2014 HYDROGEN STUDENT DESIGN CONTEST

DEVELOPMENT OF DESIGN FOR A DROP-IN HYDROGEN FUELING STATION TO SUPPORT THE EARLY MARKET BUILD-OUT OF HYDROGEN INFRASTRUCTURE

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Taiwan
In order to support the early market build-out of hydrogen infrastructure, as the designated theme of the 2014 Hydrogen Student Design Contest, our design for a drop-in hydrogen fueling station must be compact yet user-friendly under low operating and maintenance cost to face all challenges. Considering all means of energy balance to operate a portable station, our team wish to have a station which has high energy efficiency but low carbon emission; labeling as a “blue era station”.

Hydrogen Infrastructure is vital in boosting the development of zero-emission fuel cell electric vehicles (FCEVs) commercialization. Having hydrogen fueling station around an area of community will increase their interest towards having their own FCEV. However, building a stationary hydrogen fuelling station thus far costs several million dollars. Therefore, drop-in hydrogen fuelling station, which is able to redeploy from point to point is much more suitable in supporting the early build-out market of hydrogen.

Our team has designed a hydrogen fuelling station with a different approach – organic hydride, a hydrogen storage medium which enables high degree of hydrogen infrastructure development, upgrading existing conventional gas station into hydrogen fuelling station. The station adopts active booster filling which is also a huge potential expanding technology.

Organic hydride with its own competitive advantages, allows low hydrogen retail price and high feedstock supply capacity. In the sense of sustainable development, organic hydride is feasible in all aspects of development. In spite, organic hydride isn’t a mainstream studied technique, whereby insufficient of related data is a challenge in developing and/or studying.
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1. DESIGN DATA AND EQUIPMENT DRAWINGS

The momentum of environmental impact reveals what we did were full of selfishness and immaturity. There is no singular solution that satisfies all humanitarian crises as all reflections in circumstances are intertwined with each other. Yet, sustainability is the core factor that covers a large portion of the impact. Hence, the design of our drop-in hydrogen fueling station surrounds the concept of sustainability. Consequently, a novel solution to up-coming hydrogen era is organic hydride, operating through on-site production and active filling method. Major system components are designed in a 40-foot ISO standard container in order to have fast spreading supplying chain. A summary of system interconnection and system components can be seen in Figure 1.

![Figure 1: Process Schematic Diagram](image)

1.1. KEY COMPONENTS

1.1.1. HYDROGEN PRODUCTION

Centralize production is way more efficient for large scale production anyhow but in exchange, delivery is required to support the demand chain. As all known that transmission of compressed hydrogen requires complex composite tanks, which is one of the sectors that responsible to the high cost of hydrogen. Compression of hydrogen gas into these complex composite tanks not only consumes energy, but also depletes hydrogen during transmission. These losses are directly proportional to the distance transmitted. Hence, our design will address this problem by on-site production.

Current technology for on-site production is mostly referred to electrolysis and steam methane reforming (SMR). Electrolysis requires high maintenance for its electrode and electrolyte, additionally high dependency to rising water and electricity tariff. The cost for reforming is less varying but the temperature for reforming is about 800°C, which is a waste of enormous amount of energy. Although membrane reformer can drop the temperature to 500°C, but emission of carbon dioxide or carbon monoxide as a product of the reaction is in contrast with the ideology sustainable future.

Organic hydride has the same storage capacity as liquid hydrogen, at the same time, its high reversible conversion rate of organic hydride that satisfies all target values and
regulations presented by the U.S. Department of Energy (DOE) and U.S. Council for Automotive Research (USCAR). Furthermore, dehydrogenation of organic hydride is a chemical process where the Hydrogen-Carbon bonds (H-C) are cracked catalytically around 300°C at atmospheric pressure, generating only hydrogen and organic residue as product.

Since organic hydride is in liquid state even after dehydrogenation as well as its only product of hydrogen, a gas-liquid separator is in place of other purifying means, simplifying the system components. Still, a temperature swing adsorption (TSA) or polymer membrane can be used to ensure the purity of hydrogen outputs. In other way of thinking, organic hydride is very similar to SMR but has no carbon emission. The following specifications of reactor from Hrein Energy Inc. will be installed.

- Production rate: 120Nm³/h

1.1.2. COMPRESSION

Hydrogen is the lightest element ever found in universe, thus compression is needed for increasing the energy density of hydrogen fuel in practice. Ionic compression technology is leading the way to a next generation of hydrogen fuelling. Many seals and bearings were removed, reducing mechanical loss during compression, allowing energy conversion close to 100%. Linde AG has designed its own ionic compressor, which is ideal for efficient hydrogen compression due to its competitive advantages. A double line Linde ionic compressor which allows work interval shift and system redundancy with following specifications will be installed [1].

- Maximum operating pressure: 90 MPa
- Maximum delivery rate: 72 kg/h

1.1.3. STORAGE

Storage will need to be discussed in 2 parts: feedstock and pre-dispense buffer. Since our feedstock is organic hydride, high-dense wall for liquid or compressed hydrogen will be reduced to chemical tank. This reduces the high cost for storing facilities, yet two chemical tanks (20-foot, 24 kL) is needed for organic hydride and its residue. If decalin is chosen to be the organic hydride used, then the station will have a feedstock capacity of 1548 kg hydrogen.

On other hand, buffer sections are to use stored pressure and compressor capacity in the most cost-efficient manner, the station has a three-bank cascade system. It consists of three pressure storage banks in which the hydrogen for the fuelling is stored. Besides, an on-site hydrogen storage which can accommodate 48 hours shutdown is demanding preferred, a total of 280 kg of compressed hydrogen gas bulk storage at 45 MPa of hydrogen tanks is preferred as lower cost and risks, also well developed with respect to 80MPa or higher.
1.1.4. DISPENSING

Although 700 bar FCEVs are developing, early adopted communities with 350 bar are still exist. Thus, both dispensing pressure are available. The filling protocol starts by determining the initial vehicle pressure with a test pulse. Based on the test measurement and taking the ambient and hydrogen temperature into account, the final vehicle target pressure is calculated. The fuelling process starts with the equalization of the low-pressure bank, followed by the equalization of the medium-pressure and the high-pressure bank. The selection of the bank system is based on the hydrogen flow rate to the dispenser. After fuelling, the station automatically switches to recharge mode and fills the 85-MPa storage banks.

Fuelling is being carried out through Linde’s external 35/70-MPa hydrogen dispenser where all FCEVs are fuelled with pressure ramp rise control over the fuelling rate, according to SAE J 2601 specifications. The quantity of hydrogen dispensed is recorded using a mass flow meter with support for standard trading systems. The following are the key features of dispenser[1].

- Maximum flow rate: 60 g/s at 35 MPa, 60 g/s at 70 MPa
- Maximum delivery pressure: 43.9 MPa, 87.6 MPa
- Nozzle temperature: -40°C

1.1.5. SAFETY EQUIPMENT

Safety is the most concerned factor within all designs. Thus, safety equipments will be installed to prevent or lower the risk of all dangerous and/or system breakdown possibilities at hydrogen fuelling station. Safety equipment for the station includes backup power supply, automatic transfer switch, hydrogen flame detector, hydrogen leak detector, emergency shutdown switches, lighting control system, recording equipment and etc.

Lithium-ion battery is ideal for energy storage scheme by its high performances and low self discharge properties. High capacity and fast reaction time allows transition for peak hour power requirements or serving as backup power supply. Automatic transfer switch will be installed to swap source between power supplies while Emergency shutdown switches will be installed to terminate all operations instantly.

The diatomic molecule hydrogen gas has various chemical properties at standard temperature and pressure, i.e. colorless, odorless, tasteless, non-toxic, non-metallic and highly combustible. So, hydrogen leak and hydrogen flame detector will be installed to monitor all operation conditions of fuelling station. Moreover, all equipments or instruments are grounded to prevent ignition from static charge.

Lighting control system will be installed to improve the brightness within station and also achieving energy saving. As an unmanned station, video recording equipment will be installed for having direct vision within station to ensure public safety. On the other hand, fuelling nozzle has in-line breaking coupling to prevent negligence for FCEV owners in driving away with refueling nozzle attached. The station is also sensitive to shock in response to impact of vehicle crash or natural disaster (hurricane, tsunami, and earthquake). The electrical system and compressor/storage system are two compartments, separated by gas-tight wall. A pressure discharge vent is located in the roof of the gas compartment.
1.1.6. **HVAC**

Most of our design major components are integrated within a container; heat transfer and air ventilation must be under consideration. Some components may not have huge efficiency dependency on environment but a small range of thermostatic environment is recommended to avoid thermal expansion and contraction, granting optimum system operating environment and performance. Thus, air-conditioning device is needed. Regulated air from air-handling unit flows into all compartments via ductwork. No air circulation within compartments and air-handling unit whereas air circulation is between external environment. Besides, exhaust fan is installed at all compartments and cooling fan will be additional parts for power supply and dehydrogenation reactor.

1.1.7. **COMMUNICATIONS**

Base transceiver station (BTS) is a signal centralizes station that facilitates wireless communication between user equipment (UE) and a network. The network can be any of the wireless communication technologies or other wide area network (WAN) technology. All equipments and wireless communication systems will be connected to the BTS. The connection allows communication between internal and external system, achieving excellent compatibility and functionality of the system. System communicating key information includes refuelling needs, electrical outage, error messaging, user feedback, etc. Therefore, station is able to perform autonomous operation.

Through the BTS, remote operator can get the real time data of the station furthermore control all respective linked equipments and/or run diagnostic. All data is collected in a database, which is only accessible to respective administrator (site owner and supplier), for monitoring station performance including scheduling the best time period for maintenance.

1.2. **KEY FEATURES**

1.2.1. **TRANSPORTABILITY**

Our station has large hydrogen supplying capacity, which will accommodate a large footprint for station deployment. There is a main station unit and two chemical storage tanks for feedstock and residue. Hence, our station must designed to be easily transportable in compensate for the demerit of large footprint. Although auxiliaries are installed, the basic design of an ISO standard container with gooseneck tunnel and pockets are still available so that grabbers, cranes, forklifts and other commonly used conveyance can carry the work without other special tools. The overall dimensions and weight per unit container are within the standard ISO and/or shipment limitations.
1.2.2. MODULARITY

If there is an increase in demand, supplying capacity must also increase. Our station adopts active booster method, which has higher potential in system expanding than passive valve method because there are still spaces for production and compression components within the station container for parallel working.

Moreover, dispensing line can be added in a unit set of 20-foot container or 40-foot container, with a maximum of 2 and 4 dispensing line respectively, depending on available footprint and demand. These added dispenser units will be connected by on-ground piping which has extra insulation for weather proof and protected by speed hump cover. If more than 4 dispensing line are required, a stationary hydrogen fuelling station is recommended.

Our station has canopy extension which is supported by mechanical linkage, allowing deployment of canopy efficiently without any assemblage from singular parts. As we can see that all unit containers and interconnections are on-ground components, consequently, establishment and/or add-on installation process will be simplified by the modular features.

![Figure 2(a): Add-on Dispensing Island; 2(b): On-ground Piping Connection](image)

1.2.3. LOW COST

As mentioned before about the extraction of hydrogen from organic hydrides, it is also clear that the system components will be reduced as the whole system is being simplified. Hence, capital cost for system components is reduced in the first place. Secondly, organic hydride is in the form of liquid state at normal conditions, which is easy to be transported. No energy is needed for increasing storage capacity like liquid hydrogen (LH₂) as well as lower heating temperature than steam methane reforming. Hence, operation and maintenance cost is also reduced. Thirdly, the high hydrogen supply capacity per delivery allows lower hydrogen price from supplier. Furthermore, drop-in station is being integrated with existing fuelling station, allows waive of further estate rental. Of course, system components can also be leased or agreed with a lower down payment tolerance.

Organic hydride may seem to be pricy as a hydrogen carrier (chemical products) but since off-board recycling is required, the cost for organic hydride is borne by supplier in advance but shared throughout the whole period of services. As whole, the capital cost of a drop-in fueling station can be greatly reduced as most of the facilities other than the fueling station are being borne by suppliers/original equipment manufacturer (OEM), together with components reduction.
1.2.4. MASS PRODUCTION

Organic hydride is not a hydrogen production method, but an approach to store and transport hydrogen; of course, the technology in extracting hydrogen from organic hydride is slightly different. Therefore, all system after the production remains the same.

Canopy extension is an extra auxiliary to be compared with existing drop-in fuelling stations. Canopies are to provide premium shading with protection from the weather for FCEVs owners. The canopy is a mobile structure so that it is enclosed on the main container unit during transportation. These components especially mechanical linkage are actually commercially available which enable mass production in lines.

1.2.5. FOOTPRINT

![Design Footprint and Associated Driving Templates](image)

Figure 3: Design Footprint and Associated Driving Templates

1.2.6. COMPATIBILITY

This section is added for further description. Materials for the early market shouldn’t be treated as transition materials but upgrades of current system from petroleum to hydrogen. The most efficient and ideal way is to integrate ‘drop-in station’ with current fueling station in the future. Organic hydride has the same properties as gasoline (hydrocarbons), thus by integrating organic hydrides into conventional fueling system, system components may have big changes but the overall structure remains the same including miles of pipelines that were built. If transformation doesn’t include existing infrastructures, all the investment done in gas fueling system will then burn into ashes. In other words, new system functions as it originally was but in a new mode with more realistic approach in all aspects for long and short term vision.
1.2.7. APPEARANCE/ATMOSPHERE
2. **COST AND ECONOMIC ANALYSIS**

The economic analysis is divided into two subsections. The first section presents the calculation of capital cost and operating cost while the other describes scenario from selling price to return on investment (ROI). Fuelling station can be integrated with profitable convenient stores or other utilities but those are optional and far beyond our scope of discussion. A simple module would be clear and have better focus.

### 2.1. Capital Cost

The initial investment of the drop-in hydrogen fuelling station is summarized in table 1. Although we are able to get information upon specifications of components, but quotations for price are unavailable. Estimations were based on H2A Forecourt Assumption [2].

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydrogenation Reactor</td>
<td>1</td>
<td>200,000</td>
</tr>
<tr>
<td>Ionic Compressor + Chiller</td>
<td>1</td>
<td>280,000</td>
</tr>
<tr>
<td>Hydrogen Storage</td>
<td>1</td>
<td>229,040</td>
</tr>
<tr>
<td>Dispensing</td>
<td>1</td>
<td>44,800</td>
</tr>
<tr>
<td>Venting</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>Powering</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>Lighting</td>
<td>1</td>
<td>3,000</td>
</tr>
<tr>
<td>Piping</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>Safety and Control</td>
<td>1</td>
<td>30,000</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>1</td>
<td>5,000</td>
</tr>
<tr>
<td>Engineering Design</td>
<td>1</td>
<td>30,000</td>
</tr>
<tr>
<td>Deployment</td>
<td>1</td>
<td>5,000</td>
</tr>
<tr>
<td><strong>Total Investment Capital</strong></td>
<td></td>
<td><strong>856,840</strong></td>
</tr>
</tbody>
</table>

### 2.2. Operating Cost

Operating cost is another factor that determines the selling price of hydrogen which includes electricity, hydrogen supply, maintenance and insurance. There will be 2 scenarios, whereby one is the base demand (100 kg/day) where the other is high demand (200 kg/day).

<table>
<thead>
<tr>
<th>Component</th>
<th>Operation time (hr)</th>
<th>Electric power Usage (kWh)</th>
<th>Daily power Usage (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydrogenation Reactor</td>
<td>10</td>
<td>22.0</td>
<td>220</td>
</tr>
<tr>
<td>Compressor + Chiller</td>
<td>10</td>
<td>27.5</td>
<td>275</td>
</tr>
<tr>
<td>Dispenser</td>
<td>12</td>
<td>0.50</td>
<td>6</td>
</tr>
<tr>
<td>Safety Equipment</td>
<td>24</td>
<td>0.50</td>
<td>12</td>
</tr>
<tr>
<td>System Control</td>
<td>24</td>
<td>0.25</td>
<td>6</td>
</tr>
<tr>
<td>Lighting</td>
<td>8</td>
<td>1.50</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total Electric power usage</strong></td>
<td></td>
<td><strong>52.25</strong></td>
<td><strong>531</strong></td>
</tr>
</tbody>
</table>
The monthly energy requirements were estimated to be 15,570 kWh per month in the base demand case. Electricity is assumed to be 10.58 ct/kWh, which then accounts a total of $USD 56.18/mo; while for the high demand case, the electricity is expected to be a total of $USD 103.31/mo. There will be no water consumption throughout the operation.

The price for hydrogen from oil refining is $TWD 2.86/Nm³. One delivery tank carries 1548 kg of hydrogen, costs about $TWD 49,536. Since a substantial amount of hydrogen is being purchased at a time, a non-cumulative quantity discount of 5% is assumed, which is equivalent to $USD 1,553\(^a\). Considering the difference in living standards, a factor of 1.92\(^b\) from the ratio of price of McDonald is taken into account. Therefore, the hydrogen supply (hydrogenation, delivery and tank rental included) costs a total of $USD 3,500/tank H₂ or $USD 2.26/kg H₂.

In furtherance of giving solid promises to hydrogen users, maintenance and insurance are the safety barriers towards hydrogen future. An annual maintenance fee and insurance is assumed to be 2% and 10% of capital cost respectively.

The selling price will be calculated for two different demand scenarios to recover the initial investment and annual operating cost. Based on conservative principle, calculations of selling price do not include taxes and market growth. This will show the potential of growth more clearly. Hydrogen selling price will decrease if the demand increases.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Retail Price ($/kg)</th>
<th>ROI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Demand (100 kg/d)</td>
<td>8.10</td>
<td>10.23</td>
</tr>
<tr>
<td>High Demand (200 kg/d)</td>
<td>6.00</td>
<td>15.17</td>
</tr>
</tbody>
</table>

Number of stations establishment depends on the capital cost of a single station. If the capital cost is reduced per station, the number of establishment will increase. Since fuelling station has a limited speed of establishment, the reduction of cost will be linear.

Figure 4: Estimation of Reduced Cost of Fuelling Station

\(^a\) [www.xe.com](http://www.xe.com) exchange rate 1TWD=0.033USD

\(^b\) US Big Mac (USD 5); TW Big Mac (TWD 79)
Table 4: Reduced Cost of Fuelling Station

<table>
<thead>
<tr>
<th>Number of stations</th>
<th>Reactor</th>
<th>Compressor/Chiller</th>
<th>Hydrogen Storage</th>
<th>Dispensing</th>
<th>Venting</th>
<th>Powering</th>
<th>Lighting</th>
<th>Piping</th>
<th>Safety and Control</th>
<th>Auxiliaries</th>
<th>Engineering Design</th>
<th>Deployment</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-20</td>
<td>200,000(^{0%})</td>
<td>280,000(^{0%})</td>
<td>229,040(^{0%})</td>
<td>10,000(^{0%})</td>
<td>10,000(^{0%})</td>
<td>30,000(^{0%})</td>
<td>5,000(^{0%})</td>
<td>10,000(^{0%})</td>
<td>30,000(^{0%})</td>
<td>5,000(^{0%})</td>
<td>30,000(^{0%})</td>
<td>5,000(^{0%})</td>
<td>856,840</td>
</tr>
<tr>
<td>21-50</td>
<td>190,000(^{5%})</td>
<td>266,000(^{5%})</td>
<td>217,588(^{5%})</td>
<td>9,000(^{10%})</td>
<td>9,000(^{10%})</td>
<td>27,000(^{10%})</td>
<td>3,000(^{0%})</td>
<td>9,000(^{10%})</td>
<td>25,500(^{10%})</td>
<td>5,000(^{0%})</td>
<td>30,000(^{0%})</td>
<td>30,000(^{0%})</td>
<td>810,908</td>
</tr>
<tr>
<td>51-100</td>
<td>180,000(^{-10%})</td>
<td>252,000(^{-10%})</td>
<td>206,136(^{-10%})</td>
<td>8,500(^{15%})</td>
<td>8,500(^{15%})</td>
<td>25,500(^{15%})</td>
<td>3,000(^{-10%})</td>
<td>8,500(^{15%})</td>
<td>22,500(^{15%})</td>
<td>5,000(^{-10%})</td>
<td>25,500(^{15%})</td>
<td>25,500(^{15%})</td>
<td>768,716</td>
</tr>
<tr>
<td>101-300</td>
<td>170,000(^{-15%})</td>
<td>238,000(^{-15%})</td>
<td>194,684(^{-15%})</td>
<td>8,000(^{20%})</td>
<td>8,000(^{20%})</td>
<td>22,500(^{20%})</td>
<td>2,700(^{10%})</td>
<td>8,000(^{20%})</td>
<td>18,000(^{20%})</td>
<td>4,500(^{10%})</td>
<td>18,000(^{20%})</td>
<td>18,000(^{20%})</td>
<td>725,724</td>
</tr>
<tr>
<td>301-500</td>
<td>160,000(^{-20%})</td>
<td>224,000(^{-20%})</td>
<td>183,232(^{-20%})</td>
<td>7,500(^{25%})</td>
<td>7,500(^{25%})</td>
<td>18,000(^{25%})</td>
<td>2,550(^{15%})</td>
<td>7,500(^{25%})</td>
<td>15,000(^{25%})</td>
<td>4,250(^{15%})</td>
<td>15,000(^{25%})</td>
<td>15,000(^{25%})</td>
<td>683,132</td>
</tr>
</tbody>
</table>

An average of 5% reduction per quantity stage is achieved. Further cost reduction may be related to local policies.

3. **SAFETY ANALYSIS**

Various incident in the past prompts vigilance towards hydrogen energy; undeniable safety is the most concerned issue among the upcoming hydrogen era. Hence, a well done safety analysis is a must to establish safety perception towards public: research and study of current codes and standards, investigation on potential failure modes and effect analysis (FMEA), and adjustments and solutions towards safety issues.

3.1. **Codes and Standards**

Our system adopts a different approach, so codes regarding to organic hydride is also taken into account. Although some standards may cover similar topic, or even share the same codes, relevant codes which has the highest degree of requirements will be concerned. The listed codes were not the only ones but the important ones, as they are being the most referred ones such as Compress Gas Association (CGA), American Society of Mechanical Engineers (ASME), National Fire Protection Association (NFPA), Society of Automotive Engineers (SAE), International Code Council (ICC), American National Standard Institute (ANSI), International Organization for Standardization (ISO). Listed codes were up to date, ranged from 2007 to 2013.
### Table 5: List of Current Codes and Standards

<table>
<thead>
<tr>
<th>Association</th>
<th>Code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGA</td>
<td>G-5.3</td>
<td>Commodity Specification for Hydrogen</td>
</tr>
<tr>
<td>CGA</td>
<td>G-5.4</td>
<td>Standard for Hydrogen Piping Systems at Consumer Locations</td>
</tr>
<tr>
<td>CGA</td>
<td>G-5.5</td>
<td>Hydrogen Vent System</td>
</tr>
<tr>
<td>CGA</td>
<td>P-1</td>
<td>Safe Handling of Compressed Gases in Containers</td>
</tr>
<tr>
<td>CGA</td>
<td>S-1.3</td>
<td>Pressure Relief Device Standards-Part 3-Stationary Storage Containers for Compressed Gases</td>
</tr>
<tr>
<td>ASME</td>
<td>B31.12</td>
<td>Hydrogen Piping and Pipelines</td>
</tr>
<tr>
<td>ASME</td>
<td>B31.3</td>
<td>Process Piping</td>
</tr>
<tr>
<td>NFPA</td>
<td>2</td>
<td>Hydrogen Technologies Code</td>
</tr>
<tr>
<td>NFPA</td>
<td>30A</td>
<td>Code for Motor Fuel Dispensing Facilities and Repair Garages</td>
</tr>
<tr>
<td>NFPA</td>
<td>50A</td>
<td>Gaseous H2 at consumer sites</td>
</tr>
<tr>
<td>NFPA</td>
<td>52</td>
<td>Vehicular Gaseous Fuel Systems Code</td>
</tr>
<tr>
<td>NFPA</td>
<td>55</td>
<td>Compressed Gases and Cryogenic Fluids Code</td>
</tr>
<tr>
<td>NFPA</td>
<td>72</td>
<td>National Fire Alarm and Signaling Code</td>
</tr>
<tr>
<td>SAE</td>
<td>J2600</td>
<td>Compressed Hydrogen Surface Vehicle Fuelling Connection Devices</td>
</tr>
<tr>
<td>SAE</td>
<td>J2601</td>
<td>Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles</td>
</tr>
<tr>
<td>SAE</td>
<td>J2799</td>
<td>70 MPa Compressed Hydrogen Surface Vehicle Fuelling Connection Device and Optional Vehicle To Station Communications</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 7</td>
<td>Gaseous Hydrogen System</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 4</td>
<td>Emergency Plan and Preparedness</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 9</td>
<td>Fire Protection Systems</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 23</td>
<td>Motor Fuel-Dispensing Facilities and Repair Garages</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 53</td>
<td>Compressed Gases</td>
</tr>
<tr>
<td>ICC</td>
<td>IFC § 58</td>
<td>Flammable Gases and Flammable Cryogenic Fluids</td>
</tr>
<tr>
<td>ANSI/CSA</td>
<td>HGV 4</td>
<td>Fuel Dispensing for Hydrogen Gas Powered Vehicles</td>
</tr>
<tr>
<td>ISO</td>
<td>TS-20100</td>
<td>Gaseous hydrogen - Fuelling stations</td>
</tr>
<tr>
<td>ISO</td>
<td>15916</td>
<td>Basic Considerations for the Safety of Hydrogen Systems</td>
</tr>
<tr>
<td>ISO</td>
<td>17268</td>
<td>Gaseous Hydrogen Land Vehicle Refuelling Connection Devices</td>
</tr>
</tbody>
</table>

Majority of codes and standards were inaccessible by reason of under development or only available for purchase. There were no absolute codes and standards so far to ensure uniformity and facilitate deployment of hydrogen fuelling station as long as lack of safety data for hydrogen system. Hence, station design which conforms to newest standards is sufficient. However, having more safety measures rather than relying on existing codes is more reliable.

### 3.2. FAILURE MODE EFFECT ANALYSIS (FMEA)

Precaution is better than cure. An FMEA analysis helps to analyze all possible failure modes from related equipment, components and processes that may ensue with time. To avoid these potential hazards, response plans in tackling the failure modes must be prepared.
The FMEA was carried out as follows:

- Potential causes and effects of failure were listed
- The degree of severity was ranked as - 1: no effect; 10: critical effect
- The probability of occurrence was ranked as - 1: rarely; 10: frequently
- The solution is listed from precautions to responses

<table>
<thead>
<tr>
<th>Potential Failure Mode</th>
<th>Potential Cause of Failure</th>
<th>Potential Failure Effect</th>
<th>Degree of Severity</th>
<th>Probability of occurrence</th>
<th>Solution</th>
</tr>
</thead>
</table>
| Ignition               | Static discharge          | Fire/Explosion          | 10                 | 1                        | • Static Grounding  
                          |                           |                        |                    |                          | • Sensors Installation  
                          |                           |                        |                    |                          | • Fire suppression       |
| Hydrogen Leakage       | Mechanical failure        | Fire/Explosion          | 8                  | 4                        | • System Maintenance  
                          |                           |                        |                    |                          | • Sensors Installation  
                          |                           |                        |                    |                          | • Forced Venting         |
| Impact                 | Human error               | Fire/Explosion          | 5                  | 4                        | • Lighting            
                          |                           |                        |                    |                          | • Signage              
                          |                           |                        |                    |                          | • Restrict Distance     
                          |                           |                        |                    |                          | • Reinforced Wall       
                          |                           |                        |                    |                          | • Run Diagnostic        
                          |                           |                        |                    |                          | • System Shutdown       |
| Dispenser Piping Failure | Pressure relief valves on dispenser fails | Overpressure | 4 | 2 | • Maintenance  
                          |                           |                        |                    |                          | • Cut-off Dispensing    |
| Leakage of Organic Feeding | Mechanical failure | Toxicity | 6 | 3 | • System Maintenance  
                          | Inattentive assemble     |                        |                    |                          | • Cut-off Supply        |
| System Down            | System interface/communication failure | Filling process denied | 2 | 3 | • System Reboot  
                          |                           |                        |                    |                          | • System Shutdown       |
| Error Messaging        | Mechanical failure        | System disorder         | 4                  | 2                        | • System Redundancy    
                          |                           |                        |                    |                          | • System Maintenance    
                          |                           |                        |                    |                          | • Parts Replacement     |

Effects and causes of potential failure modes were determined through the FMEA process. Risk mitigation plan is used to minimize potential risks. Electrical power grid failure will caused the station out of electricity supply. The station design will be adding power backup system for emergency power failures. The power backup system can support the need of the station at least 4 hours of max operating capacity. Besides, natural disasters need to be considered such as hurricane; corrugation in wall as well small vents for pressure equalization.

These failure modes often occur in other hydrogen station. According to the failure mode of other hydrogen station, we have this analysis. Lack of studies of hydrogen system in organic hydride, leads to unknown potential risks but the safety of our station will keep improve as time goes by.
4. SITING

Hydrogen fuelling infrastructure has began to penetrate the boundaries to public with promises. As we can see that current developed stations are located in region near coast (as Figure 5), and we believed that it’s a major consequence from local policies, economic and infrastructures. To be practical, sufficient hydrogen source is needed to meet up the demands. Large amount of hydrogen can be produced as a by-product of oil refining. The by-product hydrogen can be captured and indirectly stored in some organic liquids. These hydrogen-rich organic liquids are recycled back-and-forth within refineries and stations (as Figure 6), thus also known as rechargeable organic hydride.

Figure 5: Distribution of Hydrogen Stations in U.S. [3]

Figure 6: Life-cycle of Organic Hydride
Several research and studies has been done and Louisiana suits best for the development of hydrogen with organic hydride. As mentioned that the sourcing is from oil refining, Louisiana ranked 5th in state capacity of refined oil, 24th by GDP, 44th by median household income, and of course other considerations; but it has the most well-developed pipelines in the U.S territory. In comparison, South Carolina ranked 27th by GDP and 42nd by median household income, which is quite similar to the economic power of Louisiana, supports that Louisiana is capable of, and has great potential in hydrogen development. Other than the recommended criteria of locales by the contest rules, if a middle ranked state in economic power is able to exploit the future era, then why not the higher ranked ones?

Promotion of new products or services is all about public exposure. In such a way, local population and traffic is the key for site selection. As a deduction, City of New Orleans, LA is the most favorable region for hydrogen development. New Orleans metropolitan area, the greatest population of all in Louisiana, would be a platform for hydrogen advertising. Its number of station also reveals its massive traffic volume.

Due to the huge time difference and other factors, contact with site owner is unavailable. But from the criteria developed, 4500 Chef Menteur Highway, U.S.90 New Orleans, LA 70126 is chosen to be the station establishing site. The chosen site has large available space for station establishment, in additional with increasing traffic flow on U.S. 90, provides favorable conditions for introducing the new hydrogen station to local community.

As detailed before, organic hydride is not a mainstream technology to be studied. Thus, no specific requirements, permits, certifications are directed to organic hydride. Yet, the minimum 5-foot setback distance of organic hydride storage is being complied. Underground electrical cable is available for station establishment.
The outcome of adopting organic hydride system is that distant hydrogen transmission will be put in practice. Not only Louisiana is tailored for this technology, because the overall hydrogen transportation is being reduced from hydrogen handling to conventional chemical handling. Thus, it is a feasible technology for long and short term vision which bears fruits.

5. OPERATION AND MAINTENANCE

The hydrogen fueling station will be operating from 0800 to 2000. With the installation of BTS, system is able to operate autonomously, together with remote operator monitoring. As previously mentioned, the real-time data from station can be distant monitored including run diagnostics and other remote access; process maintenance can be carried out in a more convenient and efficient way. Not to mention, with the help of current artificial intelligence operating system, system is able to debug by it itself or send error message to administrator upon precise defects. Maintenance will be done by trained personnel.

For on-site maintenance, replacing of damaged components will lower the shutdown period. Also, when supply stock reaches 20% of the total, supplier will be informed to refill on-site feedstock. Most importantly, the best time period for maintenance is suggested base on visitation of FCEVs users to improve customers’ refuelling experiences.

On-site maintenance will be conducted at least twice a year to minimum operational levels of equipment usage. Although regular maintenance keeps the performance at a certain level, but repair or replacement is preferred when relative equipment has reached its life expectancy.
6. ENVIRONMENTAL ANALYSIS

The lifestyle of humanity greatly depends on fossil resources. We acquire increasing volume of Green House Gases (GHGs) in exchange for large amount of energy; and hydrogen is no longer an alternative but a solution to global warming and environmental pollution in the view point of transportation sector. Although hydrogen technologies are still at their young age, its credit in sustainable future is undeniable. Hence, contribution of hydrogen towards sustainable future is discussed in three parts: resource, emission and noise.

6.1. RESOURCE ANALYSIS

Resource analysis examines the energy flow throughout the hydrogen fuelling system, knowing the efficiency of overall fuelling process. The efficiency can be calculated by using the equation below with respective parameters [5].

\[
\text{Efficiency} = \frac{\text{Energy of product}}{\text{Energy of input}}
\]

Electricity: 3.6 MJ/kWh
Energy of Gas: heating value + energy of pressure
Energy of pressure (E_{pf})

\[E_{pf} = R \times t_f \times \ln(p_f/p_0)\]

- \(R\) : Gas Constant (8.31510 Jmol\(^{-1}\)K\(^{-1}\))
- \(t_f\) : Temperature of Gas (°K)
- \(P_0\) : Atmospheric Pressure (101.325 kPa)
- \(P_1\) : Pressure of Gas (kPa)

Table 7: Life Expectancy of Components Used

<table>
<thead>
<tr>
<th>Item</th>
<th>Life expectancy (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydrogenation Reactor</td>
<td>10</td>
</tr>
<tr>
<td>Compressor + Chiller</td>
<td>10</td>
</tr>
<tr>
<td>Hydrogen Storage</td>
<td>10</td>
</tr>
<tr>
<td>Dispenser</td>
<td>10</td>
</tr>
<tr>
<td>Venting System</td>
<td>10</td>
</tr>
<tr>
<td>Powering System</td>
<td>10</td>
</tr>
<tr>
<td>Pipelines</td>
<td>10</td>
</tr>
<tr>
<td>Safety and Control Equipment</td>
<td>4</td>
</tr>
<tr>
<td>Lighting</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 8: Energy of Product Hydrogen

<table>
<thead>
<tr>
<th>Calculated Energy of H₂</th>
<th>LHV</th>
<th>HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 MPa gauge (298K)</td>
<td>135 MJ/kg</td>
<td>157 MJ/kg</td>
</tr>
<tr>
<td>35 MPa gauge (298K)</td>
<td>127 MJ/kg</td>
<td>149 MJ/kg</td>
</tr>
<tr>
<td>0 MPa gauge (298K)</td>
<td>120 MJ/kg</td>
<td>142 MJ/kg</td>
</tr>
</tbody>
</table>

Table 9: Energy Consumption per kg H₂

<table>
<thead>
<tr>
<th>Input</th>
<th>Consumption</th>
<th>Input Energy in MJ</th>
<th>LHV</th>
<th>HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehydrogenation</td>
<td>13.8 kg</td>
<td>193 MJ</td>
<td>193 MJ</td>
<td>210 MJ</td>
</tr>
<tr>
<td>Electricity</td>
<td>4.43 kWh</td>
<td>15.9 MJ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Calculated Energy of Product H₂: 135 MJ/kg (LHV), 157 MJ/kg (HHV) (70 MPa gauge, 298K)

Efficiency = 64.62 % (LHV) / 69.50 % (HHV)

The efficiency is quite noticeable as a drop-in hydrogen fuelling station. If a drop-in station has larger space for larger production capacity, then the efficiency will have a step in further improve. On the other hand, organic hydride is efficient in hydrogen storage when time is included. As we know that hydrogen is the smallest element in the universe. It is impossible for current science to physically store hydrogen in a cavity because the molecular structures of storage tanks have gaps which are larger than the molecular size of a hydrogen molecule. But when it comes to organic hydride, it’s a total different story as organic hydride bonds hydrogen chemically.

Figure 9: Comparison of Hydrogen Reduction Rate among Storage Technologies [6]
6.2. EMISSION ANALYSIS

GHGs, the leading substances to global warming include nitrogen oxide, sulphur compounds, carbon monoxide and countless others. Although it is clear that FCEVs have zero emissions, but during the overall process chain, GHGs are being emitted. Therefore, to what extent of GHGs is being reduced is interested.

The global warming potential (GWP) is being defined as a relative measurement for greenhouse gases that traps in the atmosphere. GWP normalized all gases emission to CO$_2$ emission. While other than CO$_2$, the global climate change in acidification is due to SO$_4$ emission.

![Figure 10: Comparison of Hydrogen Production Method in CO$_2$ Emission [7]](image1)

![Figure 11: Comparison of Hydrogen Production Method in SO$_4$ Emission [7]](image2)
Note that the bar chart shown above is unacceptable as organic hydride is not a hydrogen production method strictly speaking. Yet, comparison can be made on the point where extraction of hydrogen from organic hydride is needed. The low emission from organic hydride is a major consequence of it is a storage and transport technique, and the production really depends on the production method. In our case, hydrogen is a by-product produced at oil refinery, so the emission for hydrogen production does not account up until it is captured. From the data obtained, well-to-wheel emission can then be calculated by simply multiplying a FCEV efficiency factor with the CO₂ emission [8].

![Well to Wheel GHGs Emissions](image)

**Figure 12: Well to Wheels Analysis**

### 6.3. NOISE ANALYSIS

Continuous exposure to high noise level will cause hearing loss. The largest source of noise pollution is the compressor. It is recommended by the Environmental Protection Agency (EPA), that sound level should be maintained below 70 dB(A). From the technical datasheet given by Linde AG, the noise level of the ionic compressor is 65 dB(A). Considering the structure design of the drop-in fuelling station, the noise level will be lowered.

### 7. INTERFACE DESIGN / CUSTOMER EDUCATION

The drop-in hydrogen station doesn’t have any manpower, which a self-explanatory is needed for establishing connections with system and/or remote operators. Customers can have interaction with the system and/or remote operator via the touch screen display panel.

The refueling procedure is the following:
1. Welcome interface is shown.
2. Credit card will be inserted.
3. Nozzle is connected to the FCEV.
4. After stable connection, fuelling protocol will be activated.
5. Fuelling process is shown.
6. When filling is completed, nozzle will be put back to the dispenser.
7. As the dispenser valve is secured, payment will be completed.
8. The whole process is completed.
Fuelling Protocol Interface

Welcome to Hydrogen Refuelling Station

Insert Credit Card

Pick up nozzle and connect

Refuelling ...

01.50 kg
09.00 $

Completed

05.00 kg
30.00 $

Please take back your Credit Card & receipt

THANK

Put back the nozzle

Put back the nozzle

Online Service Interface

Calling ...

Annie

waiting for connection...

connected

online service

online service
8. ACKNOWLEDGEMENT

Y. C. Hsiao – Dept. of Electro-Optics and Energy Engineering, Mingdao Univ.
C. L. Lin – Dept. of Electro-Optics and Energy Engineering, Mingdao Univ.
J. J. Chiou – Dept. of Electro-Optics and Energy Engineering, Mingdao Univ.
Johannes Probst – Hydrogen Solutions, Linde AG

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