HAZID FOR CO2-FREE HYDROGEN SUPPLY CHAIN FEED (FRONT END ENGINEERING DESIGN)

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ABSTRACT

We、Kawasaki have proposed “CO2 free H2 chain” using abundant brown coal of Australia as hydrogen source. We developed the basic design package and finished FEED (Front End Engineering Design) in 2014. There are not only hazards of process plant system, but also the characteristic hazards of hydrogen plant system. We considered and carried out HAZID (Hazard Identification) as the most appropriate approach for safety design in this stage. This paper describes the safety design and HAZID which we practiced for CO2-Free Hydrogen Supply Chain FEED.

1. INTRODUCTION

Coal is bountiful in the amount of deposit compared with the rest of the fossil fuels, and is excellent in the aspects of supply stability and economic efficiency. However certain issues have become obvious in relation to the recent demand increase in developing countries as well as the steep rise in price linked with other energy prices, and so on. Moreover, from the viewpoint of preventing global warming, “Fossil fuel + CCS (Carbon Capture and Storage)” and exploration of new energy including renewable energy, have become formidable challenges.

In order to solve these problems, we, Kawasaki Heavy Industries, Ltd., focused on the inexpensive Australian brown coal that boasts tremendous reserves, and are now proposing the conception of “CO2- Free Hydrogen Chain,” in which a large amount of hydrogen is to be transported to Japan by liquefied-hydrogen carriers after gasifying and refining the brown coal to produce hydrogen[1)]. In addition, CO2 generated in the process is separately captured to be stored pursuant to the “Carbon Net” promoted by the Australian government. Therefore no carbon dioxide is emitted when we use imported hydrogen.

At Kawasaki, we aim to realize the commercialization of “CO2-Free Hydrogen Chain” in 2030, thereby earnestly pursuing the technical development to enable us to start in 2025 the operation of a demonstration chain equivalent to that for commercial use, following the start in 2020 of a small-scale pilot chain intended to perform technological demonstration.

In this paper, we explain a small-scale pilot chain (**Figure1**) for “CO2-Free Hydrogen Chain,” and comment on the outline of the basic design (FEED) implemented since 2012,

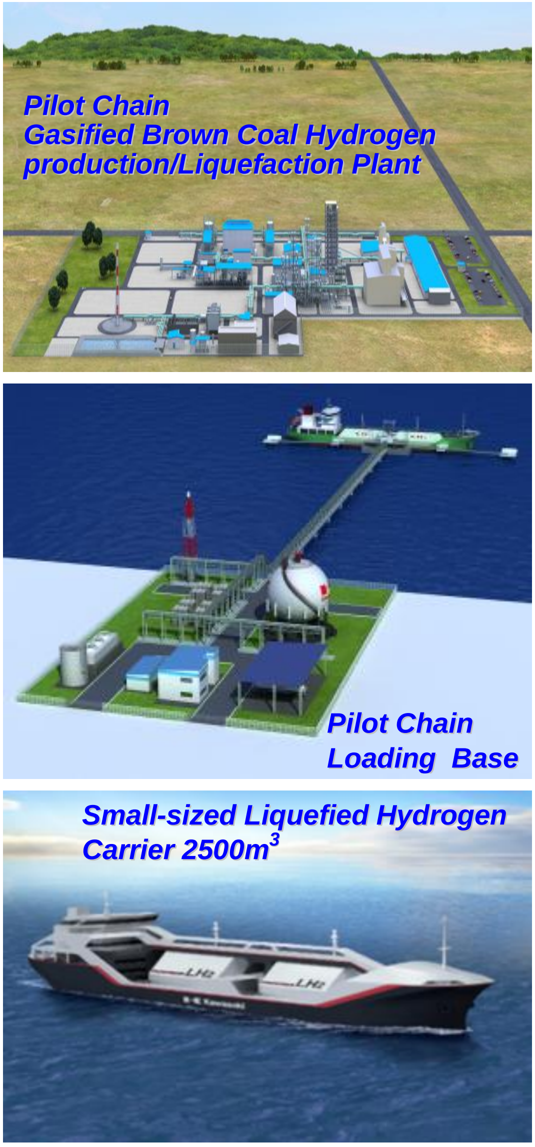


Figure1. CO2-Free Hydrogen Supply Chain

together with HAZID (Hazard Identification) enforced in the context of FEED as safety management.

1. PILOT SCALE HYDROGEN SUPPLY CHAIN PLANT FEED

We have spent two years since 2012 for the implementation of the basic design (FEED) covering a pilot chain in order to calculate the precise cost of facilities and operating cost, in parallel with the preparation/arrangement of literature for basic design making the basis for detail design. Main contents of implementation are shown below:

① Determination of hydrogen producing process and plant capacity

② Determination of postulated conditions for operation

③ Determination of designing conditions, e.g. weather condition, degree of leeway, backup perception

④ Implementation of basic design

⑤ Preparation of basic design literature

⑥ Safety review/evaluation (HAZID)

⑦ Preparation of installation specifications

⑧ Acquisition of equipment vender quotation, installation work estimates, calculation of approval/ license cost, owner expenditures including insurance cost

⑨ Calculation of total plant cost

⑩ Calculation of operating cost.

In order to establish the hydrogen production process and plant capacity, it will be necessary to obtain the approval relating to the facilities handling hazardous materials, or MHF (Major Hazard Facility) prescribed in Australian HSE (Health, Safety and Environment) to the hydrogen production plant in addition to the loading base for liquefied hydrogen constructed on shore, given that liquefied hydrogen exceeding a fixed quantity is to be stored. Besides, performance obligations for HAZID and HAZOP (Hazard Operability) as safety evaluations relating to the objective plant systems are described in the MHF guidance note, thus suggesting the necessity of safety assessment from the upper stream design process. The mass balance of the pilot plant (in normal operation) established through FEED is shown in **Figure2**.

2. PILOT SCALE HYDROGEN SUPPLY CHAIN PLANT HAZID

2.1 Purpose, Outline

As for the safety review involving plant operations, it has been mandatory for JIS (Japanese Industrial Standards) to apply the international standards represented by ISO (International Standard Organization for Standardization), IEC (International Electrotechnical Commission), etc., resulting in the introduction of the globally recognized manner of safety-oriented engineering and management into Japanese industries. In the global standards for risk management, the concept design, basic design, and detailed design deemed the most appropriate in the respective phases are explicitly stated for implementation using adequate means. Also noteworthy is the PSM (Process Safety Management) prescribed in the U.S. federal law (OSHA: Occupational Safety and Health Administration), which is one of the standards given top priority among the safety-related laws and standards by overseas plant

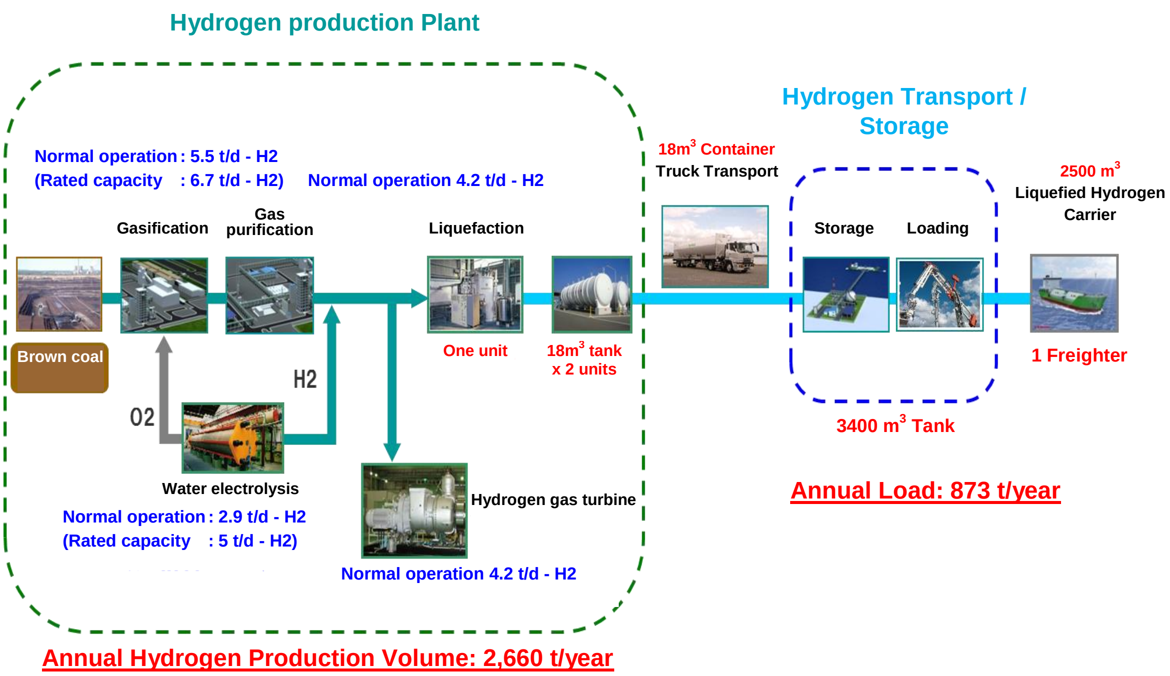


Figure2. Pilot scale plant Mass Balance

contractors. OSHA/PSM philosophies are based on the hazard analyses (PHA: Process Hazard Analysis) at various stages with the concepts of "Safety through Design" toward systematical decrement/reduction of the risks probable in the subsequent stages of procurement, processing, test run, operation and maintenance; thereupon recommending preparation of safety measures for each stage from design to maintenance, as layers of protection steadily build up to ensure the safety of plants.

In Chapter 1 ⑥ Safety Review/ Evaluation (HAZID), adequate measures to be implemented at the stage of basic design (FEED) were examined, and one or two persons in charge were selected from the design teams of each plant, and HAZID meeting was held to clarify the hazards related to each plant's system together with the review of countermeasures — all of which have been reflected in the designs.

2.2 Process safety of plant

Process safety of plant is fundamentally based on PHA (Process Hazard Analysis) at design stage and materialized at subsequent each phase such as procurement, construction, test, operation and maintenance. Safety measures are executed organizationally to eliminate or reduce risks and secure safety at each phase. Especially safety measures executed at engineering and design stage are shown as below (**Figure3**) [2)].

We applied the preliminary process hazard analysis (PPHA) as a method of HAZID in HAZID Meeting. PPHA follows up the results of the concept hazard analysis to provide further information on factors such as wanted and unwanted reactions, the reduction of hazards and hazardous characteristics on the plant, identification of incident scenarios and evaluation of emissions, effluents, wastes and off-specification products.

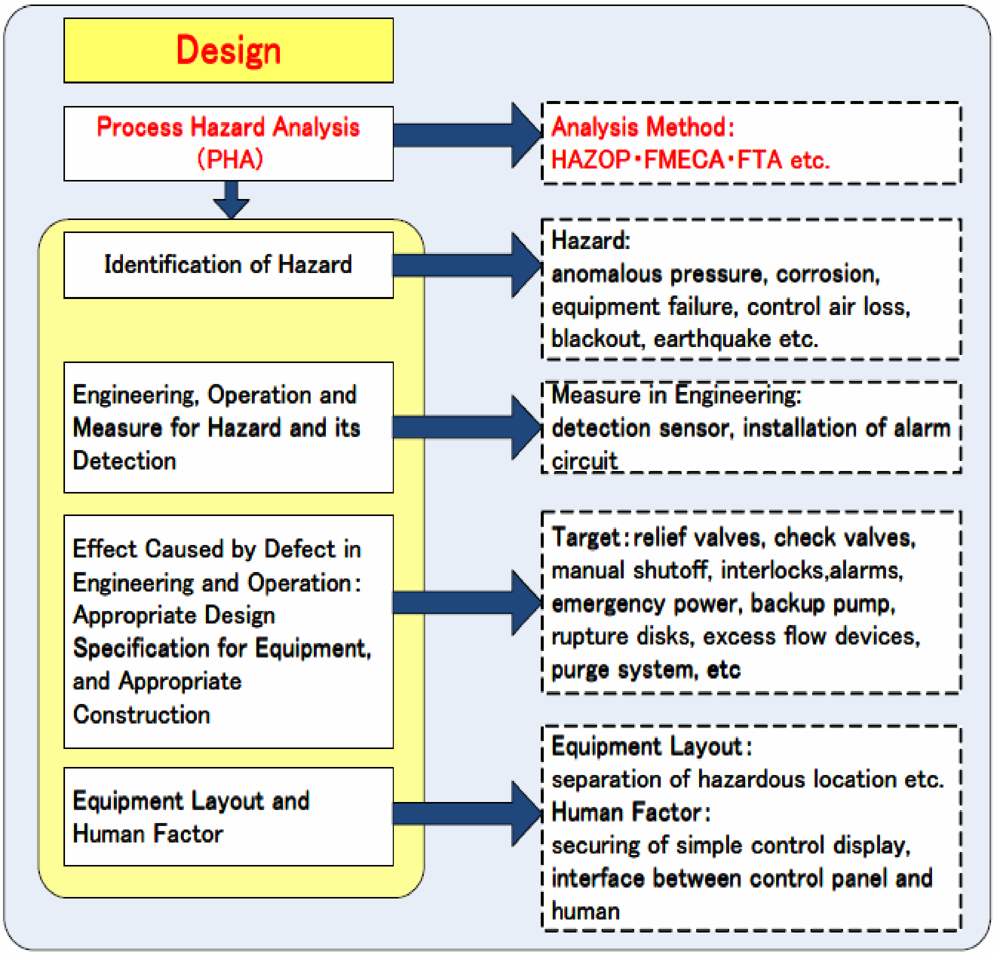


Figure3. Design Stage Safety Measure

2.3 Purpose of PPHA and Method

The incident progresses through time from the immediate disturbed state of the plant via a sequence of steadily worsening states. Between each plant state, opportunities exist to eliminate or mitigate the progression of the incident. Passive mitigation/control systems are constantly in place while active mitigation/control systems respond as event progress. PPHA aims to duplicate incident scenario down to immediate cause. The eventual outcome is an estimation of the likely impact of the event on the system's total environment. The analyst works in the same direction as the scenario unwinds, evaluating the effects of countermeasures on the release, its ignition, escalation by major events such as fire, explosion or toxic event and failure to mitigate these events to reduce their occurrence or effects. The emergency response is a vital part of such a study.

In order to assist in this task, a structured approach has been developed together with a prepared format for documentation. Both a generic fault tree and a generic event tree are used. Equipment knowledge bases assist in the task. That follows the basic structure of the analysis and development of an incident scenario. It can suggest the general causes and consequences of undesired events.

It provides more specific information on equipment and facilities. It contains information on types of equipment, dangerous disturbances leading to major releases, and typical control and emergency control systems.

2.4 Analysis work procedure

① Pilot scale hydrogen energy supply chain plant consists of 7 sub plants and has 8 working group (WG) including one for the plant integral. They are “Gas Refining ”, “Water Electrolysis ”, “Hydrogen Liquefaction”, “Truck & Loading Station”, ”Balance of Plant (BOP)”, “Hydrogen Gas Turbine”, “Gasification” and “Entire Plant”. 1 or 2 persons in charge of HAZID meeting selected from each WG.

② Charged person took the lead of analysis work in the group meeting and produced necessary documents and finished preparation for the plenary HAZID Meeting before 1 week at the latest.

③ Those who charged from all WG joined the plenary HAZID Meeting, which was hosted by Hydrogen Project Department and held weekly essentially.

④ Plenary HAZID meeting was held 2 or 3 times per each sub plant in sequence for plant design review from safety point of view. Those who charged of WG on duty explained the system, the studying results and the point at issue. Issues at the meeting were studied to incorporate in ongoing design to revise.

⑤ As for Integrated Drying and Gasification Plant, an Australian vendor company was in charge, and plenary HAZID Meeting was scheduled last and Gasification WG studied and explained instead of the company.

⑥ After all the plenary HAZID Meeting were completed, all of the HAZID results are ready to be reviewed by the outside professional company to judge the conformity with the international safety standards.

2.5 HAZID Procedure

We referred the book [3)] published by IChemE and carried out the procedure as below.

【Process 1】

Preparation of relevant data/ information

① PFD（Process Flow Diagram）:
Heat balance of process flow (temperature,
pressure, etc.) at inlet/ outlet/ inner of equipment

② P&ID（Piping & Instruments Diagram）

③ Processing details and reaction formula of process equipment

④ Operation procedure

⑤ Accident information on other similar plant

【Process 2】

Partition into the study nodes

① To partition the plant into the study nodes based chiefly on functional schematics

② To allot the node number (alphanumeric)

【Process 3】

Identification of major hazard (Latent dangerous conditions causing serious accident)

① To define clearly the heat balance of study node at inlet, inside, outlet.

② To simulate and analyse the process behaviour under control of operation in steady state in accordance with P&ID.

③ To examine possible occurrence of abnormality in process, which may proceed to significant event like as fracture of equipment, explosion, fire and discharge of toxic material, and to check and review the validity of existing safety measures for studying need of additional or revising action.

④ To find immediate cause for each possible abnormality.

⑤ If generation of hazard scenario is left something to be desired according to above mentioned manner, it may help to use HAZOP guide words.

⑥ To summarize these information and analysis and fill in the attached Forma1, producing "**Equipment knowledge base**". **Figure4** [3] is the example of Equipment knowledge about Electrolysis Plant.

<table>
<tr><td>PLANT NAME</td><td>Water Electrolysis Plant</td><td colspan="2">SHEET NO. F-2</td></tr>
<tr><td>Node No.</td><td>Node F: H2 Compressor Unit</td><td colspan="2">P&ID No. 01D3232001</td></tr>
<tr><td>EQUIPMENT NAME</td><td>C-3201A/B: H2 Compressor</td><td colspan="2"></td></tr>
<tr><td colspan="2">DESIGN INTENT</td><td colspan="2">UNDESIRED EVENTS AND THEIR CAUSES</td></tr>
<tr><td colspan="2">The role of H2 compressor unit is
1. To compress H2 gas to 2.3MPaG.</td><td colspan="2" rowspan="9">Abnormal H2 gas discharged pressure
〈Cause〉
・post-process failure
・Compressor malfunction
・Instrument failure
・32-PV-1201 failure
〈Consequences〉
・If the pressure becomes high, safety valve is operated.
・If the pressure becomes low ,
the amount of H2 gas to be used in the next step is insufficient or H2 gas flow back from the next step
Abnormal cooling water flow rate
〈Cause〉
・Instrument failure
・Cooling water system down
・Manual valve misoperation
〈Consequences〉
・The compressor is failed due to overheating.
Abnormal H2 gas discharged temperature
〈Cause〉
・Instrument failure
・Cooling water system down
・Burning in the cylinder
〈Consequences〉
・If the temperature is high impure H2 gas is supplied to the Liquefaction plant
・Compressor or other equipment are broken.</td></tr>
<tr><td colspan="2">TYPE OF UNIT</td></tr>
<tr><td colspan="2">・Reciprocating</td></tr>
<tr><td colspan="2">ANCILLARY EQUIPMENT</td></tr>
<tr><td colspan="2">・Bypass valve (32-PV-1201A/B)
・Pressure indicator (32-PT-1201)
・Temperature indicator/Flow rate indicator/
Safety valve</td></tr>
<tr><td colspan="2">NORMAL CONTROL</td></tr>
<tr><td colspan="2">・Discharged pressure is controlled by returning a part of the compressed gas through the bypass valve.
・Discharged temperature is controlled by cooling water.
[Alarm]
・H2 gas discharged pressure (32-PT-1201)/H,L
・Cooling water flow rate (32-FICA-****) /L
・H2 gas discharged temperature (32-TICA-****)/H</td></tr>
<tr><td colspan="2">EMERGENCY CONTROL</td></tr>
<tr><td colspan="2">・If H2 gas discharged temperature become HH,
・If H2 gas discharged pressure become HH,</td></tr>
</table>

Figure4. Equipment knowledge about Electrolysis Plant

【Process 4】

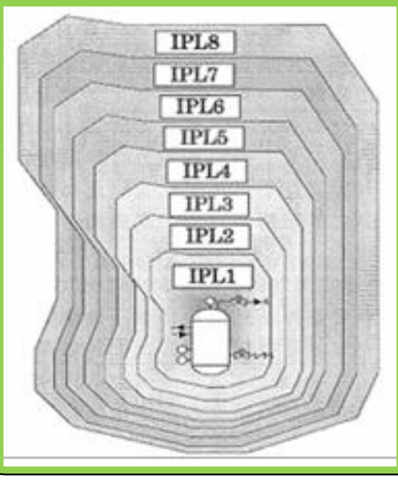
Generation of hazard developing scenario

① Chemical plant mainly treats reaction, perpetually changing condition of process flow, so unless operation conditions are adequately controlled, performance of plant tends to deviate from a steady condition, easily developing into dangerous disturbance. Accordingly, as for plant safety, layers of protection concept must be adopted in plant design.

③ Basic intension of safety correspondence in each protection layers are "Abnormality prevention", "Abnormality detection", "Hazard prevention", "Damage confinement". These safety correspondence should be materialized as a mutually independent safety measures, and when performance of each IPL (Independent Protection Layer) is poor, some abnormality develops to deviation, to hazard and finally to significant accidents. IPL1~IPL6 should be incorporated in plant design (**Figure5**) [4].

IPL (Independent protection layer) model in plant

(1) Abnormality prevention	(IPL1,2)
(2) Abnormarity detection	(IPL3)
(3) Hazard prevention	(IPL4,5)
(4) Damage confinement	(IPL6,7,8)



IPL8	Community emergency response
IPL7	Plant emergency response
IPL6	Post-release physical protection (Dikes)
IPL5	Physical protection (Relief devices)
IPL4	Safety instrumented function (SIF, Interlocks)
IPL3	Critical alarm and human intervention
IPL2	Basic process control system (BPCS)
IPL1	Process design (Inherent safety)

Figure5. Independent Protection Layer

③ To generate the hazard developing scenario about starting from occurrence of abnormality to final outbreak of significant accidents, and examine incorporated safety measure (IPL) at each stage on composition and its adequacy (**Figure6**).

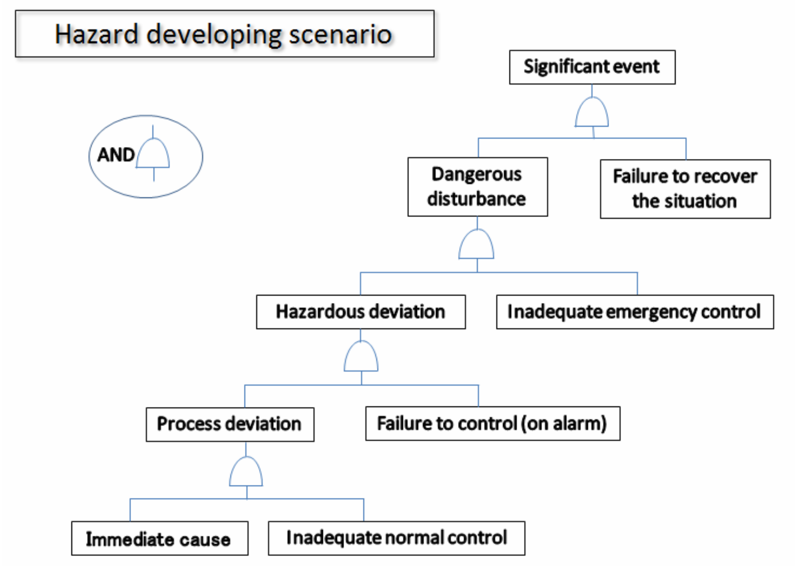


Figure6. Hazard developing scenario

④ To fill out the results of study in PPHA worksheet, review the ongoing engineering design for the issues and discuss the adequate actions against them. **Figure7** [3)] is the example of PPHA Worksheet about Electrolysis Plant.

Sub Node	Immediate Causes	Inadequate Normal Control 〔IPL2〕	Process Deviation	Failure to Control (on Alarm) 〔IPL3〕	Hazardous Disturbance 【HAZARD】	Inadequate Emergency Control 〔IPL4〕	Dangerous Disturbance	Failure to Recover Situation 〔IPL5,6〕	Significant Event
F-1	Forget to remove drainage on V-3201 inlet piping	Failure of 31-PT-1101 (Pressure of hydrogen piping) failure of visual confirmation	Pressure in the upstream pipe rises.	Misoperation of drain valve	Pressure in the upstream pipe rises.	Failure of 31-PT-1101 INT system (Pressure of hydrogen piping)	Change in pressure balance at electrolyzer. Hydrogen and oxygen are mixed.		Deterioration or damage of membrane →Hydrogen and oxygen are mixed. →Ignition and explosion
F-3	32-PV-1201 is fully opened due to a failure	Failure of 31-PT-1101 (Pressure of hydrogen piping) Failure of 32-LT-1201 (Amount of displacement of V-3201) failure of visual confirmation	Pressure rise on the low pressure side	Does not stop the compressor. (Failure of response to malfunction)	V-3201roof is risen	Failure of 31-PT-1101 INT system (Pressure of hydrogen piping) Failure of 32-LT - 1201 INT system (Amount of displacement of V-3201)	①Change in pressure balance at electrolyzer ②V-3201 roof is moved to the top.	Failure of safety valve at V-3201	①Deterioration or damage of membranes →Hydrogen and oxygen are mixed. →Ignition and explosion ②Damage of V-3201 and Hydrogen leaks
F-4		Failure of 31-PT-1101 (Pressure of hydrogen piping) Failure of 32-LT-1201 (Amount of displacement of V-3201) failure of visual confirmation	Pressure drop on the high pressure side		Pressure drop on the high pressure side	Failure of 31-PT-1201 INT system (Pressure of hydrogen piping) Failure of 32-FT - **** INT system (Flow rate of hydrogen)	Pressure drop on the high pressure side	Installa-tion of the check valve	
…	…	…	…	…	…	…	…	…	…

Figure7. PPHA Worksheet about Electrolysis Plant

⑤ To rearrange the PPHA results based on hazard item, and describe the major cause, the issues on safety correspondence in ongoing engineering design, the additional or recommended safety measure needed. These study outcomes are utilized to revise the ongoing design and system. **Figure8** [3] is the example of PPHA result of Electrolysis Plant.

PLANT NAME	Water Electrolysis Plant				Sheet No. 3-1
Node No.					Date:
#	DANGEROUS DISTURBANCE	CAUSES	EXISTING SAFETY MEASURES	RECOMMENDATIONS, COMMENTS, ACTIONS	CORRRELATION TO SCENARIO
1	Electrolyte leaks and injury by alkaline	Misoperation and failure of equipment	･Liquid surface and flow rate monitoring, ･Installation of dike, Emergency shower and eyewash, ･Connect to tank outlet and gutter	･Work rules creation ･Wearing protective equipment such as safety glasses, gloves ･Installation of rainwater drain valve and pH meter	A-1 C-1,2,5,6
2	Low pressure hydrogen leaks	Misoperation and failure of gasholder (V-3201)	･Pressure safety valve ･Pressure and amount of displacement monitoring of gas holder (V-3201)	Vacuum safety valve	F-2,3,5
3	High pressure hydrogen leaks	･Failure of equipment ･Damage of piping or eqipment	･Margin of piping Class ･Pressure safety valve ･Temperature monitoring at compressor cylinder outlet	Oxygen concentration measurement in hydrogen	F-7,8
4	Deterioration or damage of membrane	･Pressure change in the electrolyzer ･Flow of the high temperature electrolyte solution ･Impurity deposition on the electrode	･Pressure monitoring ･Temperature monitoring	Purity monitoring of demineralized water	C-1,4,5,6,7 D-1,2,3,4 E-1,2,3,4 F-1,3,5 G-1 I-1,3,5
5	...	...	...	...	...

Figure8. PPHA Result of Electrolysis Plant

2.6 Hydrogen Safety Evaluation Test

In considering the hazard scenarios for CO2-Free Hydrogen Chain, it is necessary to take the physical properties of hydrogen and plant operation into account, so that safety evaluation tests have actually been given to demonstrate the safety assessment required for the development of each plant and hydrogen carrier, not just the survey on the safety literature and simulation study of safety parameters. As an example, let us introduce the case of safety evaluation tests giving special consideration to the hydrogen leakage from the piping joints under loading/unloading of liquefied hydrogen cargo. These tests have conducted according to the concepts of the hazard scenarios incidental to the leakage of hydrogen from the joint portions of the shore-side loading arm and ship-side manifold during loading/unloading for the hydrogen carrier on the berth. Test results were utilized as effective technical information on the occasion of considering the hazard scenarios involving the hydrogen liquefaction plant and truck & rotary station, which were the subjects of the HAZID Meeting.

Figure9. Hydrogen Safety Evaluation Test

2.7 HAZID Meeting Result

After going through the preparation of work sheets by each WG, the safety review has been conducted 19 times in total (72.5 hours, 103.3 man-days) by the personnel in charge of HAZID as below **(Figure10)**.

nth	Day held	Work group name	Attendant	hour	Man-time	Place
1	2013/9/24	Water electrolysis	16	3.5	56	Akashi103
2	2013/10/1	Water electrolysis, Hydrogen Liquefaction	13	3.5	45.5	Kobe1201
3	2013/10/8	Hydrogen Liquefaction	11	3.5	38.5	Akashi107
4	2013/10/15	Hydrogen Liquefaction	11	4	44	Akashi107
5	2013/10/22	Hydrogen Liquefaction	14	4	56	Akashi107
6	2013/10/29	Truck and loading station	14	4	56	Akashi107
7	2013/11/5	Hydrogen Liquefaction, BOP	11	4	44	Akashi107
8	2013/11/12	BOP, Truck & loading station	12	4	48	Akashi107
9	2013/11/19	BOP	10	4.5	45	Akashi107
10	2013/11/26	BOP	12	4.5	54	Akashi107
11	2013/12/3	Truck & loading station, Gas Refining	11	4	44	Akashi107
12	2013/12/10	Gas Refining	12	4	48	Akashi107
13	2013/12/17	Gas Refining	7	4.5	31.5	Akashi107
14	2013/12/24	Gas Refining	11	3.5	38.5	Akashi107
15	2014/1/7	Gas Refining	8	3.5	28	Akashi107
16	2014/1/14	Hydrogen Gas turbine	10	3.5	35	Akashi107
17	2014/1/21	Hydrogen Gas turbine	11	3.5	38.5	Akashi107
18	2014/2/4	Gasification	9	3	27	Akashi107
19	2014/3/27	Entire Plant	14	3.5	49	Akashi107

Figure10. HAZID Meeting Practice

As deliverables, the following documents were prepared as the final documents by each WG, in addition to each of the minutes listed as below.

WG Name	Commentary on PID, Node, etc.	HAZID_Work_Sheet	Minute	Other data
Water electrolysis	Done	(Japanese, English)	With drawing No.	PFD, Material balance, arrangement plan
Hydrogen Liquefaction	Done	(Japanese, English)	With drawing No.	PFD, arrangement plan
Truck & loading station	Done	(Japanese, English)	With drawing No.	
BOP	Done	(Japanese, English)	With drawing No.	PFD, arrangement plan
Gas Refining	Done	(Japanese, English)	With drawing No.	PFD, arrangement plan
Hydrogen Gas Turbine	Done	(Japanese, English)	With drawing No.	PFD, arrangement plan, timing chart
Gasification	Vender Scope	Vender Scope	With drawing No.	Process flow

Figure11. HAZID Documentation

As the positive outcomes of HAZID, deeper investigations were made from the initial basic design owing to the clarification of hazardous events by the designers as well as proper postulation of risk scenarios, to say nothing of the implementation of the safety design based on the global standards. Particularly we were able to attain a higher level of safety designs through design review of each plant from broad perspective by not only the designers in charge having expertise of the plants concerned but also the participants with knowledge and experience in other plant systems. In this regards, unification and commoditizing of the safety design concepts were also effective and feasible solution of the discrepancy existed per WG before the implementation of HAZID.

3. CONCLUSION

In this paper, FEED for the pilot chain for which we are pursuing demonstration as a step of development toward the realization of CO2-Free Hydrogen Supply Chain was explained introducing the procedures and outcomes pertaining to the safety assessment (HAZID) performed as a process of safety design. From now on, we will advance our project for superior safety measures compatible with international safety standards conforming to each phase of basic design, detailed design, plant construction, operation, and maintenance.

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