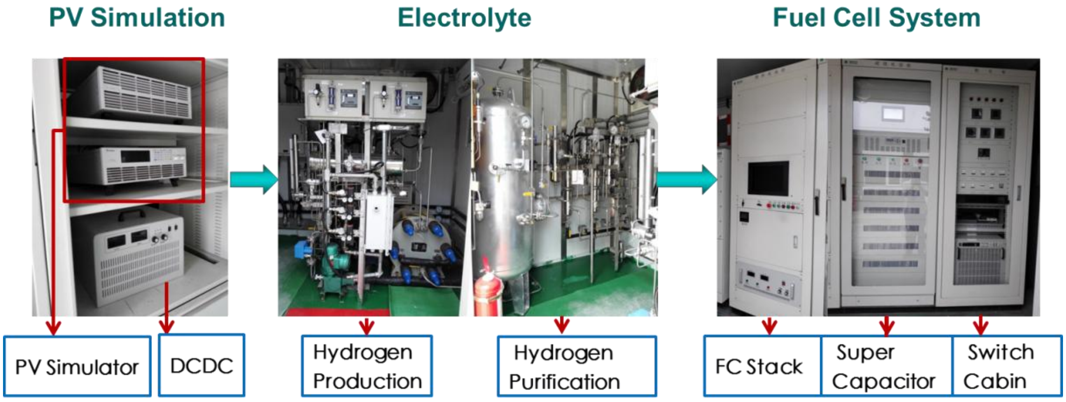

Figure 1. The configuration and equipment in the platform

To increase the overall efficiency, the platform is also designed to evaluate heat recycle concept. A heat exchanger is installed in the fuel cell coolant loop to collect waste heat. The coolant of hydride tank is coupled with the fuel cell heat recycle loop in order to re-use the waste heat to heat up hydride storage.

All equipment of the platform is configured into two containers and one storage room. PV simulator and alkaline water electrolyzer system are located in hydrogen production container. FCS, super capacitor, PEM electrolyzer and switch cabin are installed together in operation container. The storage room is adjacent to operation container and used to keep hydrogen, nitrogen and hydride hydrogen storage tank.

3.0 METHODOLOGY

In power industry, the safety issue is always of great importance. As the first hydrogen based project in China power sector, the safety level of platform had drawn great attention during the project. However, there are few standards to follow regarding safety analysis for hydrogen energy storage system in power industry. To comprehensively manage the safety of demonstration platform, the authors applied the multistage safety analysis, which has been well proven in nuclear power plant design, to this project in both design and construction phases.

The methodology applied in this project is the combination of three safety analysis methods, HAZOP, FMEA and CFD analysis. HAZOP and FMEA were performed to identify the potential risks and failure modes. Since the hydrogen is the hazardous gas and could lead to explosion if the proper safeguards are not taken after leakage, a CFD was performed to simulate the hydrogen behaviour under leakage scenario.

The three stages were performed sequentially in this project. First, HAZOP was applied to identify all potential failure modes for each component. Based on the HAZOP results, the occurrence probability, detectability and severity of each failure mode were scaled by applying FMEA and risk priority number (RPN) is then defined to indicate the significance of each failure mode. A ranking of the RPNs for all analyzed failure were obtained as the results of FMEA study. Important safeguards or protection measures were proposed for those failures with high RPN to improve the safety of the hydrogen energy station. In all potential failure modes, the hydrogen leakage cases were specially treated by additional CFD analysis. The full steps of multistage risk analysis is shown in Fig. 2.

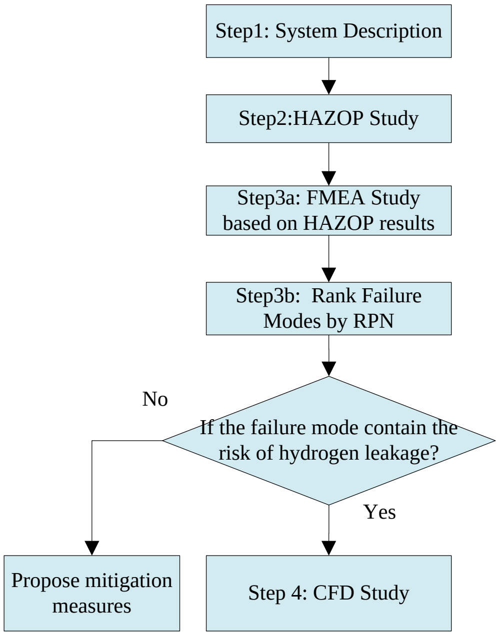

Figure 2. The stages of risk analysis

4.0 SYSTEM DESCRIPTION

The starting point of safety analysis is the pipe & instrumentation diagram (PID) as shown in Fig. 3. To identify different elements in HAZOP and FMEA study, every element in the system is specified by a unique combination of code and number. The abbreviations used in the coding are listed below.

CEV - Normal closed electrical valve

CV - Check valve

DCDC - DC/DC transformer

ELZ - Electrolyzer

EV - Normal open electrical valve

FCS - Fuel cell stack

FN - Fan

H - H2 purity gauge

HAS -H2 alloy storage

HEX - Heat exchanger

HMD - Humidifier

I - Current gauge

MV - Manual valve

P - Pressure gauge

PB - Pressure bottle

PMP - Pump

PRV - Pressure reducing valve

PVS - Photovoltaic simulator

Q - Flow rate gauge

SPT - Separator

T - Temperature gauge

TWV - Three-way valve

V - Voltage gauge

Valve – All types of valves including Electrical Valve (EV), normal Closed Electrical Valve (CEV), Manual Valve (MV), Check Valve (CV), Pressure Reducing Valve (PRV) and Three-Way Valve (TWV);

WB - Wash basin

WL - Water level

WS - Water supply

WT - Water tank

Ω - Electrical conductivity gauge

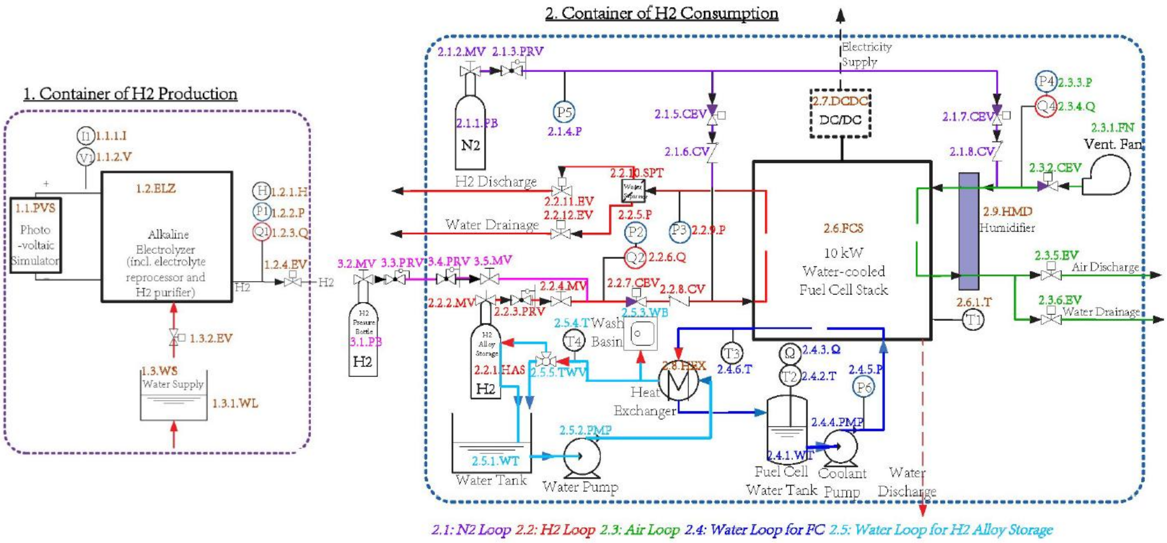

Figure 3. PID design with system and element coding and numbering

The platform was subdivided as 13 systems, including e.g. the PV simulator, the alkaline electrolyzer, the hydrogen loop, the air loop, the water loops and so on. There are totally 51 elements in 13 sub-systems, which are coded individually. The coding and numbering about the systems and the elements are listed in Tab. 1.

Table 1 System and element coding and numbering

System code	Element code	Description
1.1.PVS		Photovoltaic simulator
	1.1.1.I	Current gauge
	1.1.2.V	Voltage gauge
1.2.ELZ		Alkaline electrolyzer
	1.2.1.H	H2 purity gauge
	1.2.2.P	Pressure gauge
	1.2.3.Q	Flow rate gauge
	1.2.4.EV	Electrical valve
1.3.WS		Water supply to electrolyzer
	1.3.1.WL	Water level control
	1.3.2.EV	Electrical valve
2.1.N2		N2 loop
	2.1.1.PB	N2 pressure bottle
	2.1.2.MV	Manual valve
	2.1.3.PRV	Pressure reducing valve
	2.1.4.P	Pressure gauge
	2.1.5.CEV	Normal closed electrical valve
	2.1.6.CV	Check valve
	2.1.7.CEV	Normal closed electrical valve
	2.1.8.CV	Check valve
2.2.H2		H2 loop
	2.2.1.HAS	H2 alloy storage system
	2.2.2.MV	Manual valve
	2.2.3.PRV	Pressure reducing valve
	2.2.4.MV	Manual valve
	2.2.5.P	Pressure gauge
	2.2.6.Q	Flow rate gauge
	2.2.7.CEV	Normal closed electrical valve
	2.2.8.CV	Check valve
	2.2.9.P	Pressure gauge
	2.2.10.SPT	Water separator
	2.2.11.EV	Electrical valve
	2.2.12.EV	Electrical valve
2.3.Air		Air loop
	2.3.1.FN	Venting fan
	2.3.2.CEV	Normal closed electrical valve
	2.3.3.P	Pressure gauge
	2.3.4.Q	Flow rate gauge
	2.3.5.EV	Electrical valve
	2.3.6.EV	Electrical valve
	2.3.7 SPT	Water separator (not represented in Fig. 3)
2.4.Water1		Water loop for fuel cell stack
	2.4.1.WT	Water tank
	2.4.2.T	Temperature gauge
	2.4.3.Ω	Conductivity gauge
	2.4.4.PMP	Coolant pump
	2.4.5.P	Pressure gauge
	2.4.6.T	Temperature gauge

2.5.Water2		Water loop for H2 alloy storage
	2.5.1.WT	Water tank
	2.5.2.PMP	Water pump
	2.5.3.WB	Wash basin
	2.5.4.T	Temperature gauge
	2.5.5.TWV	Three-way valve
2.6.FCS		Fuel cell stack
	2.6.1.T	Temperature gauge
2.7.DCDC		DC/DC transformer
2.8.HEX		Heat exchanger
2.9.HMD		Humidifier
3.AHS		Alternative H2 supply system
	3.1.PB	H2 pressure bottle
	3.2.MV	Manual valve
	3.3.PRV	Pressure reducing valve
	3.4.PRV	Pressure reducing valve
	3.5.MV	Manual valve

After HAZOP and FMEA studies, hydrogen flow was simulated through CFD based on 3D drawing of the system. The geometry layouts of operation container and storage room are presented in Fig. 4. The hydrogen production container is not included in CFD analysis since in this project, it is a commercial product and its safety is already certified by the manufacture according to the national standard.

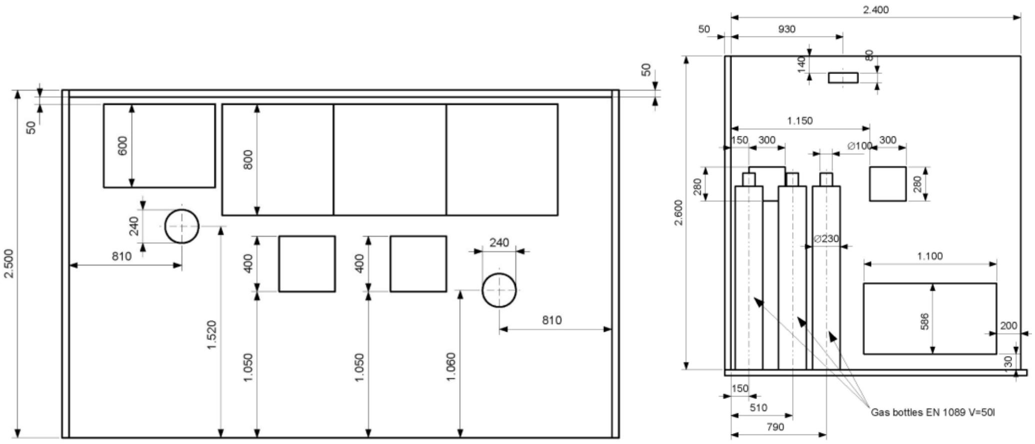

Figure 4. Layout of the operation container and storage room

5.0 HAZOP RESULTS,

By an overview of the HAZOP study results, the most typical accident scenarios that might happen to the platform are listed in Tab. 2. Accordingly, proper safeguards are proposed against the accidental scenarios which are also included in Tab. 2. The scenarios stated below are all directly or indirectly related to hydrogen event evolutions, e.g. hydrogen release, hydrogen accumulation/ distribution or hydrogen ignition and so on, which indicate further CFD study must be applied to assess the influence of hydrogen leakage.

Table 2 Potential accident scenarios and proposed safeguards

Category	Potential Accident Scenarios	Safeguards
Environmental issues	1 The ambient temperature is freezing or too hot 2 The ambient air is too humid or too dry	1 Filters at the fan inlet should be installed against any possible contamination from atmosphere 2 The gas flow into the FCS should be controlled at the entrance in terms of both temperature and humidity, i.e. air-conditioned 3 Emergency heating system is proposed in the water tanks against unexpected freezing incident 4 Anti-freezing coolant might be adopted, by accounting properly the compatibility to the surrounding facilities or other type of coolant
Overpressure of closed systems	1 Overpressure accident to closed vessels/ tanks or sealed piping systems, e.g. the H_2 loop, the air loop, the N_2 loop and so on	1 Fast responding safety valve as pressure limiter has to be installed for every closed or sealed vessel/ tank/ loop, including the H2 loop, the N2 loop, the air loop, the water loop 1 (cooling FCS), the water loop 2 (heating HAS), the HAS vessel, the FCS, the separator and the humidifier 2 The outlet pressures of both water pumps should be controlled to avoid any overdriven incident

Thermal-hydraulic fluid issues	1 Impurity of fluid, e.g. H_2, N_2, coolant water 2 Leakage of fluid, e.g. H_2, N_2, coolant water 3 Broken pipe or broken separation, e.g. plates in the heat exchanger, or membranes 4 in the FCS 5 Loss of cooling/ heating, e.g. the FCS and the HAS vessel 6 Total or partial blockage or congestion of pipe line	1 The purity of gas including H_2 and N_2 should be ensured 2 The water purity in water loop 1 (cooling the FCS) should be controlled 3 Definite separation of the H_2 alloy from cooling water must be kept in mind; otherwise serious explosion could occur 4 The minimum H_2 pressure in the HAS vessel is suggested to be maintained always above atmosphere, to avoid any air ingression into the HAS vessel 5 The temperature of H_2 alloy storage vessel should be controlled; over-heating while hydrogen charging could cause serious accident 6 The free volume at the top of water tank should be vented constantly or periodically, to avoid any H_2 accumulation in it 7 The water level and water temperature should be controlled for both tanks 8 The flow rate and pressure of the pumps should be measured and controlled 9 N_2 purging procedure should be conducted if the anode module of the FCS is contaminated 10 The pressure of the water loop for cooling the FCS is proposed to be always slightly higher than the pressure of the water loop for heating the HAS vessel, to avoid ingression of the water with lower quality in the latter loop into the former loop 11 The pressure of the N_2 bottle is suggested to be higher than that of the HAS vessel
Electrical issues	1 Wrong polarity of electrical equipment, e.g. the pumps, the fan, the electrolyzer 2 and the DC/DC transformer 3 Unstable (excess or inadequate) power supply to the electrical equipment 4 Loss of power supply to the electrical equipment	1 Fuse limiter, protection against wrong polarity and grounding must be assured to all electrical equipment, e.g. fan, pump, electrolyzer, DC/DC transformer, etc

Human error, installation and control issues	1 Human error (incorrect operation), e.g. incomplete operation to a valve 2 Wrong installation of equipment, e.g. direction of check valves, position of twophase 3 separators 4 Faulty control, mechanical defect, inaccurate measurement	1 Always correct operation to a manual valve 2 The valve 2.2.7.CEV should be surely closed during the N_2 purging procedure 3 The technicians, who construct the station, and who install the equipment, should be asked to provide installation documentation with checklist and signature 4 Measured parameters should be included in control unit as possible, e.g. pressure, temperature, flow rate, etc
Common security issues	1 Fire events 2 Flooding events	1 Fire extinguisher should be installed in/ at the containers

6.0 FMEA RESULTS

The hazards identified in the HAZOP stage are further quantified in FMEA stage, by means of scaling the failure occurrence likelihood, detectability and severity, which are defined as follow:

- Occurrence (O) — frequency or probability of the occurring failure;
- Severity (S) — harm or seriousness of the effect of the failure mode;
- Detectability (D) — probability of the failure being detected before it occurs in reality.

By using these quantities, a variable of risk priority number (RPN) is defined for every failure mode to indicate the risk significance in a whole view of the system safety. A ranking of the RPNs for all analyzed failure/effects is the result of the FMEA study.

In a typical FMEA, numerical rankings are assigned for each factor. The higher the ranking, the greater the potential harm posed by the failure and its effect. Attentions should be paid that the factor of “Detectability” is quantified in an inverse sense: a higher ranking or a higher value of “Detectability” stands for a harder situation to detect the failure. The rankings of the factors can be used on the scale of 1 to 10. The RPN can be determined by the product of the three factors, which reflects the overall measure of relative risk of the considered failure/effect. RPNs will be used to rank the significance of the risk posed by the failure/effect and the need for corrective actions to reduce or eliminate the potential failure mode.

In this project, totally 178 potential failure modes and effects of the 29 elements were analyzed. The 178 modes are categorized into three levels depending on the RPN values:

- 103 modes with RPN<40, which affect slightly the system without significant con-sequences;
- 52 modes with $40 \leqslant RPN < 100$, which could influence adversely the system or the operation. Safeguard measures should be considered;
- 23 modes with $RPN \geqslant 100$, which are strongly proposed to follow the recommended or adequate actions, to modify the design or install necessarily additional components or sensors.

The 178 potential failures/effects are also classified by the different sub-system, as shown in Fig. 5. The system name “1.H2P” in Fig. 5 is hereby defined, which is the “H_2 Production” (H2P) system including the three parts of the photovoltaic simulator (1.1.PVS), the electrolyzer (1.2.ELZ) and the water supply system (1.3.WS) to the electrolyzer. Fig. 5 manifests that the most potentially problematic system is the hydrogen loop "2.2.H2", which has 7 potential failure modes with RPN$\geqslant$

100. Second is the fuel cell stack "2.6.FCS", which has 5 modes with RPN⩾100. The third is the hydrogen production system "1.H2P" with 3.

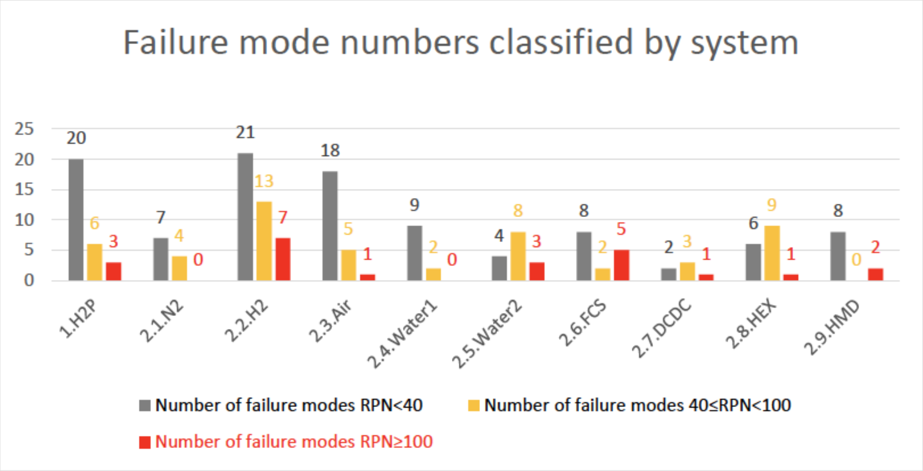

Figure 5. Number of potential failure modes categorized by system

The 178 failure modes are also classified by the different type of elements. The statistical results about the failure mode numbers distributed in different types of components is shown in Fig. 6.

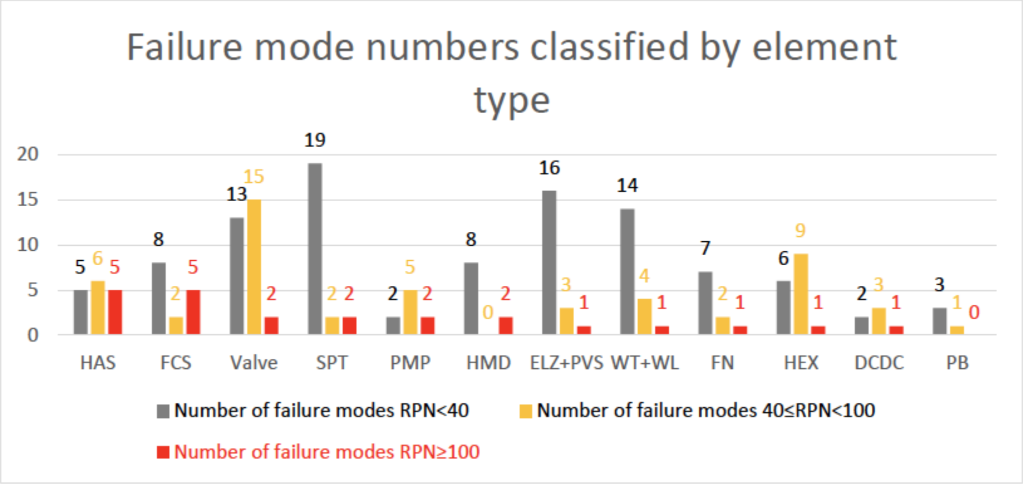

Figure 6. Number of potential failure modes categorized by element type

Fig. 6 shows that the most problematic components can be the hydrogen alloy storage vessel (HAS) and the fuel cell stack (FCS) in a sense of the highest number of failure modes with RPN⩾100. Then serious failure modes could also happen to the pumps, the valves, the phase separators and so on.

A full list of the 178 RPNs of potential failure modes of all the 29 elements or components is shown in Fig. 7. The horizontal axis lists the codes of failure modes. For an example, “2.2.1.HAS.6” means the sixth failure mode of the element 2.2.1.HAS.

Margins of RPN values in yellow and in red are drawn in Fig. 7, standing for the critical values of RPN, 40 and 100, respectively. When the RPN is lower than 40, the corresponding failure modes can be ignored. More attentions should be paid on those with greater RPN values than 40, especially those than 100.

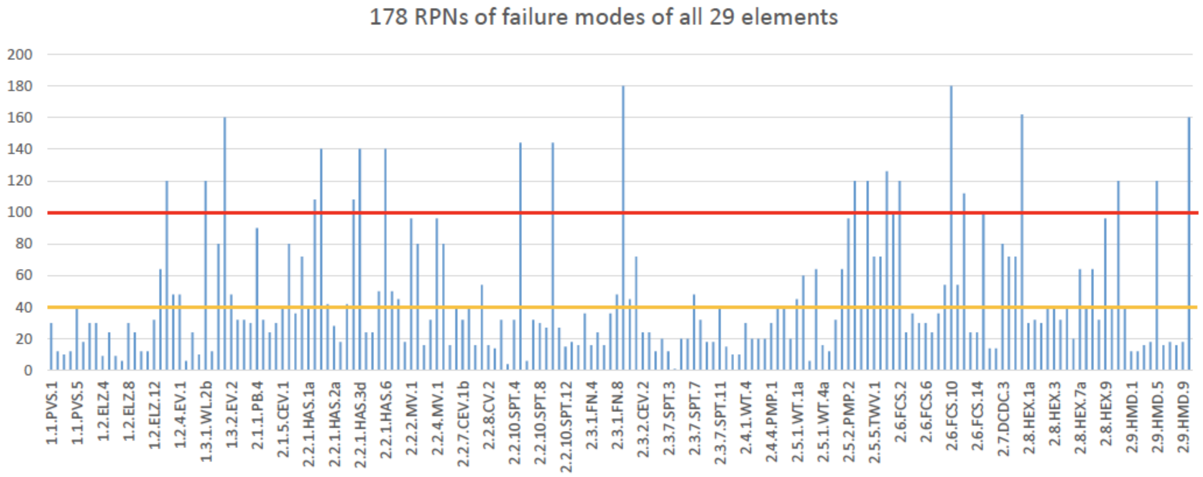

Figure 7. RPN list of 178 failure modes and effects of all 29 elements (The yellow line stands for RPN=40 and the red for RPN=100. Focus should be concentrated on those modes with high RPN values)

In another view, the analyzed failure modes are presented according the consequence severity (S) and the corresponding occurrence (O) times detectability (D), as shown in Fig. 8. It is obvious that the deeper color at the top-right corner in the plot stands for the higher risk than the lighter color at the bottom-left corner does. The two curves, the yellow curve for RPN=40 and the red for RPN=100, divides the whole region into three regimes. Fig. 8 shows that most failure modes locate in the regime of RPN<40; certain number of modes in 40⩽RPN<100; and more than a dozen of modes in RPN⩾100, which are the most critical cases from the FMEA study. (Some modes share the same coordinates of S and O x D, thus the data symbols overlap each other without reflection in the plot.)

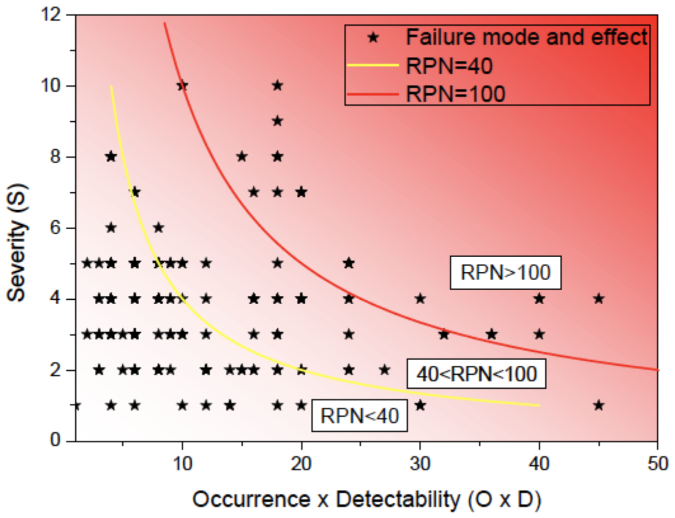

Figure 8. Severity versus occurrence x detectability plot on failure modes

Regarding the failure modes with RPN>40, the recommended actions or proposed countermeasures listed in Tab. 2 should be carefully considered. Further safeguards are also expected to improve the safety level of the hydrogen station, especially for those relevant to the failures with RPN⩾100.

7.0 CFD RESULTS

As shown in Fig. 4, two independent compartments, namely, the FCS operation room and the hydrogen storage room, are modeled and calculated separately by KIT computer code GASFLOW.

Due to the important role of the fuel cell stack, hydrogen release scenarios in the FCS cabinet are further studied independently with a refined computational grid. In extreme scenario, about 1 kg of hydrogen will be emitted in few minutes into the atmosphere outside of the container. This may pose a potential risk too, if burnable mixtures are released. Therefore the hydrogen distribution in the external environment is also modeled for different wind conditions. In summary, 35 release scenarios have been modeled for the FCS operation room, 13 cases for the storage room, 21 cases for the FCS cabinet and 4 cases for the external environment. In total 73 simulation cases (scenarios) have been analyzed.

7.1 Source Definition

Accidental hydrogen release is modeled as a source in simulations. An extreme case of double-end break of the hydrogen pipe is considered as a bounding accident scenario. According to the design, the hydrogen loop is connected to the H_2 pressure bottles, which has a high pressure of 100 bar. By several levels of pressure-reducing-vales the high pressure is reduced to 3 bar before the hydrogen arrives in the FCS operation room. Thus, the peak pressure of the hydrogen system in the FCS operation room is 3 bar, which is much higher than the ambient pressure (1 atm) in the operation room. Thus the hydrogen release flow is a critical flow at the break, which means sound speed is reached at the break opening. If hydrogen release is treated as an adiabatic process and hydrogen an ideal gas, the critical mass flow rate at the break can be computed as,

$$\dot{m} = A\sqrt{\gamma p_s \rho_s \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

where, γ –specific heat ratio of hydrogen, γ=1.41; p_s–source hydrogen pressure, p_s=3 bar; ρ_s–source hydrogen density; ρ_s=247.69 g/m^3, if the source hydrogen temperature is 293.15 K; A–break area, in the FCS operation room, the inner diameter of the hydrogen pipe is 6 mm at maximum, so the maximum value is $A=14\pi d_{in}^2=2.8274\times10^{-5}$ m^2.

The computed critical mass flow rate (5.29 g/s) is the maximal hydrogen release rate for a given break size. According to the product specification of the fuel cell stack, the nominal hydrogen supply is about 0.16 g/s to the FCS to maintain the rated output power. Therefore the minor hydrogen leak rate is defined as 100%, 50%, and 10% of the nominal rate, which are defined as, 0.16 g/s, 0.08 g/s and 0.016 g/s, respectively.

With the help of GASFLOW, hydrogen release scenarios with different leak rates ranging from an extreme level (5.29 g/s) to medium values (2.5, 1, 0.5 g/s), and to minor levels (0.16, 0.08, 0.016 g/s) are simulated for the confined volumes in the container, including FCS operation room, the FCS cabinet, and the hydrogen storage room. The FCS cabinet simulations using a refined numerical mesh, offer more detailed hydrogen distribution and transport information. A diffusion source with a leak rate of 0.002 g H_2/s is also simulated to investigate the consequences of a leak of the FCS at its end of life. The external hydrogen distribution outside of the container is simulated for a bounding scenario with a massive hydrogen emission (5.29g H_2/s, 1kg in total) from the two roof openings of the container.

7.2 Ventilation Schemes

As sensitivity analyses, parametric studies with different ventilation schemes, different hydrogen injection directions and locations are performed. The venting fans installed at the top of the FCS cabinet, the capacitor cabinet and the electronics cabinet are modeled as fans in the simulation, by specifying a volumetric flow rate at each opening:

- FCS cabinet: volumetric flow rate of 2.5E+05 cm^3/s, equivalent to 15 m^3/min;

- Capacitor cabinet: volumetric flow rate of 2.10333E+05 cm^3/s, equivalent to 12.62 m^3/min;

- Electronics cabinet: volumetric flow rate of 1.02083E+05 cm^3/s, equivalent to 6.125 m^3/min.

The three cabinet venting fans, similar to the roof venting, can operate at different power levels, to generate a volumetric flow rate at the opening as 100% (full), 75%, 50%, 25% or 0% (off), of each nominal rate, respectively.

7.3 Simulation Results

The simulation results for the FCS operation room are summarized as follows. (a) In the extreme case of 5.29g H_2/s release in different injection directions and different ventilation schemes, the generated hydrogen cloud with potential for flame acceleration, called the sigma cloud, ranges from 0.59-8.41m^3 with average hydrogen concentrations of 16-34 vol% in the operation room. The combustion of such layered hydrogen clouds can produce an overpressure of 0.13-1.8 bar, which very likely exceeds the load capacity of a standard steel container. (b) In the cases with a leak rates > 1 g/s, the sigma cloud reaches volumes of up to 1.5 m^3 with 27 vol % H_2 average concentration in the worst scenario. The overpressure loads from the ignited clouds can be as high as 0.40 bar, which is still destructive for a normal container facility. (c) In the cases with leak rates≤1g/s, only small overpressures below 0.02bar are predicted due to the combustion of a small sigma cloud. However, a fire risk still exists in the operation room. (d) For the cases with minor leakages, no overpressure risk is identified.

The simulation results for the FCS cabinet lead to the following conclusions. (a) For the extreme scenario with 5.29g/s hydrogen release, the sigma cloud volume reaches 0.8m^3 with an average hydrogen concentration of 33 vol% in the cabinet. The ignition of such a large and sensitive cloud can cause a serious local explosion in the cabinet, which could result in a maximum reflected overpressure of 0.95bar at the glass window, located in the dividing wall between the operation room and the control room. Such an overpressure certainly exceeds the stability limit of normal glass panes and of the facility itself. (b) In the medium range of release rates from 0.1 to 1.0g H_2/s, the volumes of the fast burnable sigma clouds generated in the cabinet range from 0.15-0.78m^3 with an average hydrogen volume fraction in the cloud of 15-28vol%. The local explosion of such clouds can produce overpressures of 0.08-0.90bar at the central position of the glass pane, which could be certainly damaged by the pressure wave and cause injuries in the operator compartment. (c) In the case of minor leakage rates, no over-pressure risk is identified, but a fire risk still exists. (d) In the case of a long-term diffusion leak with about 0.002g H_2/s, only up to 3 liters of slowly burnable hydrogen-air mixture are predicted, but no fast burnable sigma cloud. The pressure load at the window from ignition of such a mixture is negligible.

The simulation results for the hydrogen storage room can be summarized as follows. (a) In the extreme case of release scenarios with different injection directions, the generated sigma cloud volumes range from 0.33 – 0.83 m^3, with hydrogen concentrations of 16-26Vol% H_2 in the cloud. The combustion overpressures from such sigma clouds range from 0.34-0.71bar, which could basically destroy the storage chamber. (b) In the case with leak rates≥1g/s, the sigma clouds range from 0.15-0.52m^3, with hydrogen concentrations of 14-21vol%. The combustion of such clouds can still generate destructive overpressures in the range of 0.10-0.48bar. (c) In the cases with leak rates<1g/s, only small overpressures like 0.04bar are identified in the room after the cloud is ignited. Nevertheless, a fire risk is still not excluded. (d) In the minor leakage cases (0.016 to 0.16g H_2/s) there is no risk for overpressure development.

The simulation results for the external environment with a massive hydrogen exhaust from the container (about 1kg H_2 within 4 minutes) indicate that a large flammable cloud can be formed in a significant distance from the container, reaching up to 13m height and 4m in horizontal radius from the exhaust/ventilator location. This zone should be kept free of ignition sources and lightning rods.

In summary, the safety margin for hydrogen leakages in the hydrogen energy storage platform is conservatively recommended as 0.1g/s to guaranty safety of the personal and facility. Apart from those mitigation measures recommended by national hydrogen safety regulations and mentioned Tab. 2, One of the most important recommendations concerns the tolerable hydrogen leak rates. Hydrogen sensors are recommended to be installed in the container. An additional mitigation measure proposed for the FCS cabinet is a small ventilator, which could be installed beneath the FCS body to counteract possible hydrogen accumulation there, when a downwards hydrogen leak should occur at the FCS. At last, the passive ventilation condition of the storage room can be improved by a simple opening in the floor, or by replacing the solid container walls with grid plates.

9.0 CONCLUSION

Through HAZOP, FMEA and CFD study, the potential risks were thoroughly identified. The multistage risk analysis methodology delivered both overall safety evaluation and insight of hydrogen leakage risk. In the study, the safeguards were also proposed. All the safeguards are already applied in the design and the effect of safeguards need to be further evaluated in the future. Generally, the safety of hydrogen energy station fulfils the requirement of normal operation in company campus. However, in practical application, the hydrogen energy station will operate close to high power electric equipment, which needs to be studied before it could be widely implemented in power system. The methodology proposed in this paper could be a reference for future hydrogen safety analysis in power industry.

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