CO2-FREE HYDROGEN SUPPLY CHAIN PROJECT AND RISK ASSESSMENT FOR THE SAFETY DESIGN

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ABSTRACT

We, at Kawasaki Heavy Industries, have proposed a "CO2-free H2 supply chain" using abundant brown coal of Australian origin as the hydrogen source. This chain will store CO2 generated during the process for producing hydrogen from brown coal in a project (Carbon Net) that the Australia Government is promoting. Thus, Japan can import CO2-free hydrogen. The supply chain consists of the hydrogen production system, the hydrogen transport /storage system, and the hydrogen use system. Related to their designs, we have to consider their hazards, pollution scenarios and safety measures via a safety assessment process that is complaint with international risk assessment standards. To verify safety designs, related experiments and analyses will be conducted. This paper describes the approach to safety design for especially the related liquid hydrogen facilities.

1. INTRODUCTION

Most of energy resources in our country depend on overseas imports. After the Great East Japan Earthquake caused the accident at the Fukushima Nuclear Power Stations in 2011, however, the Japanese Government was forced to review its Basic Energy Plan, while it is still required to promote the prevention of global warming. For these reasons, the Government has been introducing solar energy, wind power, and other renewable energies. Due to the issues of generation costs and energy security, however, imported energy resources have become increasingly more important.

Focusing on the vast untapped reserves of low-cost brown coal in Australia as a possible solution to these issues, Kawasaki Heavy Industries has proposed as a "CO2-free H2 supply chain" initiative in which the brown coal would be gasified and purified into hydrogen, and then a large quantity of hydrogen would be liquefied and transported to Japan by liquid hydrogen carrier.[1)] As CO2 generated in the process of hydrogen production is separated, recovered and stored by "Carbon Net," which is promoted by the Australian Government,

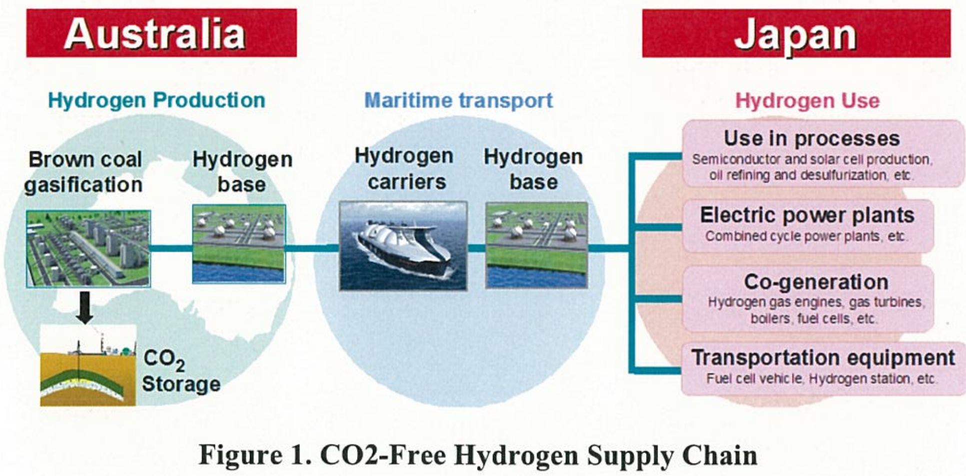


Figure 1. CO2-Free Hydrogen Supply Chain

hydrogen imported from Australia will not emit CO_2 when being used. This "CO_2-free H_2 supply chain" consists of a hydrogen production system in Australia, a hydrogen transport and storage system for import, and a hydrogen use system in Japan. In order to design and develop these systems, it is necessary to sufficiently implement hazard and impact analyses and safety measures that conform to international safety standards.

This paper gives an outline of the "CO_2-free H_2 supply chain" and presents plant systems that are addressed by Kawasaki Heavy Industries for the realization of this supply chain, in particular, the design of safety systems for liquefied hydrogen.

2. 0 CO_2-Free Hydrogen Supply Chain

2.1 Feasibility Study for CO_2-Free Hydrogen Supply Chain

The reserves of brown coal in the State of Victoria in Australia are 112 billion tons. It has been reported that 35 billion tons of that total can be economically extracted by open-cut mining.[2)] Due to brown coal's high water content, the efficiency of coal transport is low, and drying the brown coal increases its flammability. Consequently, brown coal is currently limited to local purposes such as power plants at mine sites. Focusing on this unutilized brown coal, we have constructed an H_2 chain model (Figure 1) that is made up of hydrogen production using brown coal, hydrogen liquefaction and transport, and consumption of hydrogen in Japan, and assessed the feasibility and economy of the model.

The brown coal would be gasified and purified near the mine to produce hydrogen, while CO_2 would be separated and recovered in the process of the production and transferred to and stored in the "Carbon Net" that is promoted in the State of Victoria, Australia. The amount of hydrogen produced per day would be 770 tons. The produced hydrogen would be transferred to a port facility about 80 km away from the mine through a pipeline, where it would be liquefied and stored. About 160,000 m^3 of this liquid hydrogen (load capacity of liquid hydrogen: 10,840 tons) would be transported to Japan by two liquid hydrogen carriers at the frequency of an annual total of 22 shipments at a one-way distance of about 9,000 km. It is assumed that the relevant hydrogen will be consumed for commercial power generation in Japan.

As a result of the feasibility study of the H_2 supply chain, hydrogen (CIF) will costs about 30 JPY/Nm^3 in 2025. In addition, if hydrogen derived from brown coal in the State of Victoria, Australia is used for commercial power generation, the cost of this generation will be higher than that of other fossil fuel generation, but lower than that of wind, solar or other renewable sources. Owing to the reduced cost of hydrogen production and the increase in hydrogen generation efficiency, it is assumed that the cost of hydrogen generation based on brown coal will be reduced. Therefore, the H_2 supply chain is believed to be fully feasible.

2.2 Demonstration by Pilot Supply Chain

Our company holds basic technologies for plants and equipment that compose the H_2 supply chain, such as gasification plants, hydrogen purification plants and storage plants for liquid hydrogen for rocket fuel of our Plant & Infrastructure Company, cryogenic liquefied natural gas carriers (LNG carrier) of our Ship & Offshore Structure Company, and gas turbines/gas engines of our Gas Turbine & Machinery Company. Since the projects would include some of the world's biggest and first ever plants and equipment, such as a brown coal gasification plant, a plant for large-capacity storage of liquid hydrogen and liquid hydrogen carriers, there are risks in developing the H_2 supply chain. In addition, since this is the world's first attempt at a business model for a liquid hydrogen commodity, it becomes absolutely necessary to demonstrate pilot-scale technologies for the supply chain and the applicable business model. Therefore, our company has planned the operation of the CO_2-Free Hydrogen Supply Chain on a 2017 pilot scale, and examined optimized locations, scales, configurations and cost efficiencies of the different plants of the pilot chain. The specifications of the pilot chain, and the conceptual images of a hydrogen production plant, a hydrogen storage tank and loading port, and a liquid hydrogen carrier, are shown in Table 1, and Figures 2, 3, and 4, respectively.

Table 1. Pilot Scale Chain Main Specifications

PLANT SYSTEM	CAPACITY	NUMBER	REFERENCE
Brown Coal Gasification Plant and Hydrogen Refining Plant	5.5t/d-H2	1set	Annual Hydrogen Production Capacity 2,660 ton
Electrolytic Hydrogen Production Plant	2.9t/d-H2	1set	
Hydrogen Liquefaction Plant	4.2t/d-H2	1set	
Hydrogen Gas Turbine Generation Plant	4.2t/d-H2	1set	-
Hydrogen Storage Facility	3,400m3	1set	Annual Cargo Capacity 873 ton
Hydrogen Carrier	2,500 m3	1set	

Our company's development schedule for the CO2-Free Hydrogen Supply Chain Project is shown in Table 2. In order to accomplish the hydrogen supply chain project under this schedule, it is important to conduct system design and development while developing safety designs and technologies that are needed for social acceptance. Chapter 2 presents our company's efforts to establish a safety system towards realizing our CO2-Free Hydrogen Supply Chain.

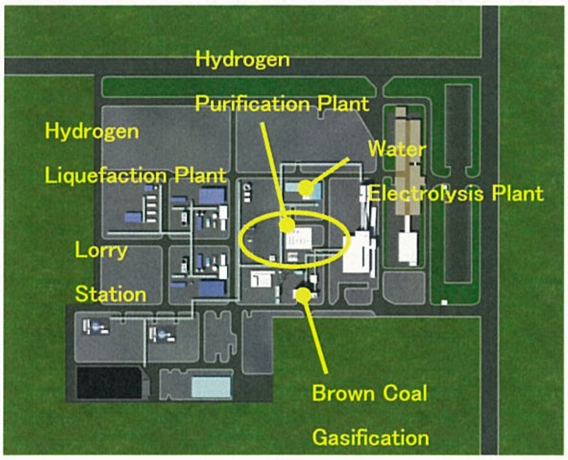


Figure 2. Hydrogen Production Plant

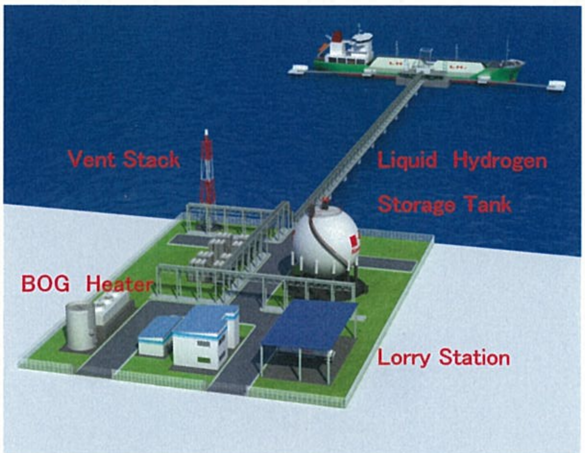
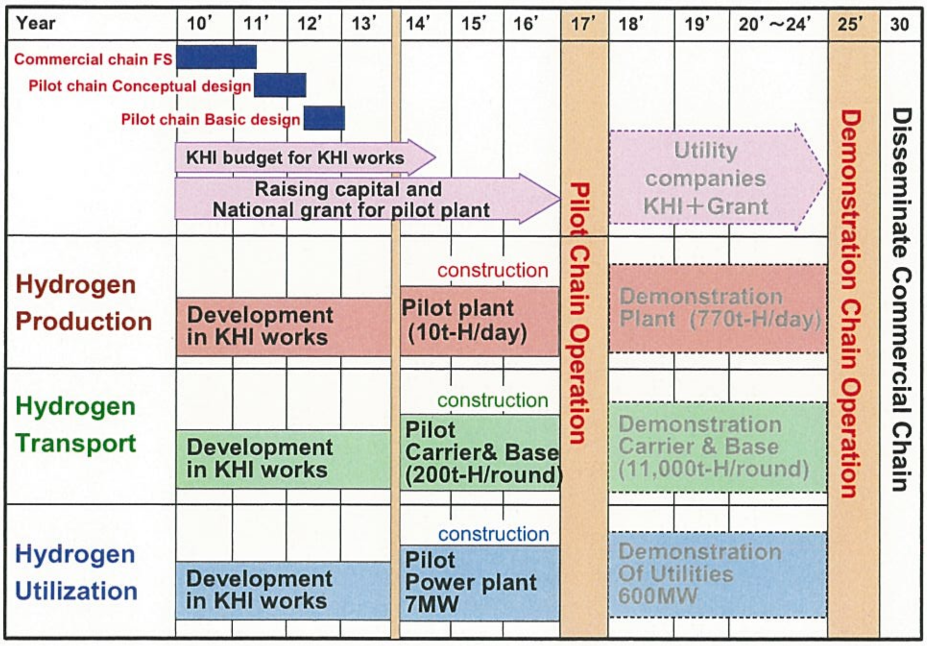


Figure 3. Hydrogen Storage Tank and Loading Port

Figure 4. Liquid Hydrogen Carrier

Table 2. Latest Tentative Schedule of CO2-Free Hydrogen Supply Chain Project



3. 0 Establishment of Hydrogen Safety System

3.1 Establishment of International Safety Standards

As mentioned above, the design and development of a liquid hydrogen carrier between Japan and Australia for the development of the pilot-scale CO2-Free Hydrogen Supply Chain must conform to the IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) that the International Maritime Organization (IMO) stipulates for manufacturing of liquefied gas carriers. The current IGC Code, however, does not cover liquid hydrogen. Consequently, it is necessary to develop a design for a liquid hydrogen carrier while formulating international standards for marine transport. In the design of a liquid hydrogen storage system, the liquid hydrogen storage tank (3,400 m^3) planned for the pilot supply chain has almost the same capacity as the currently biggest NASA liquid hydrogen storage tank in the world (3,218 m^3). The liquid hydrogen storage tank (50,000 m^3) for the Demonstration Chain, whose development is planned for 2025, will be the biggest in the world and falls outside of most international standards.[3)] Consequently (Figure 5), it will be necessary to study a proper safe separation distance between the liquid hydrogen carrier and other ships, and formulate an international standard for the distance.

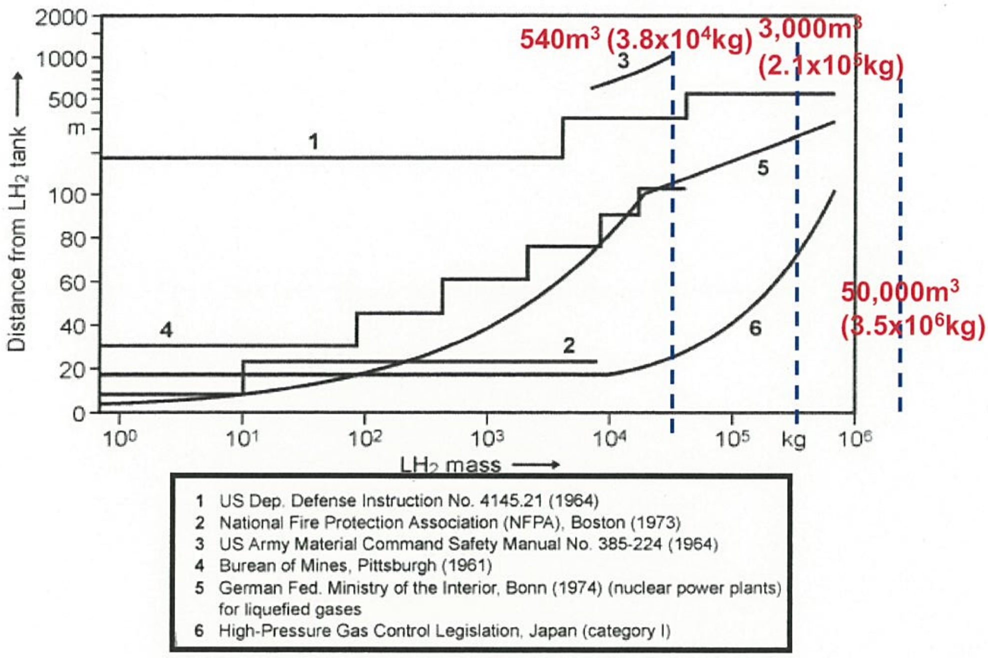


Figure 5. Safety Distance from LH2 Tank

3.2 Development of Hydrogen Safety Technologies

In general, it is often thought that hydrogen is an explosive and dangerous material. Therefore, our company is making efforts to develop a hydrogen safety program, "NEXT H2: Non-Explosion Technology for H2" (Figure 6), with the aim of establishing the world's most advanced hydrogen explosion-proof technology towards the realization of the CO2-Free Hydrogen Supply Chain. This program is made up of four steps and based on our "Safety Policy," under which no hydrogen explosion accidents must occur.

"NEXT H2" Program

("Non-EXplosion Technology for H2" Program)

We,KAWASAKI is developing the indispensable hydrogen technologies to realize "CO2 Free Hydrogen Utilization Society".

Through the best "explosion proof technologies for hydrogen" in the world, we give you the safety and security in Hydrogen Utilization Society.

STEP 1	We appreciate the hydrogen properties concerning safety through acquisition of the fundamental data resulted from hydrogen leakage, ignition, explosion experiments.
STEP 2	We analyze the hydrogen leakage, ignition, explosion phenomena for safety thoroughly with computer simulation.
STEP 3	We never cause a hydrogen explosion accident due to equipment failure, human error through thorough evaluations of system safety and reliability.
STEP 4	We develop and produce the highly safe and reliable explosion proof devices and systems for hydrogen.

Figure 6. Non-Explosion Technology for H2 Program

3.3 Establishment of Safety Management System

Representative international standards of the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and other organizations have been incorporated into Japanese Industrial Standards (JIS). As a result, engineering and management concepts concerning international safety have been also introduced into Japan's industries. Accordingly, risk analysis and safety measures in the design stage have become important. Since hydrogen produced from Australian brown coal is imported to Japan on the open sea by marine transport under the CO2-Free Hydrogen Supply Chain, a safety management system that conforms to international standards must be established and introduced to design and develop plants and equipment that compose the hydrogen supply chain. Consequently, we are making efforts to conduct PHA (Process Hazard Analysis) in the design stage that includes research and development.

Considering that the CO2-Free Hydrogen Supply Chain will be accepted by society only if all the requirements for "establishing international safety standards," "developing hydrogen safety technologies" and "establishing a safety management system" are met, our company is making efforts to construct these hydrogen safety systems (Figure 7).

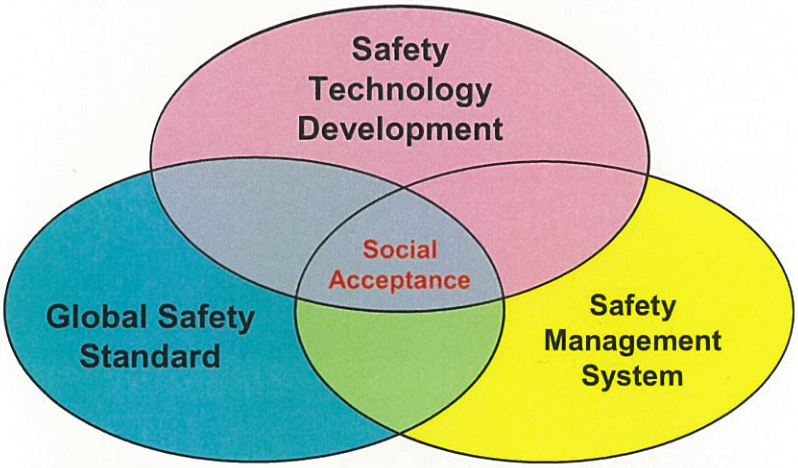


Figure 7. Establishment of Hydrogen Safety System

4. 0 Efforts for Establishment of Safety System for Hydrogen Liquefaction Plant

4.1 Outline of Hydrogen Liquefaction Plant

A hydrogen liquefaction plant uses a heat exchanger in a cold box to significantly reduce the temperature of high-purity hydrogen that is purified in a gas purification plant, and ultimately lowers its temperature by isenthalpic expansion in a J-T (Joule-Thomson) valve to liquefy the hydrogen (Figure 8). Gas and liquid hydrogen that is released from the J-T valve is divided into gas and liquid by a catch tank in the liquefaction plant. The liquid hydrogen is self-pressurized by an evaporator and discharged to a hydrogen lorry. The separated low-temperature gaseous hydrogen is led to the inside of the cold box and re-liquefied. After pre-cooling the hydrogen feed by liquefied nitrogen, it further cools the feed to 20 K in the refrigerating cycle of a recycling system that uses hydrogen as a coolant, for liquefaction. In order to reuse the relevant nitrogen, a nitrogen refrigerating cycle is installed. The specifications of a hydrogen liquefier in the pilot supply chain are shown in Table 3.

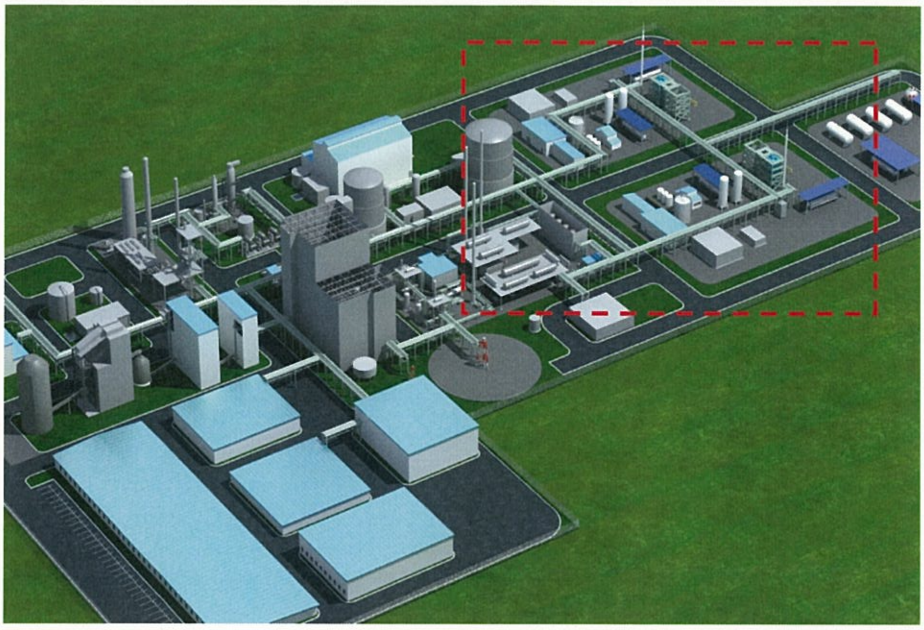


Figure 8. Overview of Hydrogen Liquefaction Plant

Table 3. Specifications of Hydrogen Liquefier for Pilot Supply Chain Project

Quantity	2 units
Liquefaction Process	Hydrogen Claude Cycle
Liquefaction Capacity	5 ton/day/unit
Inlet Hydrogen Purity	>99.999 Vol %
Inlet Pressure	2.0 MPaG
Inlet Temperature	Ambient temperature

5.2 Outline of Hydrogen Test Facility

In the review of the basic design of the hydrogen liquefaction plant, the occurrence of any deviation from normal conditions was assumed from a HAZOP (Hazard and Operability) study that is used for the safety design of processing plant. Next, the effect of the deviation on the system was examined, and it was considered whether the safety of the plant would be ensured by taking measures to alleviate the effects (Figure 9). As a result, hazards that were not assumed in the basic review stage were identified. Accordingly, the introduction of additional countermeasures into the design can improve the safety of the plant. Furthermore, a risk assessment of the plant was done in accordance with the guidelines of CCPS (Center for Chemical Process Safety, Figure 10). In addition, the Safety Integrity Level (SIL) that is required for the plant's Safety Instrumented System (SIS) in adherence to the international standards concerning functional safety, or IEC61508/IEC61511, was analyzed to review required equipment configuration and the reliability of the equipment.

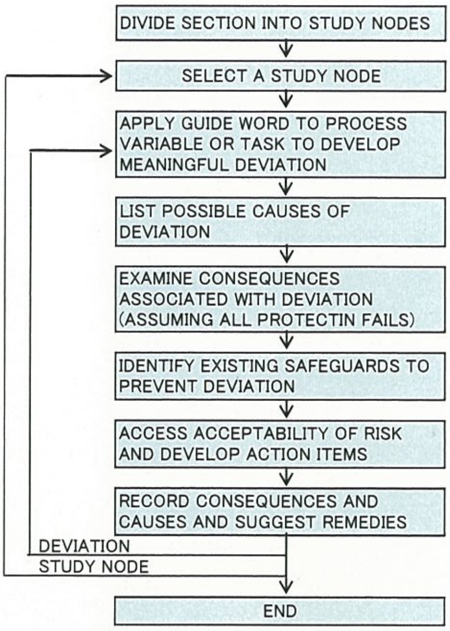


Figure 9. HAZOP for Basic Design

INDEPENDENT PROTECTION LAYERS

IPL8	Community Emergency Response
IPL7	Plant Emergency Response
IPL6	Post-Release Physical Protection (e.g. Bunding)
IPL5	Physical Protection (e.g. Relief Devices)
IPL4	Safety Instrumented System prevention action
IPL3	Critical Alarms and Operator Intervention
IPL2	Basic Process Control System, Operating Discipline/Supervision
IPL1	PROCESS DESIGN

HAZARD LEVELING

Risk Parameter		Classification	
Hazardous event Severity	C1	Minor	Minor injury
	C2	Serious	One death or permanent injury to one or more persons
	C3	Extensive	Several deaths
Event Likelihood	W1	Very Slight	$<10^{-4}$/year
	W2	Slight	$10^{-4}\sim10^{-2}$/year
	W3	Relatively High	$\geqq 10^{-2}$/year

Total Number of Independent Safety-Related systems

MINOR (C1)

	LOW (W1)	MED (W2)	HIGH (W3)
3	SIS: not required		
2	SIS NR		SIL1
1	SIS NR	SIL1	SIL2
	EVENT LIKELIHOOD		

SERIOUS (C2)

	LOW (W1)	MED (W2)	HIGH (W3)
3	SIS: not required		
2	SIS NR	SIL1	SIL2
1	SIL1	SIL2	SIL3
	EVENT LIKELIHOOD		

EXTENSIVE (C3)

	LOW (W1)	MED (W2)	HIGH (W3)
3	SIS NR	SIL1	SIL1
2	SIL1	SIL2	SIL3
1	SIL3	SIL3	SIL3
	EVENT LIKELIHOOD		

Figure 10. HAZOP for Basic Design

6.0 Conclusion

This paper described our proposal of a "CO2-free Hydrogen Supply Chain," and safety efforts for realizing this chain, and presented an example of safety design practiced for design and development of the liquid hydrogen carrier and hydrogen liquefaction plant in a pilot supply chain scheduled to start in 2017. In order to realize the pilot supply chain, efforts described in Chapter 2 must apply to all plant systems that make up the chain, and must be accepted by the international community. This paper presented some of the current efforts. We will continue to make efforts to formulate international standards and safety design from upstream processes, parallel to the design and development of each plant system in the supply chain.

Reference

1) Y. Yoshino, Feasibility Study of "CO2-free Hydrogen Supply Chain" Utilizing Australian Brown Coal Linked with CCS, WHEC 2012, Toronto, Canada, June 5, 2012.

2) Fact Sheet - Victoria's Brown Coal; www.powercor.com.au/Secondary_School_Fact_Sheets/

3) K. Verfondern, Figure 6-5 Safety Distances, Safety Considerations on Liquid Hydrogen, p53-54, 2008.

4) Agreement on Technical Barriers to Trade