Report

International Workshop on Liquefied Hydrogen Technology

Japan Ship Technology Research Association

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1 Introduction

With the commercialization of Fuel Cell Vehicles (FCVs) in December 2014, Japan is steadily moving forward hydrogen society.

In order to realize hydrogen society at large-scale, it is necessary to develop efficient hydrogen technologies from production, delivery/storage and application, and liquefied hydrogen technology is considered as one of key fundamental technologies to realize such society.

With this background, we invited key persons from Japan and the world, and organized International Workshop on Liquefied Hydrogen Technology, which is the first one of this kind in the world, in order to enhance the exchanges on information among researchers and engineers, to encourage academic-industrial alliances and international collaborations, and to promote the liquefied hydrogen technology.

This becomes the unique opportunity to have comprehensive discussion on liquefied hydrogen technology by exchanging latest knowledge and information on the technology.

International Workshop on Liquefied Hydrogen Technology

Date:	March 2, 2015 (Mon) 9:30-17:30
Venue:	RIHGA Royal Hotel Kyoto (Kyoto, Japan) 1-Taimatsu-cho, Shiokoji-sagaru, Higashi Horikawa-dori, Shimogyo-ku, Kyoto 600-8237, Japan
Organizer:	Japan Ship Technology Research Association (JSTRA)
Support:	Japan Science and Technology Agency (JST)

**Photo 1 - Welcome speech: Mr. Shigeru Muraki,
Program Director, Cross-ministerial Strategic Innovation Promotion Program
(Executive Vice President, Tokyo Gas)**

**Photo 2 - Plenary Session: Mr. Shoji Watanabe,
Director, Research and Development Division,
Industrial Science and Technology Policy and Environment Bureau,
Ministry of Economy, Trade and Industry**

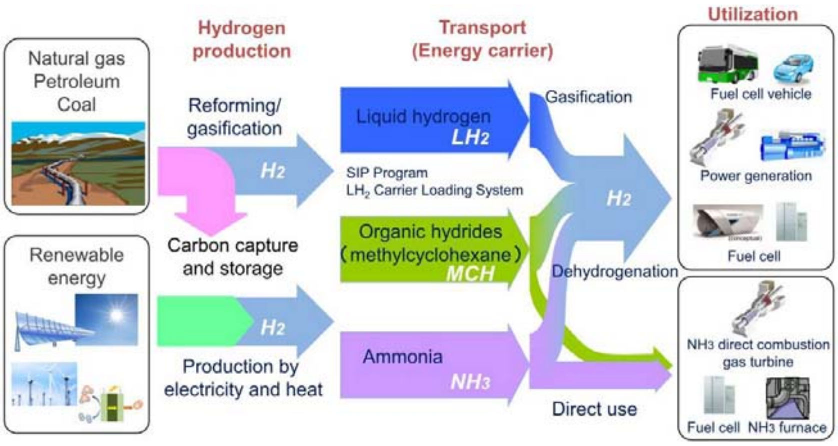
Photo 3 - Panel discussion: Toward promotion of R&D and wider use of liquid hydrogen

2 Welcome Speech

2-1 Energy carrier -Toward the realization of new energy society-

Mr. Shigeru Muraki, Program Director, Cross-ministerial Strategic Innovation Promotion Program (Executive Vice President, Tokyo Gas)

- Council for Science, Technology and Innovation (SCTI) is Japan's headquarter for science and technology. It announced three arrows in 2014, as follows:
  - Improvement of the process for policy-making "S&T Budgeting Strategy Committee" and "Action Plans for S&T Priority Measures"
  - SIP (Cross-Ministerial Strategic Innovation Promotion Program)
  - ImPACT (Impulsing PAradigm Change through disruptive Technologies)
- To solve societal issues and achieve economic growth, SIP has selected 10 topics, one of which is "energy carrier" covering all hydrogen supply chain technologies. The basic concept is CO2-free hydrogen.



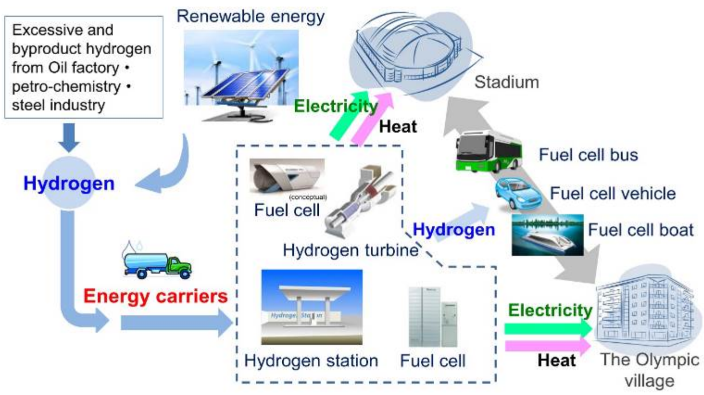
CO2-free hydrogen supply chain at SIP program

- One of main liquid hydrogen R&D topics is the development of carrier loading system, targeting in 2018. Also we are working on international rule-making.
- The vision of "Energy Carrier" is as flows:

  1st Phase (-2020):
  - CO2 free hydrogen R&D
  - Demonstration at Tokyo Olympic and Paralympics Games

  2nd Phase (2020-2030):
  - Expansion of FC markets
  - Introduction ofH2 power generation

  3rd Phase (2030-):
  - Commercialization of large-scale H2 power plant
  - Introduction of CO2-free hydrogen at large-scale



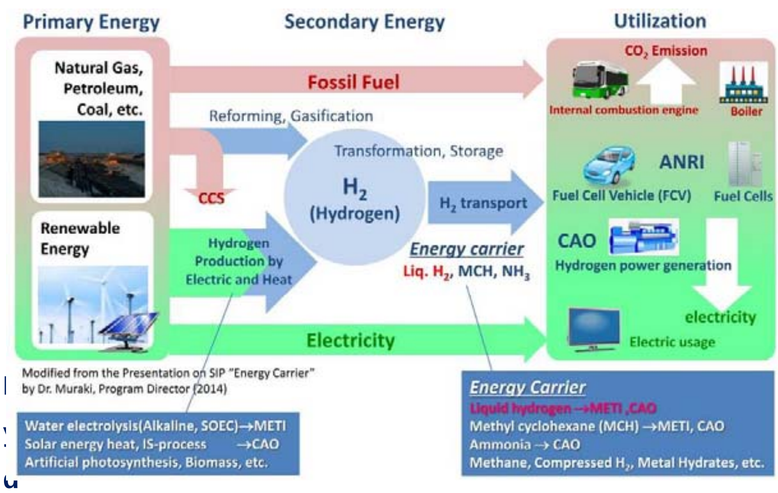
Demonstration at Tokyo Olympic and Paralympic

3 Plenary Session

3-1 Outline of Research and Development on Hydrogen Projects

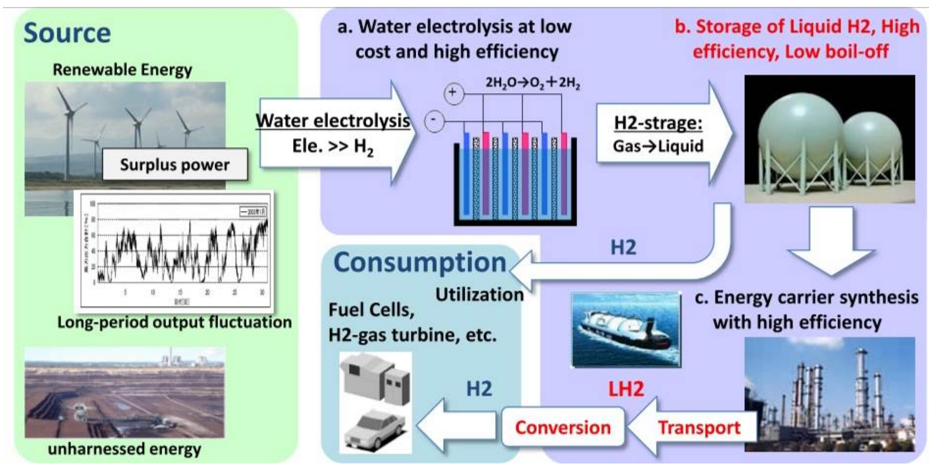
Mr. Shoji Watanabe,
Director, Research and Development Division,
Industrial Science and Technology Policy and Environment Bureau,
Ministry of Economy, Trade and Industry

- Hydrogen is considered as an important energy in term of competitiveness and environment protection, and the deployment of hydrogen, energy carrier technology is the key.
- Japan's 4th Strategic Energy Plan, adopted by the Cabinet in April 2014, also features hydrogen as one of important secondary energies.
- To follow the Strategic Energy Plan, METI announced "Strategic Road Map for Hydrogen and Fuel Cells" in June 2014, targeting 2040 aiming to depoly CO2-free hydrogen.
- Japan conducts hydrogen R&D projects through Inter-ministerial efforts. At SIP program, hydrogen carrier technology R&D including liquid hydrogen, chemical hydrides are conducted.



rogen supply chain and Japan's R&D structure

- METI conducts hydrogen supply chain R&D (FY 2014-2022), including liquid hydrogen R&D. Total budget for FY 2014 is 1.66 billion yen.

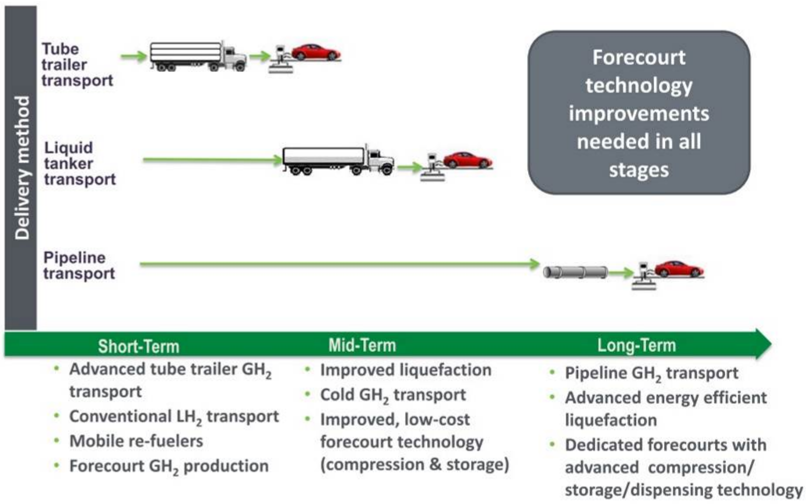


METI's hydrogen supply chain R&D

3-2 Overview of US Activities on LH2

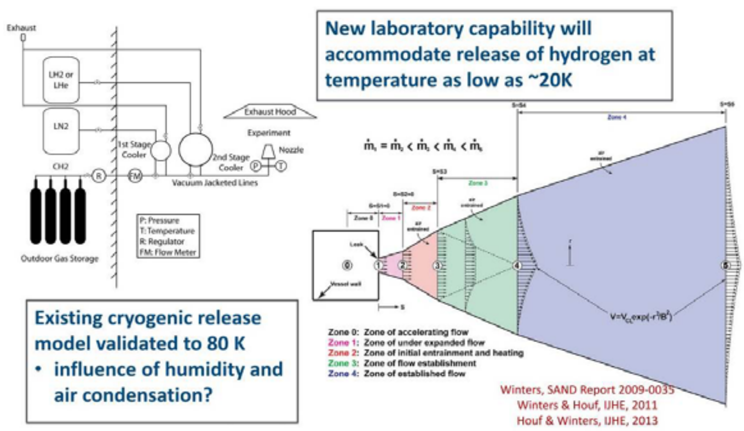
Dr. Will James,
Project Manager, Safety, Codes and Standards Program Lead,
Fuel Cell Technologies Office, U.S. Department of Energy

- DOE has joined the public-private partnership "H2USA," which was created to deploy hydrogen infrastructure, by working on the cost reduction and location selection of hydrogen stations and enhancing the investment to the hydrogen infrastructure.
- The US has 1500 mile-long hydrogen pipeline, and annual hydrogen production volume is 9 million ton. There are about 50 hydrogen stations, among which around 10 are public. Most of public stations are in California, which is investing $100 million by 2023 to install 100 hydrogen stations in the state.
- 8 states, CA, CT, NY, MA, MD, OR, RI and VT, have signed the MoU to promote Zero Emission Vehicles, including FCV. CT, NY and MA have also started the hydrogen infrastructure deployment.
- For hydrogen delivery, compressed hydrogen and liquid hydrogen are the option for short-term and pipeline delivery is also the option for long-term.



Hydrogen delivery mode (shot-tem and long-term)

- The US has two liquid hydrogen stations (West Sacrament and Irvine).
- DOE is conducting simulations on liquid hydrogen behaviors especially on safety distance and risk analysis.

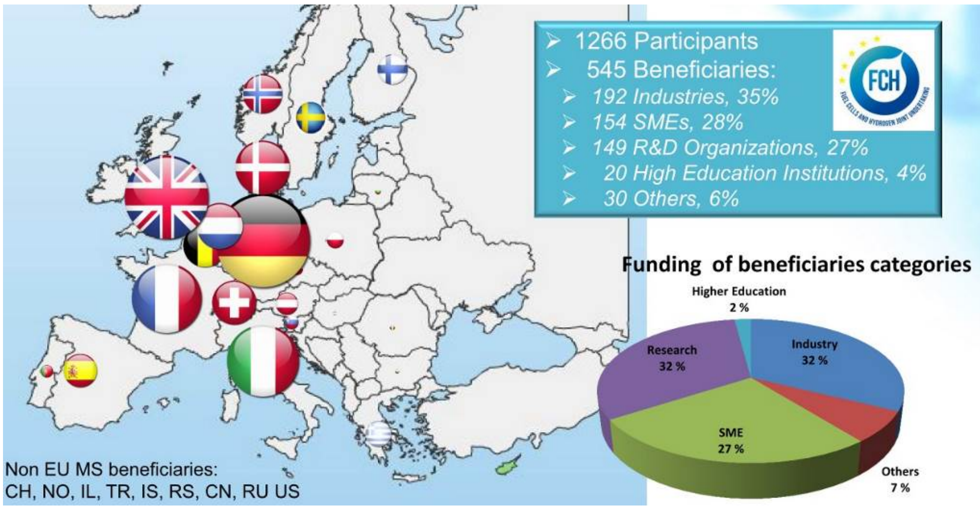


Example of simulation of liquid hydrogen

3-3 European hydrogen activities - in an international perspective

Dr. Steffen Møller-Holst
Vice President – Marketing, SINTEF
(Leader of Norwegian Hydrogen forum Hydrogen council)

- Europe consume 94% of oil at transport sector, and 84% of oil is imported. Also Europe spends 1 billion euro/day for oil in 2011. 25% of CO2 emission is from transport sector.
- European policy package of “Clean Power for Transport” in 2013 is aiming to introduce alternative energy, including hydrogen.
- October, 2014, European Commission adopted “European Climate and Energy Policy Framework” to reassure2020 target of “20-20-20” (introduction of renewable energy up to 20%, improvement of energy efficiency by 20%, and reduction of GHG by 20%) and to set new target for 2030 (introduction of renewable energy up to 27%, improvement of energy efficiency by 27%, and reduction of GHG by 40%).
- For Europe, FCHJU (Fuel Cells and Hydrogen Joint Undertaking) is the main platform to promote hydrogen RD&D with 22 member states. The main target is transport sector.



FCH JU

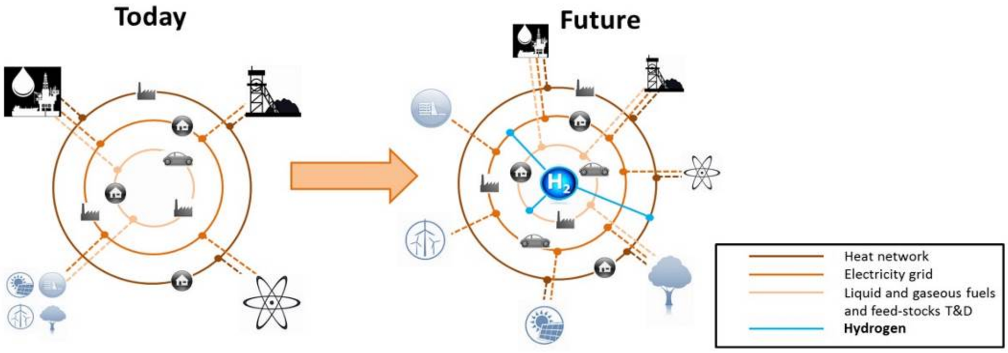
- Norway has large wind power potential in northern part, but electricity grid capacity is low. Therefore using such wind–power can be converted into hydrogen, and it can be transport to Japan

Hydrogen transport through Arctic route

3-4 Hydrogen Technology Roadmap

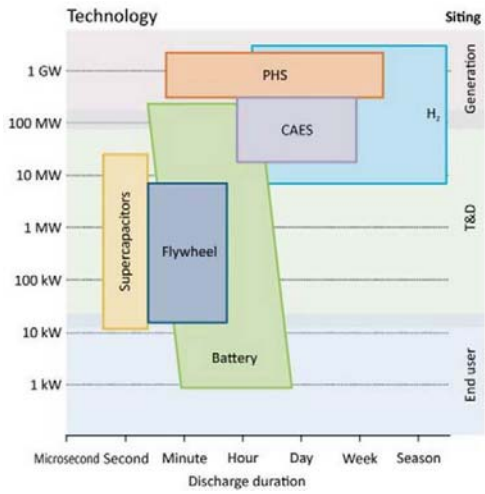
Mr. Yasuhiro Sakuma
Programme Officer for Implementing Agreements related to renewable energy and hydrogen Renewable Energy Division,
International Energy Agency

- IEA has developed 24 technology roadmaps and now we are working on hydrogen technology roadmap. This work has started in 2013, and we have competed three regional workshops (Paris, Washington DC, and Yamanashi). It will be released in Q2 of 2015.



Vision of IEA hydrogen technology roadmap: Today's separated energy network (left) and Future's integrated energy network (right)

- Hydrogen can be flexible energy system (energy storage system), however, low energy efficiency of entire system is the main issue.



Storage options for surplus renewable electricity

Total energy efficiency of hydrogen-based energy storage

3-5 Current Development of Liquefied Hydrogen and its Prospects

Mr. Ko Sakata
Director, Hydrogen Program, Research and Development Division,
The Institute of Applied Energy

- Today's energy mix is not suitable and we need low-carbon energy system at large-scale. For Japan, importing large volume CO2-free hydrogen from the world is expected.
- In the past, there were several studies on large-scale hydrogen transport network, such as EQHHP between Canada and Europe, Hysolar between Germany and Saudi Arabia, and WE-NET in Japan.

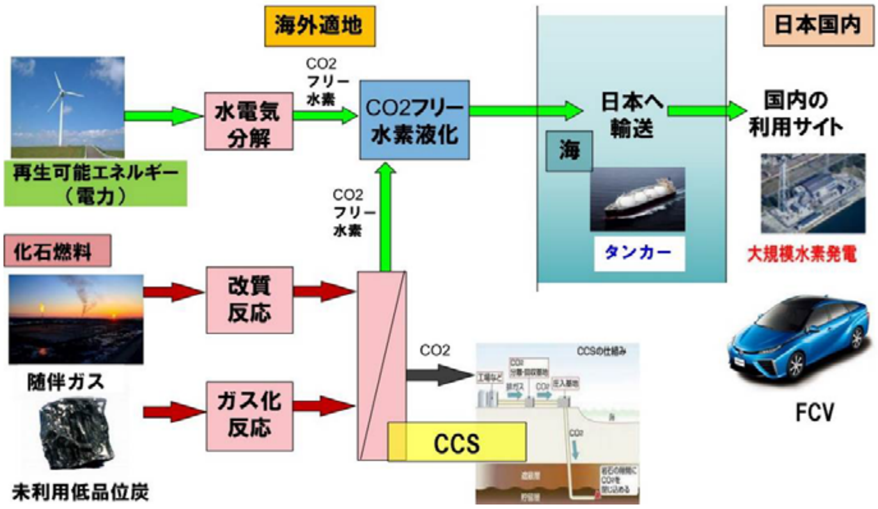
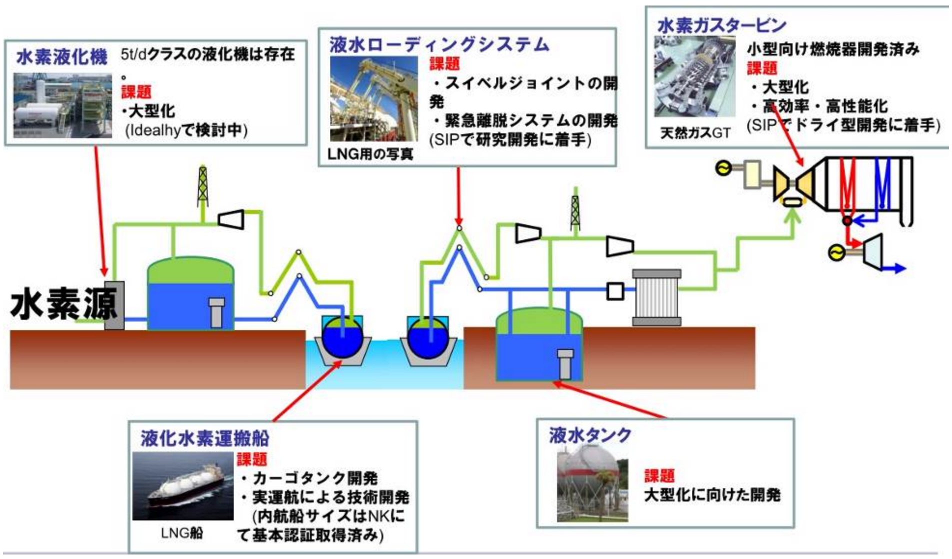


Image of Low-carbon hydrogen transport system

- For the large-scale transport, liquid hydrogen and chemical hydrides are main options, are they are used depending on applications. Liquid hydrogen is already matured technology.



R&D items for large-scale liquid hydrogen chain

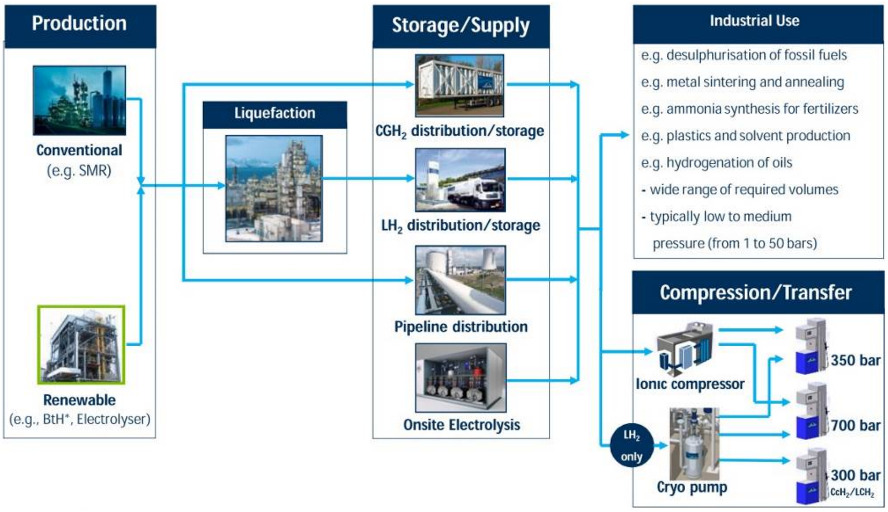
- R&D Issues for liquid hydrogen include the development of liquid hydrogen carrier, compact liquefaction facility, and hydrogen-based gas turbine for electricity generation.

4 Technical Session 1: Major players

4-1 Liquid Hydrogen Technologies from Linde

Mr. Markus Bachmeier
Head of Hydrogen Solutions and Advanced Customer Applications, Gases Division, Linde

- Linde is offering best delivery options depending on applications. Key factors are delivery cost, footprint of site, demand volume, and required purity of hydrogen.



Hydrogen delivery option by applications

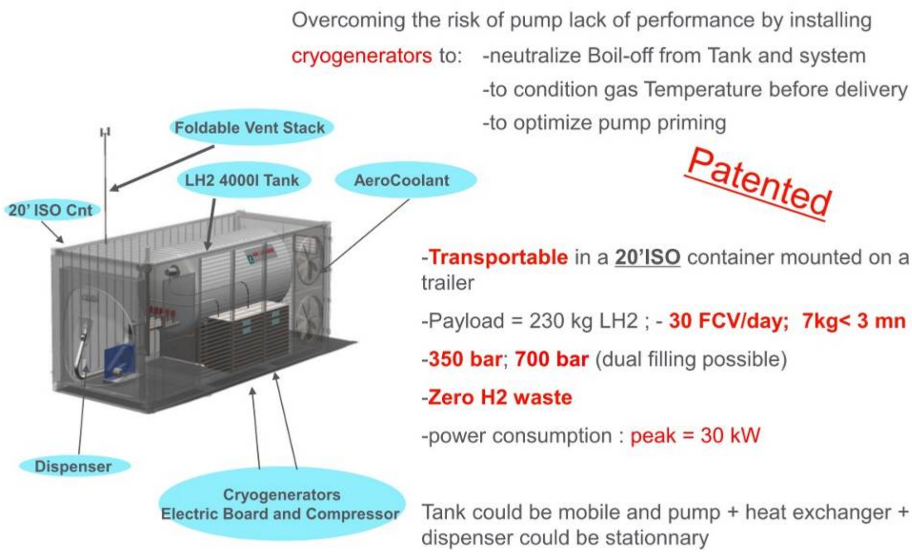
- Currently hydrogen liquefaction energy efficiency is10.8-12.7kWh/kg, but future energy efficiency will be 7.5-9.0kWh/kg.
- For hydrogen delivery, liquid hydrogen can be good potion for delivery distance of more than 150 km and with large hydrogen demand. For the larger hydrogen demand, pipeline can be the option, but it requires large investment.

Key factors for hydrogen delivery

4-2 Liquid Hydrogen Applications for Mobility in Automotive, Space and Aeronautics

Mr. Pierre Crespi
Director of Innovation, Air Liquide Advanced Technologies

- Air Liquide is investing hydrogen supply chain in the world. The company has 545km long pipeline in the US and 950km long pipeline in Europe. Also Air Liquide has deployed 4,000 FC forklifts and 70 hydrogen stations worldwide.
- The company had operated the world largest liquid hydrogen station in Whistler for FC buses with 500kg/day supply capacity. The total refueling number is more than 300.
- Liquid hydrogen station can be more affordable and more compact than compressed hydrogen stations.

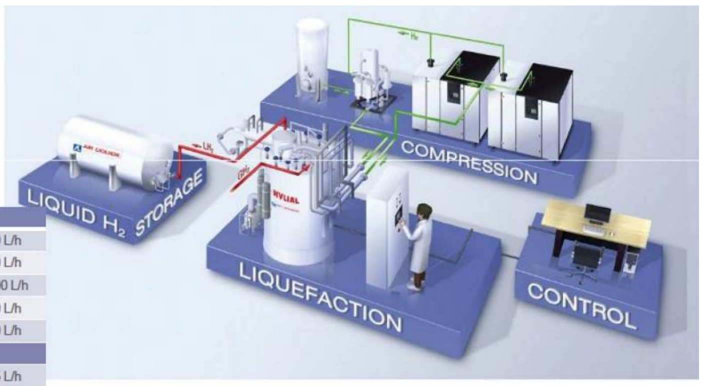


Air Liquide's packaged liquid hydrogen stations (patented)

- Air Liquide has developed hydrogen liquefaction facility using Turbo-Brayton technology (patented). Liquefaction energy efficacy can be improved by 30%

References

HYLIAL		
2012	BLC, China	600 L/h
2011	Xichang, China	600 L/h
2011	Hainan, China	1500 L/h
2011	HTEC, Canada	800 L/h
2007	BLC, China	600 L/h
Previous H2 Liquefiers		
1990	Ariane Space, Guyana	375 L/h
1988	Pacific H2, Japan	850 L/h
1987	Hydrogenal, Canada	6000 L/h
1987	Air Liquide, France	6000 L/h
1977	Iwatani, Japan	760 L/h
1966	Frais Marais, France	600 L/h
1964	Predictown, USA	3600 L/h
...and over 30 H2 small liquefiers in several labs (14-40 L/h)		



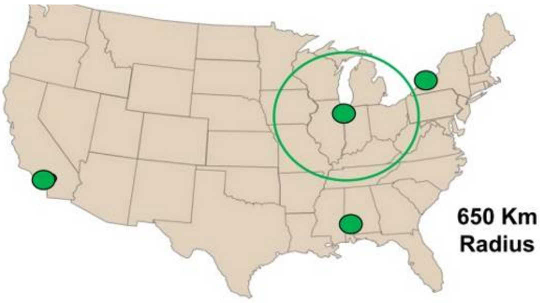
	1 ton/day	1.3 ton/day	2.5 ton/day
	HYLIAL 600	HYLIAL 800	HYLIAL 1500
LH2 production (l/h)	600	800	1500
Expected Compressor Power (kW)	550	690	1260
Cold Box size (L x W x H) in m	8.1 x 4.8 x 5.5 (with gangway)	8.1 x 4.8 x 5.5 (with gangway)	9.0 x 4.5 x 5.5

Image: Air Liquide's patented technology for hydrogen liquefaction facility

4-3 <u>Challenges In Scaling Up Production</u>

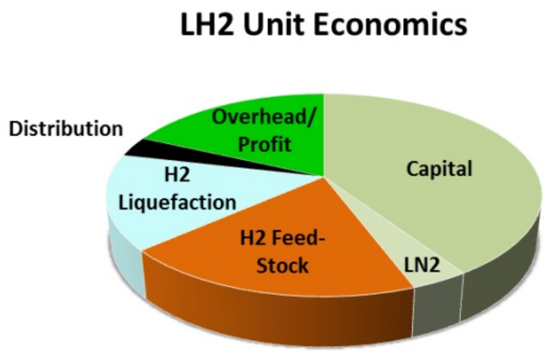
Mr. Al Burgunder
Director, Energy & Environment Business Development, Praxair

- Praxair has four liquefaction plans in North America, with the liquid hydrogen market share of 45%.



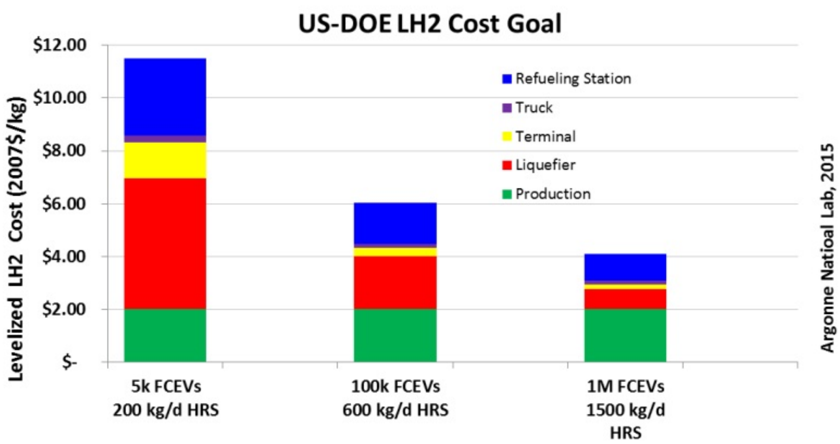
Praxair's hydrogen liquefaction plants

- For liquid hydrogen supply chain, capital cost and H2 feedstock cost are major cost factors. For better economics, the reduction of capital cost, more affordable feedstock, and the improvement of liquefaction energy are needed. Other issues are proper investment with FCV market expansion, and proper investment risk management.



Cost Analysis on Liquid Hydrogen Supply Chain

- US DOE's target on liquid hydrogen delivery is $4/kg, and it is necessary to reduce the cost at liquefaction process.

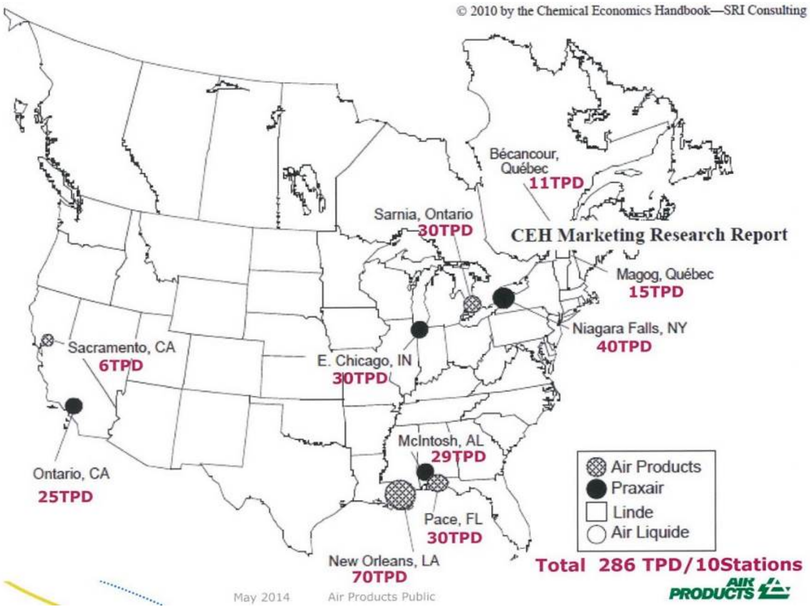


US DOE's target on liquid hydrogen delivery

4-4 <u>Air Products Liquid Hydrogen Technologies</u>

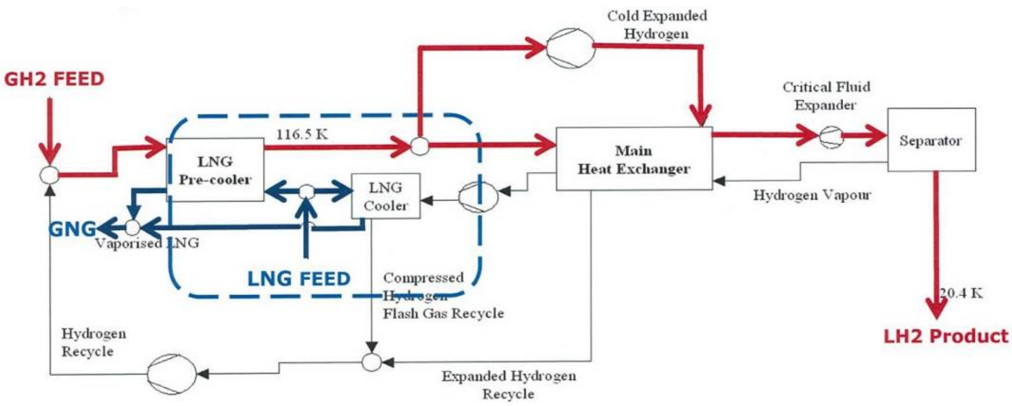
Mr. Hideo Shigekiyo
Commercial and Technology Manager, TGEE group Customer Plant Support,
Air products Japan

- Among 10 hydrogen liquefaction plans in North America, Air Products has 3 with the market share of 45% (>110 ton/day), and supplies liquid hydrogen to more than 500 customers.



Hydrogen liquefaction plans in North America (Air Products has four)

- By combining LNG facility, the energy efficiency of liquid hydrogen production can be improved from 11kWh/kg to 2-3.2kWh/kg. For the production of 1kg of liquid hydrogen, 20.4kg of LNG is needed.



Liquid hydrogen production using cold heat from LNG

- Air Products has developed large-volume cryopump of 250kg/hr, which can produce 96.5MPa hydrogen. It also can compress liquid-gas mixed phase hydrogen.
- Air Products' dual phase hydrogen tanker can deliver liquid hydrogen and compressed hydrogen at the same time.

5 Technical Session 2: Advanced Technology

5-1 IDEALHY project and Liquid Hydrogen activities at Dresden Technical University

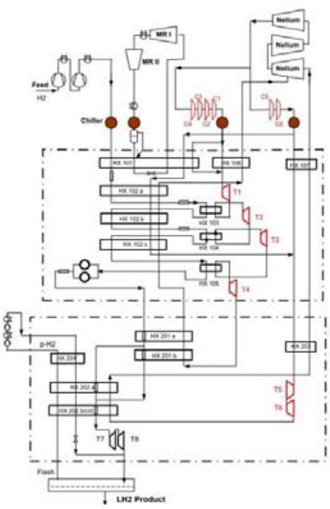
Dr. Christoph Haberstroh
Associate Professor, Institute of Energy Technology,
Faculty of Mechanical Engineering, Dresden University of Technology

- Dresden University of Technology is working on low temperature technologies, including liquid hydrogen. For liquid hydrogen, onboard tank, cryopump, ortho-para conversion, and liquid hydrogen loading arms.
- Optimum liquefaction energy is 6.2kWh/kg (18.7% of hydrogen energy), but current technology's energy is 12-15kWh/kg (36-45%%). The improvement of efficiency is needed.

Liquefier	specific energy consumption	= .... % of lower heating value
Minimum exergy for liquefaction	14.2 MJ/kg = 3.9 kWh/kg	11.8 %
Optimized liquefier	22.4 MJ/kg = 6.2 kWh/kg	18.7 %
Existing liquefiers (typ. 5 – 10 tpd)	43 ... 54 MJ/kg = 12 ... 15 kWh/kg	36 ... 45 % (⇨ intolerable)

Liquefaction facility in the world and Liquefaction energy

- We have working on IdealHy project to reduce the liquefaction energy by 50%. The target liquidation cost is 1.72 Euro/kg.



Definition of key boundary conditions:

H_2 feed	20 bar / 293 K / 99.99 % purity
LH_2 outlet parameters	2 bar / 22.8 K / > 98 % para

⇦ **final IDEALHY proposed cycle**

- 80 bar
- Mixed refrigerant pre-cooling cycle
- Brayton cycle (expander partly overlapping in temperature, power recovery)
- „Nelium“ as working fluid ⇨ highly efficient multi-stage turbo compressors
- 6 °C Chiller
- Liquid expander instead of JT valve
- Flash gas recycling

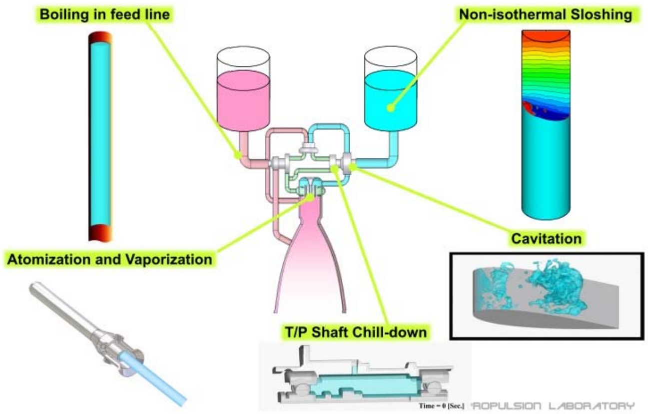
IdealHy Project

5-2 Prediction of Liquid Motion and Heat Exchange in Space Propulsion Systems

Dr. Takehiro Himeno

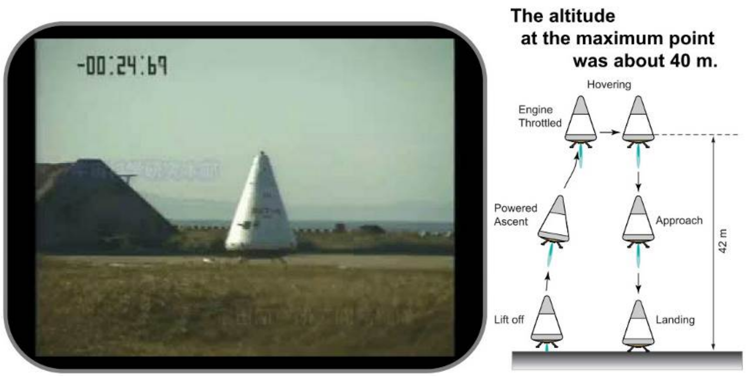
Associate Professor, Department of Aeronautics and Astronautics, University of Tokyo

- It is important to predict motion of free-surface flows in liquid Propulsion.

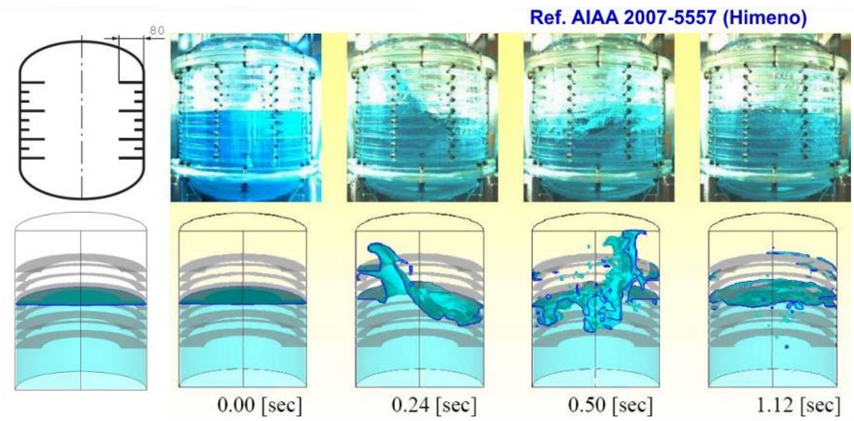


Free-surface flow at propulsion system of space vehicles

- For sloshing prediction, RVT (Reusable Vehicle Testing) and model tank with baffles RSR (Sub-orbital Reusable Sounding Rocket), and CIP-LSM simulation are used.
- Liquid hydrogen sometimes behaves like gaseous hydrogen. University of Tokyo is working with Japan Aerospace Exploration Agency to understand the behavior of boiling liquid in confined area. The knowledge can be applicable for liquefied hydrogen at pipe or tank.



Reusable Vehicle Testing

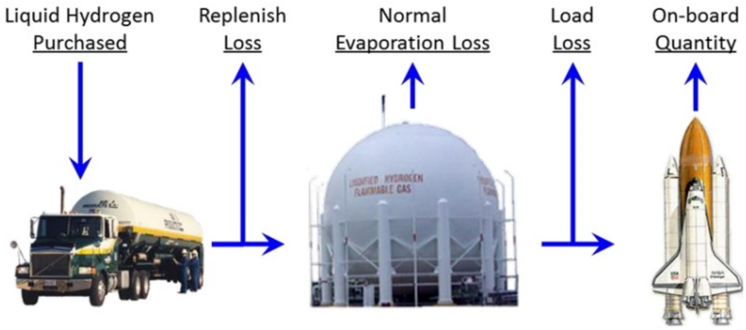


Model tank simulation with baffles RSR (Sub-orbital Reusable Sounding Rocket

5-3 <u>Cost Efficient Storage and Transfer of Liquid Hydrogen</u>

Mr. James E. Fesmire
Sr. Principal Investigator, Cryogenics Test Laboratory,
NASA Kennedy Space Center

- Aerospace industry is the largest LH2 user.
- At NASA Kennedy Space Center, 45% of purchased LH2 is lost.



Liquid Hydrogen Consumption over Entire Space Shuttle Program

Liquid Hydrogen Purchased	100.0%	54,200,000 lb
Replenish Loss	12.6%	6,800,000 lb
Normal Evaporation Loss	12.2%	6,600,000 lb
Load Loss	20.6%	11,200,000 lb
On-board Quantity	54.6%	29,600,000 lb

Liquid hydrogen usage at NASA Kennedy Space Center

- Integrated Refrigeration and Storage (IRAS) Tank System can reduce hydrogen losses and contribute to the cost reduction and safety assurance. It is already demonstrated at laboratory level (150L).

I

RAS Tank System

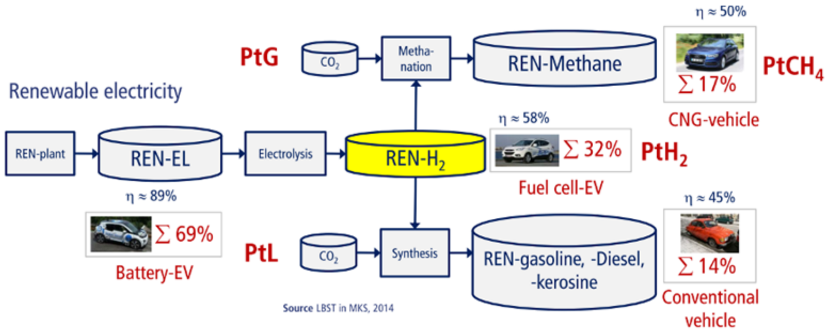
- Insulation material is the key for liquid hydrogen delivery and storage, and international standard setting is on-going.
- Liquid hydrogen application is expanding by the collaboration with industry. It may have synergy effect with other industry sectors like intercontinental-transportation, superconductivity, LNG and medical.

6 Technical Session 3: New applications of liquid hydrogen

6-1 Large Volume Hydrogen Application: Power-to-Gas

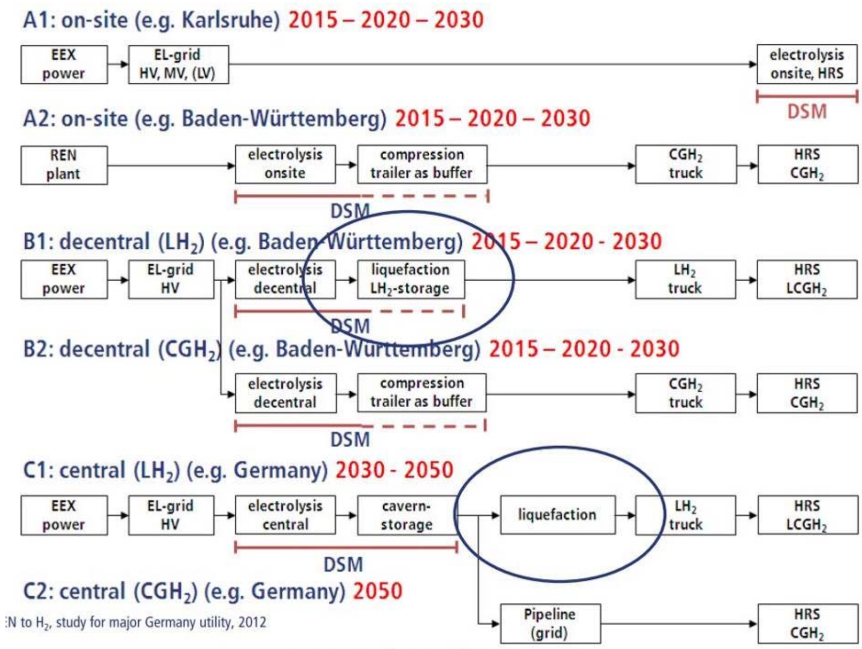
Dr. Ulrich Buenger
Senior Scientist, Ludwig-Bölkow-Systemtechnik (LBST)

- Power-to-Gas (PtG) is the technology to convert renewable electricity to hydrogen or methane.
- Renewable portion of German electricity should be 50 % in 2030 and 80% in 2050, so we need energy storage technology. Hydrogen can contribute to the stabilization of the grid.
- Renewable electricity can be supplied to EVs (total efficiency is 69%), to FCVs by converting to hydrogen (32%), to CNGVs by converting to methane (17%), and to gasoline ICEs by converting to synthesized gasoline (14%).



Suplying renewable electricty to vehciles

- In PtG scheme, LH2 is useful for long distance delivery, including international delivery.



Power-to-Gas and LH2

- It can be said that the US is for Gas-to-Power (due to shale gas), Europe is for Power-to-Gas (to introduce renewables), and Japan is for Gas-to-Power (due to LNG import).

6-2 Introduction to a Pioneer Liquefied Hydrogen Carrier

Dr. Yukichi Takaoka
Technology Division Chief, Ship & Offshore Structure Company, Kawasaki Heavy Industries

- Kawasaki Heavy industries, Ltd. (KHI) is promoting hydrogen supply chain between Japan and Australia. Producing hydrogen by gasification of brown coal in Australia and subgenerated CO2 is captured and storage to Australian national CCS (CO2 capture and storage) project called CarbonNet. By applying CCS, produced hydrogen will be CO2-free hydrogen, which is then liquefied and transported by liquefied hydrogen (LH2) carriers to Japan. For this purpose, KHI started developing an LH2 carrier.
- KHI is now developing the "Pioneer ship (carrier)" with the LH2 cargo total capacity of 2,500 m3. The ship will be powered by diesel-electric engine, but the ship also has testing spaces as void spaces in way of the cargo holds for testing of fuel cells, hydrogen gas turbines, and so on aiming to utilize boil-off hydrogen gas from the cargo for propulsion in the future.
- The Pioneer ship has two Cargo Containment Systems to store LH2 (1,250m3 x 2), where vacuum insulation double-hull structure are adopted. A horizontal cylindrical pressure vessel that freely enable thermal shrinkage by LH2 carriage independent of the ship's hull structure, adopted as the inner hull. It is supported by the supportive structures connecting to the outer hull at fore and aft saddle positions with very low heat penetration in the vacuum space.
- 1,250-m3 LH2 Cargo Containment System of this ship (Total 1,250 m3 x 2) had been already obtained the AiP (Approval in Principle) from Japanese Classification Society, ClassNK (Nippon Kaiji Kyokai), in December 2013.
- A Draft Minimum Requirement for Carriage of LH2 in Bulk based on the IGC code (The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases), proposed by the Japanese government and discussed with the Australian government, has been already agreed provisionally by the two on February 2015 in preparation for her first voyage.
- KHI has been developing LH2 loading system technologies led by the JSTRA in one of SIP (Strategic Innovation promotion Program) projects coordinated by JST (Japan Science and Technology Agency). This system will be applied in shipping facilities in LH2 terminals both of Japan and Australia. In this SIP project, KHI also has joined the R & D of the international rules and standards for LH2 loading system.

6-3 Deployment of liquid hydrogen to hydrogen refueling station

Mr. Jun Miyazaki
Executive Managing Officer, Iwatani Corporation

- Iwatani has been promoting hydrogen energy since 1941.
- Japanese liquid hydrogen market is about 40 mil m^3, only 1/60 of the US market.
- Liquid hydrogen has advantages on large-volume delivery (a LH2 truck carries 7 times larger than compressed gas trucks), large-volume supply, large-volume storage, small footprint (LH2 storage facility footprint can be 1/3 of compressed gas storage facility), high purity (99.9999%), and utilization of low temperature energy (20 K).
- Iwatani has three hydrogen liquefaction facilities in Japan (hydro-edge in Sakai, Iwatani Gas in Ichihara, and Liquid Hydrogen in Shunan), and they are covering entire Japan.
- Iwatani was the first company to announce hydrogen cost for FCVs. The cost is competitive with gasoline cost of hybrid cars by 2020, which is the 2020 target of METI's roadmap.
- Ariake hydrogen station is the first LH2 station (35 MPa) in Japan. This demonstration station will be upgraded for 70 MPa system with capability for FC bus refueling.
- Iwatani will install 20 hydrogen stations. In July 2014, Iwatani opened Japan's first hydrogen station in Amagasaki, and will open new station with showroom near Tokyo Tower. We will also install hydrogen refueling system at convenience stores (Tokyo and Aichi prefecture).
- Future hydrogen stations will be LH2 stations. For compression, ionic compressor or cryo-pump will be used. We need to work on hydrogen station packaging, regulation review, and cost reduction and establishment of installation process.

7 Panel Discussion: Toward promotion of R&D and wider use of liquid hydrogen

Chair: **Dr. Takehiro Himeno (University of Tokyo)**
Panelist: **Dr. WillJames (DOE)**
Dr. UlrichBünger (Ludwig-Boelkow-Systemtechnik)
Dr. SteffenMøller-Holst (SINTEF)
Mr. Ko Sakata (The Institute of Applied Energy)
Dr. Eiichi Harada (Kawasaki Heavy Industries)
Mr. Jun Miyazaki (Iwatani Corporation)

7-1 Chair's Session Summaries

Prior to Panel Discussion, Chair summarized the sessions, as follows:

Plenary Session

(1) Major countries consider hydrogen is an important energy option to realize low-carbon society. They have clear commitment and vision for hydrogen deployment.
(2) It is generally agreed that liquefied hydrogen is one of the major technologies to support large-scale deployment of hydrogen.
(3) Several countries are even working on the realization of the international transportation of hydrogen.
(4) Hydrogen-based power generation is one way to create large-scale hydrogen demand.

Technical Session 1: Major players

(1)Major key-players use different hydrogen transportation technologies, depending on conditions such as hydrogen demand and distance.
(2) For the deployment of liquefied hydrogen, the improvement of energy efficiency is a common issue.
(3) Major players are already doing business on liquefied hydrogen, and they seem to believe on liquefied hydrogen promising technology to deliver and store hydrogen at large-scale.
(4) Reliable liquefied hydrogen technologies are available today, but we need more technology development to improve its performance and reduce cost

Technical Session 2: Advanced Technology

(1) Research organizations are working on fundamental research of liquefied hydrogen, which may have the potential to reduce cost and improve the energy-efficiency of such systems.
(2) Also, simulation and safety technologies can help the commercialization of liquefied hydrogen technology.
(3) International collaborations are on-going, but we need to strengthen and further promote such collaboration.

Technical Session 3: New applications of liquid hydrogen

(1)There are emerging applications to use hydrogen at large-scale.

e.g. Power-to-Gas

Hydrogen-based power generation

Established industries (e.g. Chemical companies)

(2) Energy storage technology is needed to realize large-scale hydrogen deployment.

(3) Liquefied hydrogen is also useful for medium-scale hydrogen applications, mainly hydrogen stations, because of its delivery efficiency.

(4) Regulatory framework is needed to deploy liquefied hydrogen at large-scale (especially for international transportation).

7-2 Comments on Session Summaries

- Each company has different condition. For the US, compressed hydrogen delivery is main option for the movement, and liquid hydrogen can be the option with FCV deployment.
- Hydrogen is already a commodity but it is delivered by compressed gas technology. With the increasing hydrogen demand by FCVs, FC buses and FC trains, liquid hydrogen can have advantage.
- Norway is energy-exporting country, but hydrogen is not widely recognized as energy. Japanese commitment may stimulate Norway, so that we look very much to Japanese government and Japanese companies (e.g. KHI and Iwatani) as the front runner.
- It will be needed to have good balance between energy supply and demand internationally. For Japan, LNG has been the major energy, but the international transportation of unusable energies such as brown coal is needed, and hydrogen delivery can be the key energy carrier.
- For the application of unusable energy such as brown coal, liquid hydrogen carrier is needed. In old days, LNG was the dream, but Japan became the pioneer on the technology and now Japan is the largest consumer of LNG. So, Japan can be the pioneer on liquid hydrogen technology, so that Japan can contribute to the world.
- We need low cost hydrogen for expansion of market. For that purpose, we need large hydrogen consumption. Japan became the first nation to commercialize FCVs, but we need to promote hydrogen as one o important energies.

7-3 Panel Discussion Topics

With above summaries and panelists' comments, Chair proposed three discussion topics

(1)What is the liquefied hydrogen's role and position as energy carrier?

(2) Recognizing some of the challenges generally understood today such as cost, energy efficiency, load-factor on liquefaction process and the need for an established regulatory framework, what is needed to overcome these and other key issues to promote the wide use of liquefied hydrogen as an energy carrier and promote the underlying R&D?

(3) Is there any possibility to create international hydrogen network, especially for liquefied hydrogen?

7-4 What is the liquefied hydrogen's role and position as energy carrier?

Panelists' Comments

- Toward large-volume liquid hydrogen application, International cooperation should be led by government, and international collaboration should be led by industry.
- Liquid hydrogen can work for large-scale delivery and small-scale delivery. So, liquid hydrogen technology should be competitive with hydrogen pipeline as well as small scale onsite hydrogen production and tube truck delivery. Hydrogen can be complement with electricity for the introduction of renewables.
- We need to identify applications which have potential benefits using liquid hydrogen. We also need to support front runners. In that sense, we appreciate Japan's commitment. Chicken and Egg is still the issues and liquid hydrogen is also larger chicken, so that we need international collaborations on this technology. This workshop can be the good start.
- For intercontinental transport, hydrogen tankers (e.g. liquid hydrogen tanker) are superior to pipeline delivery. Other than liquid hydrogen, chemical hydride and ammonia delivery technology have also been developed. With the technical maturity of liquid hydrogen technology, we expect that technologies on large-volume hydrogen may be progressed.
- For intercontinental transport, liquid hydrogen has advantage because of its simple concept. Liquefaction requires certain energy, so that it should be operated at the place with low energy cost. There is still some room to reduce the energy. Also, there are a lot of potentials for technology improvement, if we consider the theatrical efficiency.
- Liquefied hydrogen technologies are already used for domestic delivery. There are some problems like high cost, but there are also advantages. Through addressing issues like BoG, it is needed to identify the benefit of liquid hydrogen and prove it to the world.

Chair's Summary

- Liquid hydrogen has advantage for intercontinental delivery.
- With comparison with other energy carriers, liquid hydrogen is matured technology and there

is still some room to reduce the energy. We need to work on this technology.

- Japan should commit this technology as the front runner, with showing its results.

7-5 Recognizing some of the challenges generally understood today such as cost, energy efficiency, load-factor on liquefaction process and the need for an established regulatory framework, what is needed to overcome these and other key issues to promote the wide use of liquefied hydrogen as an energy carrier and promote the underlying R&D?

Panelists' Comments

- As mentioned at Session 3, regulation is also important. In the US, with the experience of hydrogen stations, safety aspect of liquid hydrogen is discussed and reviewed. Also, international regulations on international delivery are important.
- In the past, there were several studies on international delivery such as Norway-Germany, Canada-Europe, and WE-NET. Since then, liquid hydrogen technology has been improved and it becomes very promising option. We need to continue the R&D.
- "Continuation" is the keyword, and R&D and public fund are still needed, so we need to promote this technology among public sector.
- Main issue is the cost. First we need to identify competing technologies and liquid hydrogen cost also should be competitive with such technologies. Also we need a common platform to discuss issues on intercontinental transport. Hydrogen transport from Australia can be the model case with issues like negotiation with IMO and an exporting country. International collaboration is needed.
- We need more efforts on R&D on large-scale energy transport. International collaboration make R&D more efficient. For realization of the technology, related regulations should be internationally standardized.
- Each country has different idea and standard on safety, so we need more collaborations to harmonize safety regulation and safety measures.

Chair's Summary

- Other than R&D, we need efforts on international rule-making and common view on liquid hydrogen.
- Such efforts require international collaboration.

7-6 Is there any possibility to create international hydrogen network, especially for liquefied hydrogen?

Panelists' Comments

- International network on liquid hydrogen is needed, we need to identify the best option for collaboration platform, such as IPHE (International Partnership for Hydrogen and Fuel Cells in the economy) as intergovernmental collaboration and hydrogen infrastructure workshop among Japan, the US, Germany and Scandinavian counties. We need to identify the best collaboration pathway (flexibly and practically) to promote this technology.

- We have been working on international collaborations so that liquid hydrogen network is also possible. Each country has different condition, but we share the common purpose of "achievement of hydrogen-base system". We will contribute to this network. The first task is to creation of common vision.
- We need more efficient alignment not only on liquid hydrogen R&D also on entire hydrogen R&D. Decision-making also should be efficient. One idea is to create new task at IEA HIA (hydrogen implementing agreement).
- IEA's one of main purposes is establishment of low-carbon society, so that CO2-freee hydrogen is on the same direction. Since we need international collaboration on CO2-free hydrogen, and IEA can be one option. Also we need collaboration network among researchers and engineers.
- Such international network cannot be achieved by one company's efforts, and we would like to propose the idea to create the network, such as "Liquid hydrogen network" with other companies having same vision in order for regular information exchange toward hydrogen-energy international network.
- Toward hydrogen society, we need international collaborations with international entities and agencies. We would like to cooperate on the establishment of such network.

Chair's Summary

- Now we have concrete proposal of the creation of "Liquid Hydrogen Network (LH-NET)". If you agree on this idea, please give an applause. (all panelists applaud the proposal).