form from function:
a fuelling station

mark a. longo
20103726
prof. terri meyer-boake
august 25 2004

Contents:

Preface:

The following essay pertains to the first annual competition organized by the National Hydrogen Association of America, as a student element for their April 2004 National Conference in Los Angeles, California.

The scope of the competition was to design a Hydrogen Fuelling Station.

The Waterloo team comprised of a supervising chemical engineering faculty member, Dr. Michael Fowler, four engineering students and two architecture students. The team was lead by Erik Wilhelm, in association with Jamie Fairles, Sumit Kundu, Benjamin Shin, Aaron Holmes and myself.

The extensiveness of the competition covered technical design of the fuel generation, dispensing and storage processes, through to the aesthetic design of the components, station and site.
A business plan was also created to offer expansion opportunities stemming from our initial, chosen site in Rochester, New York.

My purpose on the competition team was to undertake a site visit with Aaron Holmes at the start of the project, organize all documents, record minutes of each online meeting, and construct a digital 3D model of the design. I had minimal involvement on the actual design aspect of the technical or architectural elements. Therefore this article attempts to outline that which I was able to observe, and in turn address the role tradition plays in the conception, design, and construction of fuelling stations.

Form from function: a fuelling station

Mark A. Longo
#20103726

Fuelling stations are elements of society which serve a functional purpose, and lack the need for any aesthetic consideration. Conceptually they are a means of attaining a source of energy which allows us to function daily in a fuel-dependant society. Physically they are a convenience placed on major arterial roads. Architecturally they are an eye sore. Tradition plays only a small role in the design of such an element of the societal landscape. The bare elements of this type include a pump, two nozzles, and a booth or building with a cash register. Anything extra such as a canopy, snacks, cigarettes, washrooms and a debit machine are at the discretion of the fuel company's designer, to provide convenience, and are modes of enhancing the consumer experience. Its form is contemporary and created out of the site conditions found there, function, construction, material and methods of manufacture. The fuelling station discards tradition, "it discards the ornamental façade, and develops its forms from [its function]."[i]
And as Gropius commented on the modern movement,

> "The forms of the New Architecture differ fundamentally…from those of old, they are…simply the inevitable, logical product of the intellectual, social and technical conditions of our age."[ii]

The construction, material and methods of manufacture are the main technical conditions which influence the station's design. Through modularity, prefabrication and a conservative material palette, the station could easily be replicated in various locations, depending on the site specifications and requirements. The fuelling station is simply a series of compartments, covered or uncovered, enclosed or not along its perimeter, and as primary and secondary forms of use. For example, the car wash is an add-on feature. The housing yard for the hydrogen reformer[iii] is only for principle fuelling locations, as a source of production for other satellite stations in a specified mile-radius. The canopy and pumps could be multiplied and placed in adjacency to each other, depending on the consumer demand at the site. Therefore, as seen in the plan appendixed to this article, the station can transform from a polygonal feature at the corner of Lake Ave. and Ridge Rd. to a simple trapezoidal shape at a satellite location, depending on the inherent needs of the area it serves.[iv]

The material palette is modest and includes precast concrete panels for the retail store, modular metal fence screens/sections for the reformer yard, roof and canopy cover, steel for the structural elements, and glass undoubtedly for the glazing. If there is any traditional echo of aesthetic sensibility, it exists in the precast concrete forms, which mirror Ron Tom's treatment of the poured concrete cladding for his design at Trent University in Peterborough, Ontario. Rough saw-cut lumber forms are used in the factory, to create the slight front-and-back alternating depth of the precast façade. Whether the choices were based on economy of material, ease of fabrication and assembly, or modularity, a common influence stems from contemporary observations of fuelling stations, factories, and institutions seen throughout New York State, and Ontario.

The placement of the station's components was driven by the required efficiency needed for the production, storage and dispensation processes. The competition required a minimum set of components for the station. The programmatic/intellectual arrangement, such as additions and modifications of the components were left to the discretion of the student design teams. Therefore, the engineering aspect provided the function of the building, in turn influencing the architectural form. On the production side, the natural gas is transformed by the reformer into hydrogen, then piped to the storage tanks and finally dispensed via the distribution pumps. The piping system links these various components.[v] Exposing this process as much as possible, guided the placement of the station's components, and the decisions whether to expose, enclose, elevate or bury certain elements.

The program of the station itself simply focuses on customer arrival, dispensation of the product, payments and departure. The treatment of these main components produces the raw form for the station, which then provides opportunity for a more detailed approach to its design. A carwash, a convenience section, washrooms, a canopy, etc. are methods for marketing, as well as improving the user experience. Though these elements are extraneous when it concerns the fundamental function of the station, they are elements observed, learned and borrowed from contemporary retail and station designs, as encountered in the Mobil petrol station on the opposite end of the intersection.[vi] Since the fuelling station is becoming more and more the one-stop-shop along any route of travel, these conveniences become a necessity for the economic success of the station. Thus they become an integral part of the programmatic influence on the building's form. And where economy is the underlying decision maker, ornament is discarded, and only raw form remains.

In addition, as the developer is concerned with minimizing cost, maximizing economy and profit, the architect and engineer have responsibilities to the environment and site. The technological enhancements are derived from this responsibility and lead to the inclusion environmentally sustainable elements such as safety sensors and a building management system (BMS). Guidance on safety sensors were given by experts in the field, whereas the BMS, overhangs, low-e glazing and stack ventilation were observed from projects learned in the scholastic setting, as well as those specifically undertaken by Mountain Equipment Co-op throughout Canada.

The technical and intellectual/programmatic aspects of the fuelling station only go so far as to describe the contemporary influences which inspired the decisions behind the building's design. What remains last for discussion in this article, but is considered first in any design process is the site – the social interaction of the building with the community. Rochester was chosen as the host city for our first station due to its central location in northern New York State. It would also act as the link between Canada's future Toronto hydrogen village, and the north-western United States via the fast ferry service. The vision was not only to create a fuelling station at a principle intersection, but rather expand the idea into a research, education and practical centre, the first of its kind in North America.

On a macro level, as Kodak was the symbol and support for the City of Rochester during its development and growth in the last Century, the Hydrogen Research and Fuelling Centre would have acted as the new attracting gem at the turn of this Century. The traffic volume was an influential factor in choosing the site, due to the site's location along the interstate Highway 96 and Lake Ave, an arterial road running from the lakefront ferry terminal straight into the downtown core of Rochester. Its location across the street from the Kodak plant, and on the property of a General Motors dealership would have reflected an old industry with a new one. Partnership with General Motors was important since their alternative fuel research labs are located just outside of Rochester, in Honeyone Falls.

On a physical and much more concentrated note, the site is mainly flat. The dealership was selling a section off to the city and State for realignment of the interstate highway at that intersection. In turn, an efficient entry and exit point were made for the station, taking shape from the momentum of the interstate highway's curve as it approached the intersection. Orientation of the main façade in a south-westerly placement addressed the corner of the intersection frontally.

As Vittorio Grigotti outlined in his address to the New York Architectural League in 1983:

> "The worst enemy of modern architecture is the idea of space considered solely in terms of its economic and technical exigencies indifferent to the ideas of the site."[vii]

Tradition only sets precedence for a fuelling station design with respect to maintaining efficient circulation, dispensation of fuel and customer service at the site as seen in contemporary fuelling stations. The task will remain the same: cars pull up on either side of a pump, the cars are filled, the customers pay, the cars leave. Grigotti outlined earnestly how the site can easily be ignored if all focus is placed on economic and technical requirements. As noted in this competition, all the deciding factors for choosing Lake Ave. and Interstate 96 were economic based. The concept was traditional, the only change attempted through this competition was to incorporate a new resource into the traditional routine. This building type of fuelling stations therefore, is set apart from all other architecture that Grigotti speaks about. It is part of an architectural type which manifests form through function; through its components based upon the most efficient sequence of events.

The aim in designing the fuelling station is to take the basic elements of its type, and to build upon that base through the conditions of circumstance which influence it, such as locality and specific building task. In the words of Louis Kahn, “What does the building want to be?” one can argue that the fuelling station in raw form, is a compartmentalized entity, organized according to open and closed spaces, clusters and groups, disciplined symmetrically and/or asymmetrically, all jumbled together due to intellectual, social and technical conditions of our age. The underlying theme of functional economy refers to the condition of how it can serve the people in the most efficient way possible, but at the same time provides the greatest return at the lowest cost. Through clarity, simplicity, and bare bone nature in construction, materiality and methods of manufacturing, fuelling stations do not appear beautiful from afar or even up close. Yet, its beauty lies within its function. A heart in a surgeon’s hand is grotesque at initial sight, but if the thought of its function is considered rather than the image that remains imprinted on our minds, in turn it is beautiful, for the simple fact that it is the entity which sustains human life. A fuelling station in its rawest form holds an important position in our society due to the dependency we have placed on our raw materials. It is the end means through which our main dependable resource is acquired. Without it, much would cease to function and so its type and form remain the same for as long as its function remains unchanged.

---

[i] Tschichold, Jan. "The New Typography." trans. Ruari McLean. California: University Press, 1995. Pg. 65.

[ii] Norberg-Schulz, Christian. "Genius Loci: Towards a Phenomenology of Architecture." Gabriele Borsano. New York: Rizzoli, 1980. Pg. 194.

[iii] a main component of the hydrogen production process, which converts natural gas into hydrogen.

[iv] see image 1, pg. 10

[v] see image 2, pg. 11

[vi] see image 3, pg 12

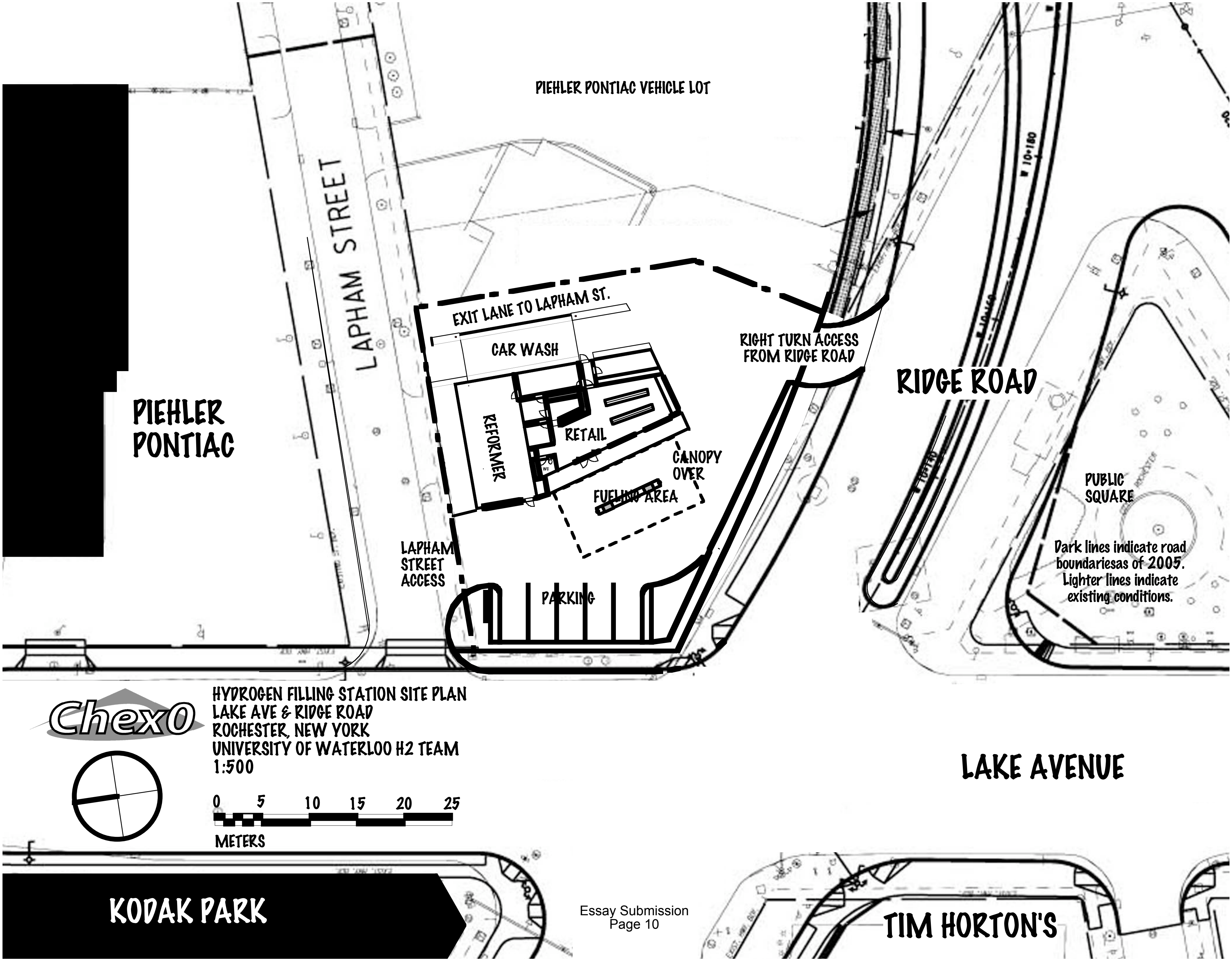
[vii] Frampton, Kenneth. "Modern Architecture: A Critical History." 3rd ed. New York: Thames and Hudson, 1997. Pg. 392

Bibliography

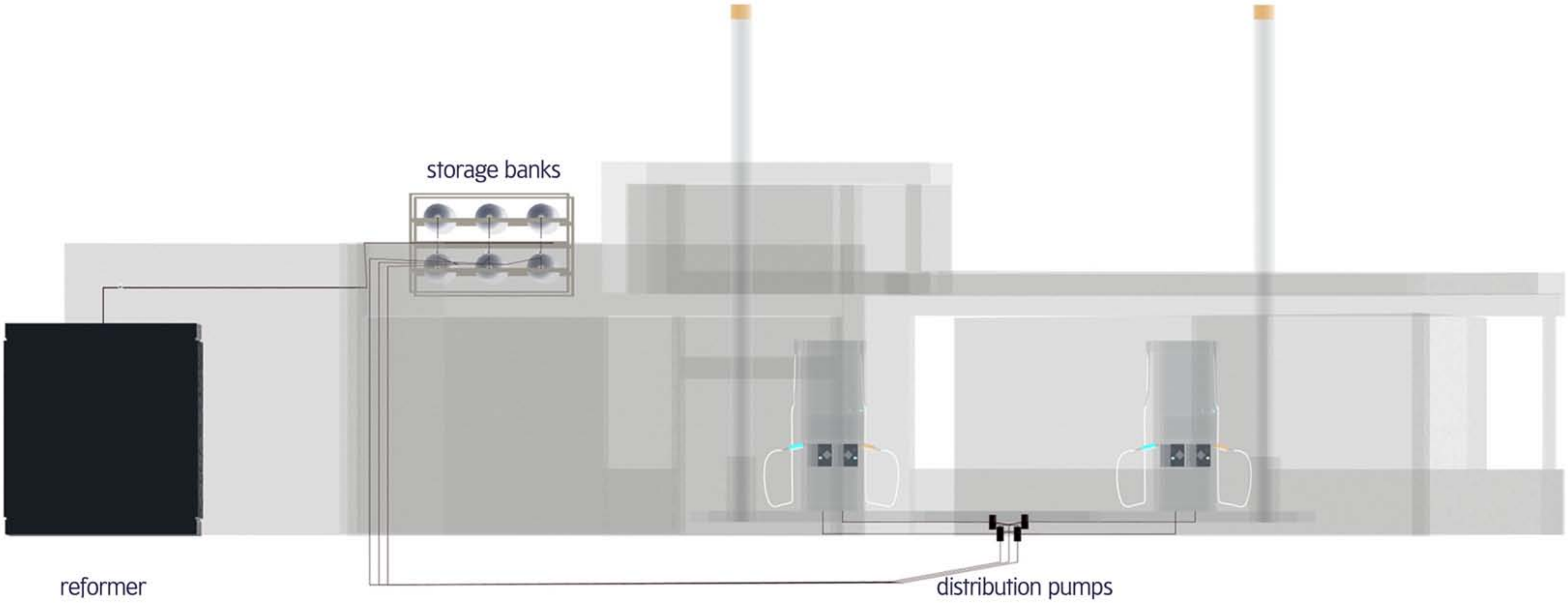
Frampton, Kenneth. "Modern Architecture: A Critical History." 3rd ed. New York: Thames and Hudson, 1997.

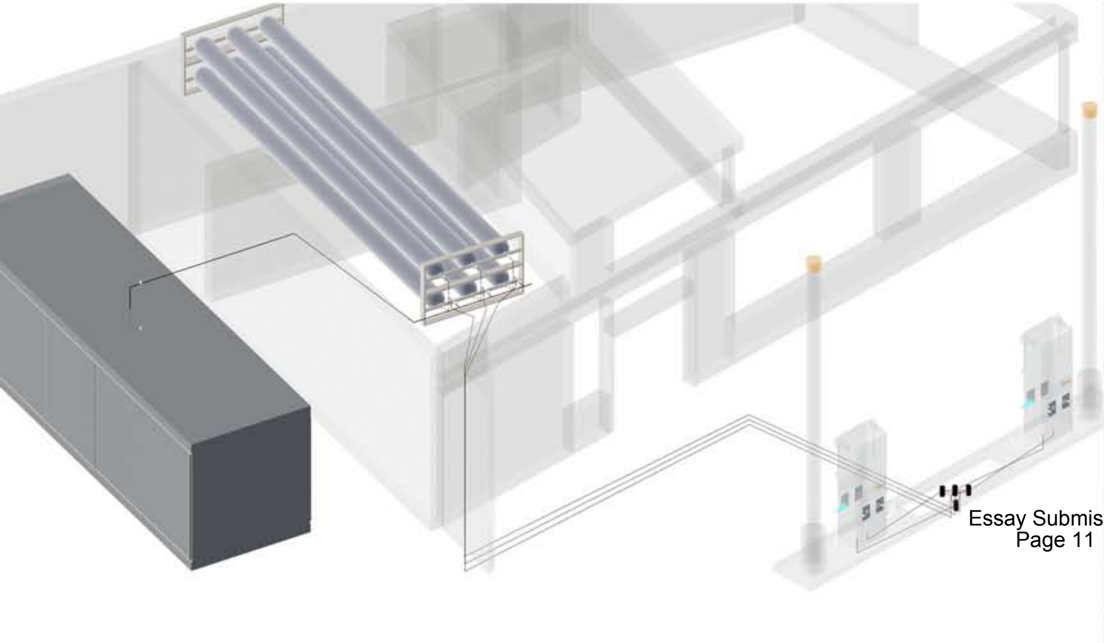
Norberg-Schulz, Christian. "Genius Loci: Towards a Phenomenology of Architecture." Gabriele Borsano. New York: Rizzoli, 1980.

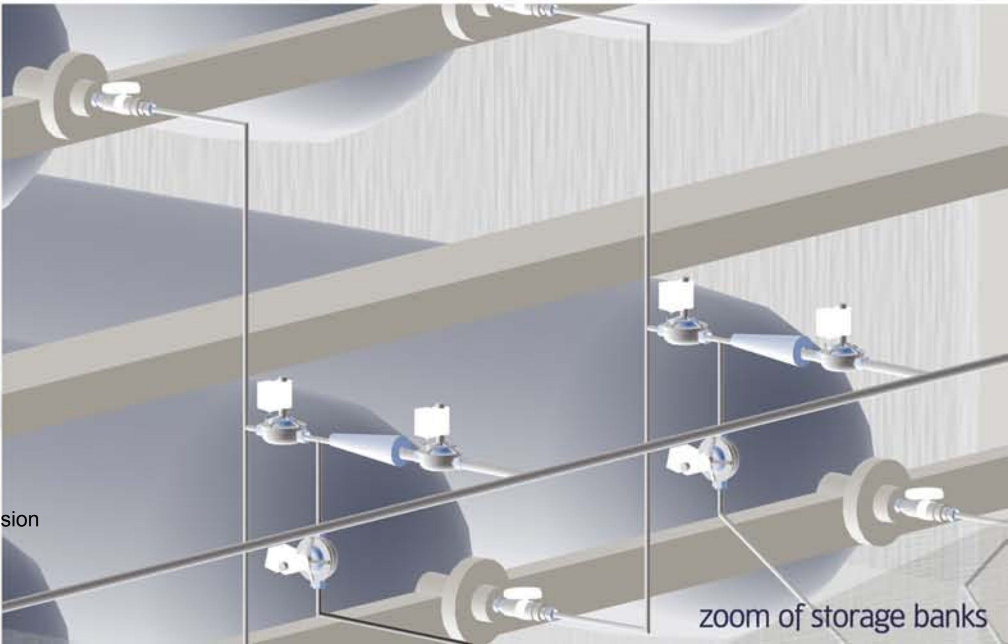
Tschichold, Jan. "The New Typography." trans. Ruari McLean. California: University Press, 1995.



HYDROGEN FILLING STATION SITE PLAN
LAKE AVE & RIDGE ROAD
ROCHESTER, NEW YORK
UNIVERSITY OF WATERLOO H2 TEAM
1:500


storage banks
reformer
distribution pumps




zoom of storage banks


Mobil


Soda
Doritos


Coffee
Bakery
Fountain
Bakery
Pepsi
ACCESSORIES

the site

the main intersection at Ridge Rd. and Lake Ave. in Rochester provided a location of one of the highest traffic areas in north-western New York.

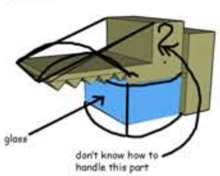
landmarking the site is the founding company of Rochester, Kodak. Sharing the location is a GM dealership complex.

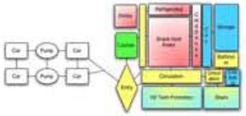
the vision

the business element of Rochester as an advantageous city was the fact that it would also act as a new transportation link between Canada and the US, through the introduction of a fast ferry service between Ontario's capital and the home of Kodak.

an added element was to complement Toronto's initiative in constructing a hydrogen village, by creating an icon of discussion and expansion in north-western new york.

the development





design discussion and development occurred strictly over the internet.

the group was presented with a unique challenge, due to each member's various location across the globe: from Bethany or Waterloo, Ontario, to Hamburg to Sydney. One member worked strictly out of internet cafes while backpacking asia and australasia.

TOLERANCES
DIMS OVER 36" : +/- 0.080"
DIMS 12" ~36" : +/- 0.040"
DIMS UNDER 12" : +/- 0.02"
HOLE POSITION : +/- 0.02"
ANGULAR DIMS : +/- 0.5°
UNLESS OTHERWISE STEATED

DRAWN ZMC DATE NOV05/02
APPROVED
CUSTOMER Praxair
THIRD ANGLE PROJECTION
UNITS IN
SCALE NA
DWG/NAME: H2 Disp–2H1L, Car/Bus Fill
DWG. NO.: P30013
REV. A
SHT. 1 OF 1
TORONTO, CANADA
FAX: 905 669 7581
E-MAIL: fuelingtech@fuelingtech.com

Energy Design Award Writeup

Hydrogen Filling Station Project description

Filling stations do not seem like a likely target for architects. Their bland practicality and numbing ubiquity make them and their dirty little secret glaringly invisible to public eyes.

It is hard, on that note, to imagine a more public architecture. It is possible to make a life for yourself in Toronto, for example, without ever visiting Toronto's City Hall. It is possible to live in Bilbao without visiting the Guggenheim. But It is nearly impossible to exist anywhere in urban North America, without making routine trips to the filling station.

Even though they are used by all, they barely register on the radar of public consciousness except as a place where they can gas up 'n go, preferably for a tenth of a cent lower than the one across the street.

Chex0 is different. Instead of existing unnoticed like every other gas station, it will command attention because of the change of mentality that allows it to exist. You see Chex0, which stands for "Canadian Hydrogen EXample Zero" is a Hydrogen filling station.

Its purpose is to build a bridge from oil to clean hydrogen. Currently, it is expensive to make Hydrogen in large quantities from renewable energy, however the problem is that without economies of scale, it will never get cheaper. We are addicted to the automobile and the oil that powers it, and without a change in our method of fueling them, we will succumb to the poison in our atmosphere as surely as smoking catches up with a smoker.

Addictions wouldn't be called addictions if they were easy to break. Same story with oil. As much as we tried to run the station on hydroelectricity and electrolysis (the generation of H2 from water-like the science experiment seen in many high schools), we could not do this with any measure of economic efficiency. The energy costs do this are still too high. With the looming democratization of energy which will be made possible through distributed electrical generation and the internet, hydrogen will be playing a major part in the future. The bridge to the future is a filling station slated for a site in Rochester.

Aside from not requiring leaky subterranean gasoline tanks, the station has several features which make it worth consideration for the Energy & Design award.

Heat gain:

Windows - are highly efficient, with a low emissivity coating and a low U-Value.

Sunshades - The horizontal sunshades on the south facing windows block unwanted sun during the summer and allow the sun to stream in during the winter. The east sun is blocked with a wall (the simplest shading device known). As for the west sun, it is more difficult to shade but the canopy blocks it during the summer afternoons, with the exception of about half an hour in the middle of the afternoon.

Stack effect ventilation - As heat builds up in the building cool air can be drawn in from low windows, and operable and electronically controlled clerestory windows allow for exhaust ventilation. They also serve double duty, daylighting the deeper public parts of the store.

The reformer which generates the hydrogen for the fueling station is located on the north side of the building. Though it generates a great deal of heat, it is naturally ventilated, which saves us the energy to mechanically cool it. A series of fixed louvres on the perimeter of the reformer compound, block view and access to the mechanical equipment, but does not restrict air flow. The excess heat from the reformer, will be captured via snaking heat recovery tubes along its exposed surface area, similar to an underground heat pump system, absorbing the heat via radiation, and transferring it to the car wash, and other building services.

During the winter, excess heat from the reformer will be used in a hot water radiant floor heat system, which will be supported by a small furnace which we hope we will not have to use. During the summer, the concrete's thermal mass will absorb some of the heat that would have gone into the room, and will release it back to the air through night flush cooling. In this way, we hope to avoid mechanical air conditioning all together. The exposed concrete flooring also eliminates the use of additional flooring treatments and finishes.

The green roof will help reduce heat gain in the summer, and will provide increased insulation values in the winter. It also reduces the impact of the heat-island effect caused by the the site treatment, which is unavoidably mostly paved.

We hope to avoid the need for mechanical air conditioning in summer, and make use of waste heat from the reformer to heat the building in the winter.

Lighting:

Sensors connected to a computerized building management system monitor not only the temperature, humidity and ventilation, but also the lighting levels. During the day, when the space is lit by the windows, the sensors keep track of the light levels, and the lights are turned off when they are not necessary, rather than leaving them on all day long, further reducing our energy consumption. Also, occupancy sensors which control the lights are installed in the office, storage, utility room, locker room and washrooms.

Materials:

Given the fact that the station would be located in place of an existing Jaguar dealership, an analysis would be completed prior to demolition, to determine how much of the original materials could be salvaged in the construction of the new building.

The site is designed based on the changes to Rochester's Lake Ave & Ridge Road intersection which will be made in 2005. This changes the site dimensions and road paths slightly, and only allow a right turn in off of Ridge Road traveling west. The rest of the access is from the Lake Avenue Side, and on exiting, you circle around behind the station, and past the car wash to return to the road.

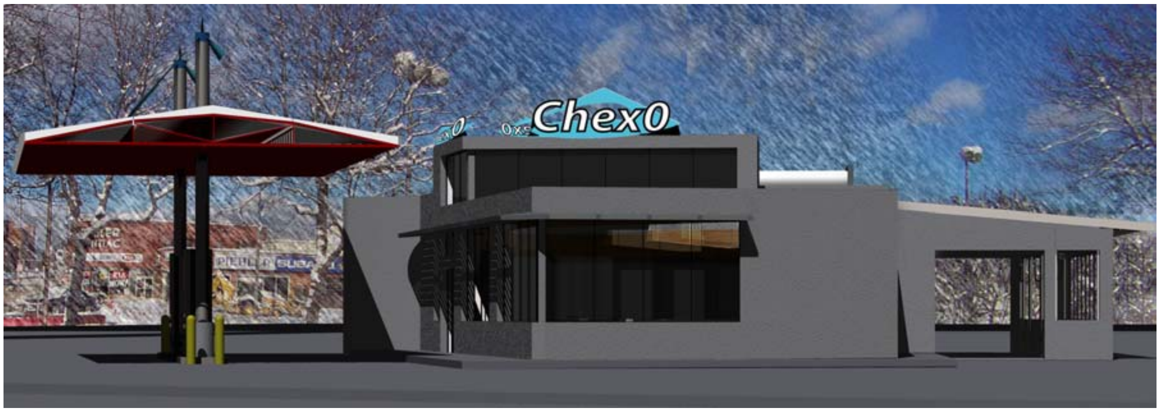
The design is expected to work in concert with Piehler Pontiac, a GM dealer who allowed us to use the site for our competition entry. Specifically, once GM begins selling Fuel Cell cars, having the station nearby would make it a plausible alternative to gasoline vehicles.

The green aspects of the design were driven by a desire to make the ubiquitous gas station both economically and environmentally efficient, while simultaneously providing a bright space for customers. Future plans of development for the station include incorporating a photo-voltaic system into the dispensing canopy and Piehler buildings, and the installation of a 'speedpass' system, where people can fill up their cars and go without having to go inside.

Tomorrows possibilities depend on today's vision. Given adequate support, a project such as this could be realized. Even if this particular Hydrogen Station in New York is not built, the research and design work that into making this competition entry will be useful to Dr. Fowler, who has expressed interest in building a Hydrogen Filling Station on campus as part of his fuel cell and alternative fuel research activities. Changes like this are possible. The world will kick its oil addiction, either by choice, or later, when we have no choice. The sooner we start the switch to a hydrogen fueled future, the less painful the switch will be.

Competition Entry

Hydrogen Fueling Station ´Chex0´for the 2004 National Hydrogen Association Student Competition



University of Waterloo
Waterloo, ON, Canada

Prepared By:
Jamie Fairles
Aaron Holmes
Sumit Kundu
Mark Longo
Benjamin Shin
Erik Wilhelm
Faculty advisor: Dr. Michael Fowler

Table of Contents

Appendices

List of Figures

List of Tables

1.0 Introduction

In the last decade, global trendsetters in industry, government and academia have been supporting the development of hydrogen-fuelled energy systems to replace the current fossil-fuel energy economy. The main reasons for the push to adopt hydrogen technologies are economic and environmental. Hydrogen energy systems using renewable energy sources delocalize global energy production and storage, creating energy self-sufficiencies where unprofitable energy import dependencies presently exist. This has many positive economic results, ranging from job creation to the establishment of a more sophisticated energy-trade economy. The environmental benefits of hydrogen energy technology are fully realized when renewable energy sources are used in the hydrogen production process. In this case, hydrogen can be used in a closed-loop system, generating no waste materials. The use of fossil fuels as an energy source for hydrogen production is an appropriate and economically viable transition technology, providing a bridge to future clean-energy technologies.

One of the most promising applications of hydrogen technologies is in the personal transportation sector. From the sheer volume of cars on today's roads, and the quantity of exhaust gasses that they produce, application of closed-loop energy systems to automobile technology promises vast environmental and economic benefits. The replacement of 50 standard automobiles with fuel cell powered cars will save over 383600 kg CO_2 per year. CO_2 is a greenhouse gas responsible for global warming, a natural phenomenon by which the earth's surface temperature increases. Through the influx of man-made greenhouse gasses such as CO_2 this natural process is accelerated, wreaking havoc on local ecosystems and weather patterns. The use of hydrogen as an energy vector in urban environments improves local air quality, and thus the general health of the population. Selling locally produced hydrogen to the transportation market will create jobs and stimulate local economic development.

A significant impediment to the widespread introduction of fuel cell-powered cars is the lack of a fuelling infrastructure. Without a sufficient quantity of hydrogen fuelling stations, car drivers will continue to buy gasoline-fuelled cars. It is a challenging "chicken and egg" type problem facing the proponents of hydrogen energy. One of the possible solutions is to design low-cost hydrogen refueling stations that can be built along major commuter and transport arteries. These stations would not only sell hydrogen, but also promote the safe, clean and efficient image that hydrogen should posses.

It is the objective of this report to propose a design for a near-term hydrogen refueling station that accommodates both current energy market, technical, and cost realities, while promoting the transition to a hydrogen economy.

2.0 Background

Innovative and effective solutions to the lack of a hydrogen-fueling infrastructure are being proposed by teams of students competing in a design competition run by the National Hydrogen Association (NHA). The report examines the technological, economic and social challenges facing hydrogen-fueling stations.

The University of Waterloo NHA Design Competition team consists of students from several disciplines. Engineering and architecture strengths are complimented by solid training in economic principles and environmental awareness. We are drawn together by a common passion for elegant design solutions and a clear vision of the tomorrow we wish to share with out children.

3.0 Rochester NY- Station Location

Important cities for the emerging hydrogen economy are cities that stand along major transportation arteries. Hydrogen fuelling infrastructure built in such cities will be a frontier for H_2-powered transportation that will spread across North America.

Rochester, New York, was chosen as the site for the hydrogen refueling station "Chex0". This was based on its proximity to a major transportation artery, the I-90, which runs from Boston to Buffalo and links the eastern US to Canada. It is also located in an area that is being developed for wind power, and receives some electrical energy from the hydro power plant at Niagara Falls. There are also smaller hydroelectric installations (1) in the area that could be used to generate electricity for the electrolysis of water into hydrogen and oxygen. Significant interest in hydrogen energy projects has already been shown in Rochester, including an October 2003 feasibility study by Deloitte and Touche (1). A fast-ferry between Rochester and Toronto is being implemented, linking two cities active in building up hydrogen infrastructure. The proximity to the GM hydrogen fuel cell research center in Honeyone Falls makes Rochester a good candidate for early hydrogen technology introduction. Rochester is also considered to be a mid-sized city, which simplifies scaling the design to suit other locations.

The Lake Avenue and Ridge Road intersection in Rochester, New York, was selected as the location for the "Chex0" hydrogen filling Station. It has a strong combination of attractive features, including a very high traffic volume of 63,750 cars per day (Average Annual Daily Traffic - 2001 study), location on the Ridge Road, leading to the fast-ferry entrance, and next to a GM dealership that intends to sell fuel cell cars in the near future. The land upon which the station would be built will be reconstructed in 2005, which coincides perfectly with the plans for a new station there.

4.0 Technical Design

The hydrogen refueling station design consists of four sub-systems: production, storage, distribution and safety. Several alternative technologies exist for the four major systems, each with its own strengths and weaknesses. The system options and design considerations are outlined in each of the following subsections.

4.1 Hydrogen production

Hydrogen production can either take place on-site, or in a centralized production facility. Centralized production makes economic sense when there is a great demand for hydrogen within a reasonable shipping distance by tanker truck or by pipeline. On-site production is economically viable during the initial phases of the transition to a hydrogen economy when hydrogen transit corridors are being established, and a minimum number of fuelling stations exist.

Hydrogen production can be accomplished thermochemically, by steam reforming of natural gas, chemically, by complex catalytic and biological reactions, or electrochemically by water electrolysis. For 2006 consumer retail hydrogen, the most technologically viable methods are either electrolysis or steam reforming. Catalytic and biological methods are still under experimental development and therefore not capable of large-scale production. Electrolysis is well coupled with renewable energy sources, particularly with hydro/wind electrical energy. It is decidedly energy-inefficient to produce electrolytic hydrogen from electricity generated by fossil fuel combustion. In this case, it is more efficient to use steam reforming to separate hydrogen from both methane and water. A disadvantage of steam reforming is that it produces CO_2 in an exhaust stream.

For the design outlined in this proposal, hydrogen production was chosen to occur on-site, using steam methane reforming technology. The main motivation for on-site production was that the competition request for proposal was for one station only, to be opened March 2006 (4). Selecting a centralized productions scheme within this time frame would require too much speculation on future market conditions to be economically viable. In order to justify the capital investment in a centralized production scheme, a request for proposal for more than one station in the region must exist. Based on an early cost comparison outlined in Table 4.1, the decision to use steam reforming to produce hydrogen for the station was made (please note that these numbers are not the final costs, they simply provide a costing approximation). This calculation assumes that the only difference between an electrolyzer and reformer system is the energy and capital costs. In practice, many major station components would depend on the system selected.

Table 4.1: Comparison of capital and operating costs for steam reforming and water electrolysis.[ ] Source: Rochester Gas & Electric, Hydrogenics Corporation

	Energy (USD/year)	**Total (USD/kg)**
Electrolyzer	1682083.52	5,55
Reformer	10674.56	1,6

The calculations made assume that the cost of energy will be reasonably constant over the next twenty-year period. According to the US Energy Information Administration office, this is a safe assumption for both natural gas and electricity (5). Without any changes in the price of energy over the next 20 years, hydrogen produced from natural gas should remain a more economically attractive source of hydrogen for the 20-year period discussed. The primary source for electricity in Monroe County is coal combustion, however 'green power' packages are available from the utility at premium prices. Calculations show that the use of grid electricity to produce the hydrogen from electrolysis in 2006 would not provide any economic, or environmental advantage.

The cost of global warming caused by the release of the greenhouse gas CO_2 is not factored into the figures discussed, but it was not overlooked in the decision making process. The choice of steam reforming for the station was justified by viewing it as a short-term solution to encourage rapid market acceptance of hydrogen. A station designed for the 2006 North American market based on renewable energy-powered water electrolysis would sell hydrogen at a price beyond the reach of many consumers. This would harm the long-term prospects of a renewable energy-based hydrogen economy, no matter how environmentally benign the station would be.

4.2 Hydrogen storage

There are many options for storing hydrogen. It can be stored as a cryogenic liquid, a compressed gas, or in a multitude of chemically bonded forms. Hydrogen liquefaction is a very energy-intensive process, requiring, in some cases, half of the energy content of the fuel for the liquefaction process. Compressed gas storage is less energy intensive; however it requires larger vessels than liquid storage. Hydrogen can be physio-chemically bonded to metals such as Mg-MH (magnesium metal-hydride), or converted into a storage compound such as sodium borohydrate. This method is rather expensive, and is better suited to vehicular storage.

For the "Chex0" station, high-pressure gaseous storage technology was chosen for its simplicity, cost-effectiveness, and wide availability. As per the RFP, hydrogen is delivered to the customers as a pressurized gas. On-site storage density is not a major concern, due to the ample lands afforded to the station. Considering these factors, the cheap, simple, compressed gas tank system is an attractive choice. Compressed gas is also the standard storage method for gaseous hydrogen in industry, making the selection of supplier of H_2 storage tanks relatively broad.

4.3 Hydrogen distribution

Distribution systems are highly dependent on the type of production and storage systems applied in the station, and on the form of the hydrogen being delivered to the customer. Cost, filling time, and filling nozzle-compatibility are the major factors to be considered.

After calculating that the maximum filling time allowed per vehicle during the peak period is 3 minutes for a single pump-single nozzle arrangement, it was decided to design for two pump heads, with two filling nozzles per head. With this arrangement four cars can fill simultaneously increasing the maximum filling times at the station to 12 minutes. Standard gasoline filling stations are designed for a shorter filling time, so customer satisfaction is assured.

4.4 Safety system

The safe operation of the fuelling station is of paramount concern. The public perception of the Hydrogen Economy will be governed by the safety of these early retail stations. Compressed hydrogen presents both flammability/explosion and pressure-burst danger. As a result, state-of-the-art fire detection and hydrogen sensors must be used to ensure safe operation of the station.

A full section of this report is dedicated to the safety system designed for this station.

4.5 Specific system components

The proposed hydrogen refueling station was designed to service 50 cars per day with a one-hour peak of 20 kg H_2 (roughly 7 cars). The number of cars that visit the station in any hour is crucial to the design and sizing of the reformer and storage system. The proposed customer distribution consists of a small peak early in the morning (representing those who fill up before going to work) with associated build-up and tail-off. Another small peak is seen at 12:00 PM with the largest peak at 5:00 PM. This type of distribution was modeled after the one used in a 1997 DOE report (7). A full bill of materials can be found in Appendix A.

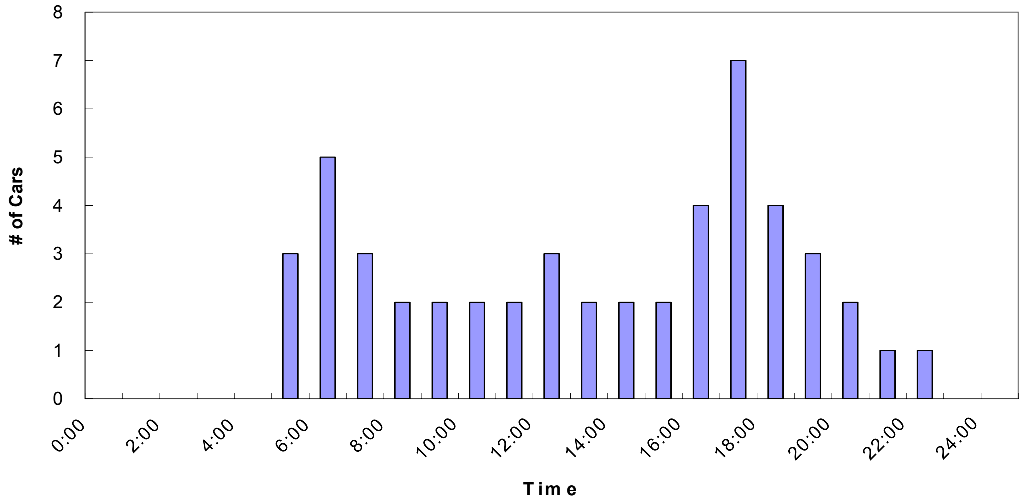


Figure 4.1: Customer distribution for the proposed refueling station, based on 50 cars total.

Figure 4.1 aided in the design of the filling algorithm, as well as serving as a guideline for the number of filling nozzles, pump heads and several other components.

All components in the design of the system are available either on the open market, or through contracts with established companies. All systems have been field-tested and most are already operating in various installations around the world. Please not that the standards to which the components adhere are all located in the Safety section.

4.6 CNG Reformer

A request for proposal for a natural gas reformer system was submitted to Hydrogenics Corporation. Hydrogenics offers a wide range of energy system solutions, and were able to meet the requested design requirements with pre-built and field tested systems. The key features of the reformer are:

- Fail-safe integrated safety system with remote status monitoring via a LAN or telephone connection
- Maximum hydrogen output pressure of 6000 psig
- Maximum hydrogen output rate of 2600 standard cubic feet per hour (6,25 kg per hour) of 99.9% pure hydrogen
- Required city gas feed of 1350 standard cubic feet per hour city gas
- Required municipal water feed of 6 US gallons per hour nominal, 10 USGPH maximum
- 5 year extended warranty coverage

An edited quote from Hydrogenics for the reformer containing a complete listing of the technical specifications can be found in Appendix B. Pricing has been removed fore reasons of confidentiality. The use of actual supplier quotes in this report guarantees the functionality of the technology, and therefore represents significant progress towards the achievement of a functional station.

The reformer would be ordered in October 2004. The lead time for the reformer is 12 months, which means it would be delivered October 2005, allowing 4 months installation and integration time.

4.7 Storage Tanks

CPI supplies the stations' compressed hydrogen storage tanks, using standard designs and materials. The storage system used in this station is composed of six tanks, each with a volume of 1038 L, which can hold 35 kg of H_2 at its design pressure of 6000 psi. The tanks are manifolded in pairs to make three larger hydrogen storage banks. An excerpt form the CP Industry quote can be found in Appendix B. The valves used in the storage tank to distribution system are all piston valves. They were selected over solenoid valves because they are actuated with compressed air and thus represent no significant fire risk. Detailed renderings of the connections between the tanks and the other components can be found in Appendix C. Further a full process flow diagram can be found in Appendix D.

There were three reasons for choosing multiple independent storage banks. First, when in use, a tank cannot be refilled by the reformer. Having three tanks allows two tanks to be used during a fill while the third accepts hydrogen from the reformer. Secondly, there is a requirement to fill to a pressure of 5000 psi. If only one tank was used for filling cars, once the tank pressure falls below 5000 psi it could no longer be used, and the remaining hydrogen in the tank becomes useless. With two tanks, when the first tank drops below 5000 psi it can still be used for a low pressure fill after which point the second tank can "top-off" the cars to the required 5000 psi. Finally, the use of multiple tanks also reduces the amount of dead hydrogen (hydrogen that is used to keep the pressure in the storage tanks high, but will otherwise not be used) onsite as well as improves reliability in the overall design.

The critical time of day for the storage tanks is the 5:00 PM to 7:00 PM peak time where there is almost a steady stream of cars. In the worst-case scenario, cars come one after another, leaving the high-pressure tank little chance to refill. Therefore there must be enough hydrogen in the tank to sustain a pressure above 5000 psi until the heavy rush is over.

In order to minimize the amount of hydrogen stored on site while still being able to meet the worst case filling scenario the following criteria were set for the operation of the station.

1) At least one of the tanks available for filling must have at pressure above 5000 psi.
2) When the storage pressure of a tank drops below 4000 psi, it goes offline to accept hydrogen from the reformer (this ensure that the tank can be refilled to base pressure in a reasonable amount of time).
3) From 5:00 to 7:00 PM storage refilling priority is given to the tank with the highest pressure

Appendix E outlines the control strategy of the tanks. Figure 4.2 illustrates the pressure in each bank over the period of one day. The actions taken in each step are identified in the Figure.

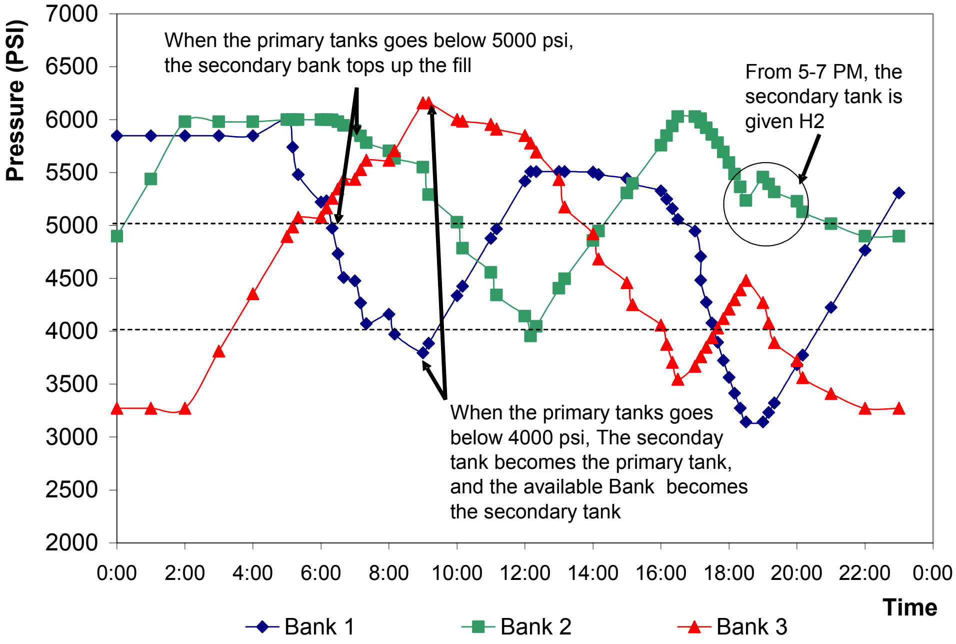


Figure 4.2: Daily variation of storage bank pressures

4.8 Distribution system

The distribution system chosen for the “Chex0” station is designed and manufactured by FTI of Concord, Ontario. The distribution system contains control electronics and algorithms, as well as the complete interface for the control of the filling tank actuators. Although these features are integrated into the distribution system proposed by FTI, an algorithm was developed in order to ensure that the system operates according to the performance specifications outlined in the contest RFP. Some of the features of the distribution system are highlighted below:

- Maximum meter flow rate of 20 kg per minute
- Maximum working pressure of 447 bar (6483 psi)
- Dual filling hoses
- Operating temperature ranges from –40 °F to +160 °F
- Electronic computer displaying sale volume and price, in backlit, intrinsically safe, displays.
- Fully grounded, preventing unsafe static build-up
- Vehicle communication and interfacing electronics match the California Fuel Cell Partnership Interface Specification

The distribution system has been tested and evaluated at Thousand Palms, California, among several other locations. The system is sold modularly, allowing for the selection of different components at future sites.

From the system operating data provided by FTI and the station system characteristics, a fill time of 0.9 minutes, or 54 seconds, for 3 kg of hydrogen was calculated. This figure was confirmed by the FTI, and represents a significant filling-time improvement over gasoline filling systems.

Customer billing is performed on a mass basis. FTI refueling pumps calculate the mass of hydrogen distributed to the customer, and communicate this information to a sales computer. Optional "electronic payment" may be easily integrated in the future.

4.9 Architectural Building Design

The fueling station is designed to be safe. The canopy design includes lightning rods on top of the supports to direct lightning-strikes away from the Hydrogen tanks. The canopy has vents at the apex of its ridge to keep Hydrogen from collecting there, as well as sensors to detect unsafe hydrogen levels. The hydrogen tanks are located on the roof, so that in the case of an accident such as a major leak or explosion, the hydrogen will disperse or burn upwards leaving the station and customers unharmed. The ceiling inside the building is slightly sloped towards the clerestory windows which open to allow natural exhaust of possibly accumulated hydrogen by the stack effect. Even when closed, a hydrogen sensor located in the trigger alarms before the hydrogen levels become dangerous.

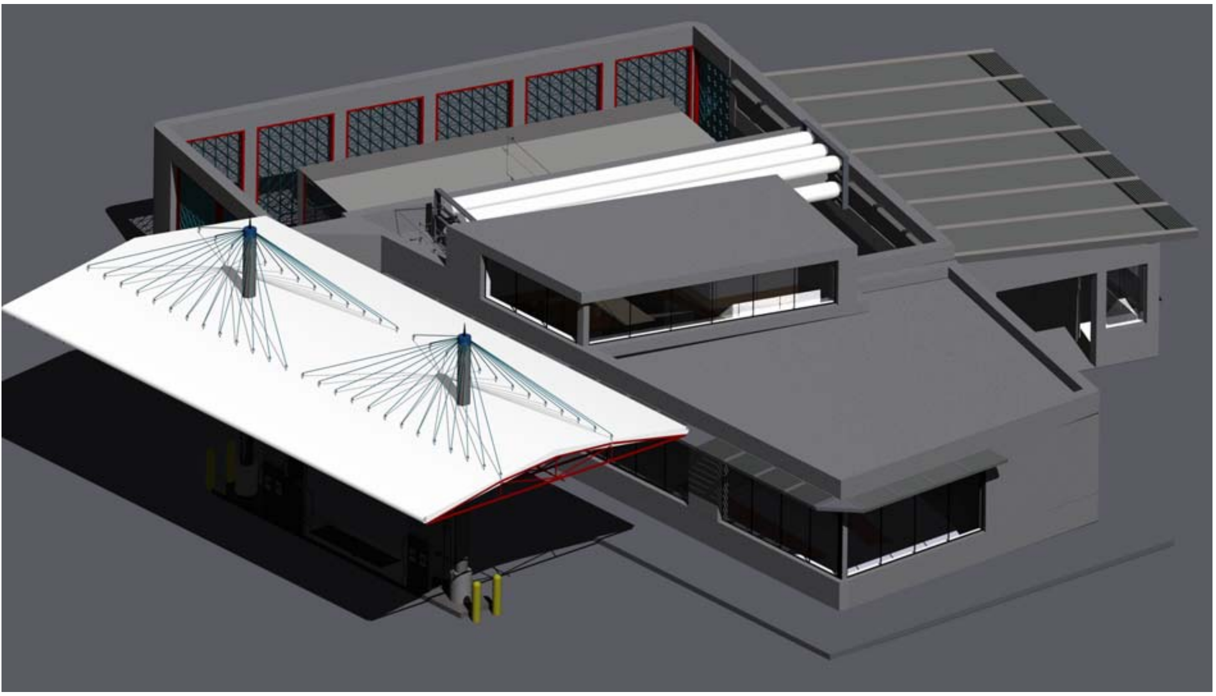
The building is organized so that customers have the option to either pay for their fill immeadiately and leave, or make purchases from the convenience store or peruse the hydrogen literature before continuing on their way. The shaded clerestory lights allow diffuse light in the summer and direct light in the winter, brightening up the station so that electric lights are only necessary at night. Clerk and office manager sight lines were designed to discourage theft, and a one-way mirror is installed in the cashier center. Detailed site and building plans can be found in Appendix F and G respectively. The site was selected by visiting Rochester to look for available locations in high traffic areas of the city.

The reformer is housed outside, out of direct sunlight for most of the day, in order to prevent overheating. The piping to the roof, and then from the roof to the tanks is as direct as possible to help eliminate potential leak points and minimize pumping losses. There are lightning rods on the roof of the station which protect the tanks from being struck by lightning.

The station has several modules that make it easily adaptable to other sites in New York and across the United States. The canopy is self supporting, and defines a four car filling area. If more capacity is required, another canopy can be easily added beside the first. The car wash is not integral to the station, and may be easily removed from the plan for an installation if site or economic circumstances do not favour it.

All of the components of the station structure are currently available on the open market. The lighting system is intrinsically safe, and is designed for operation in explosive-gas environments.

Renderings of the station are shown in Figures 4.3, 4.4 and 4.5.



.
Figure 4.3: Angled top view of station

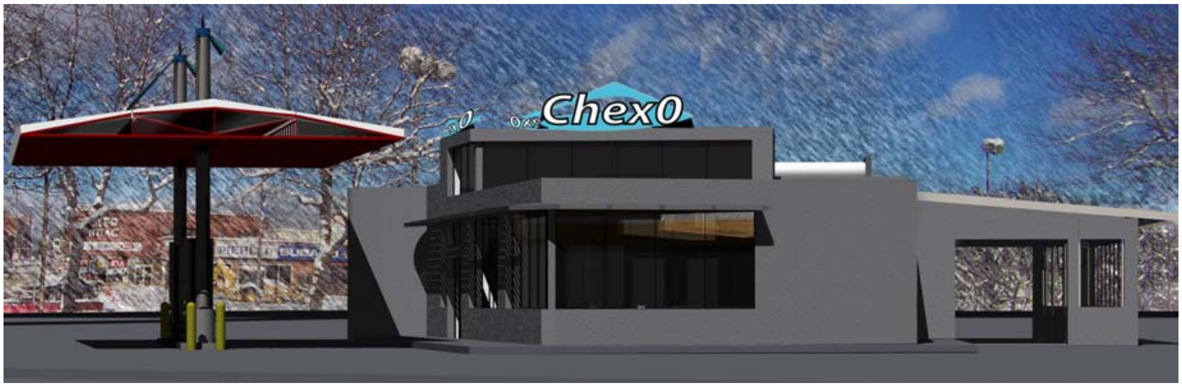


Figure E.2: Front view of station

Figure E.3: Angled street level view of station

5.0 Safety Analysis

Safe operation of the hydrogen fueling station is crucially important in establishing confidence in hydrogen as a fuel for the future, therefore safety in the design of the proposed hydrogen retail station was given careful consideration. The design of the station was assessed using a modified Hazop-type process which helped to identify risks, their overall hazard level, and to identify appropriate design strategies to mitigate them [9].

In order to perform a safety assessment on the station, it was separated into several different nodes as shown in Figure 5.1:

Node 1: Natural Gas Feed	Node 2: Natural Reformer	Node 3: Gas Storage
Node 6: Control System	Node 5: Piping	Node 4: Dispensing

Figure 5.1: The different nodes for analysis.

This section will outline the different safety codes and standards that were used in this station as well as specific hazards and their mitigation strategies.

5.1 Standards

Standards for the hydrogen fueling industry are still far from being complete. Some standards do exist, and those of close relatives such as natural gas can be used in certain situations as general guidelines. Wherever possible in the design of this station, existing standards were taken into account by the design team as well as the original equipment manufacturers. In most cases, manufacturers that adhered to the most current and appropriate safety standards supply the component systems that make up the station. This includes items such as the reformer, storage tanks, and dispensers. The components as well as the standards to which they were built can be found in Table 5.1 [10,11,12]:

Table 5.1: Code compliance of retail station equipment

Component	Specification
Reformer	ASME Certified to Process Pressure Piping: ASME B31.3 Electrical Location classified as: Class 1, Division 2, Groups B & D Electrical Supply: 575V, 60 Hz, 3 phase Vessels: ASME VIII Div 1, cyclic stress standards to BS5500 for 200,000 hours operation NFPA 50A: Standard for Gaseous Hydrogen Systems at Consumer Sites NFPA 54: National Fuel Gas Code CSA B-51 part 2, NGV2-2000: Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers

Storage	ASME UPV Code Section VIII, Division 1, Appendix 22, Safety Factor 3:1 for dry gas, non-corrosive service. Design temperature -20 °F to +200 °F. Vessel material is SA372 Grade J Class 70.
Dispenser	NEC for Class 1, Division 2, Group B Hazardous Location ASME B31.3

The planning process will follow a standard construction permitting and licensing process. In addition an 'environmental impact assessment' will be conducted which will include public meetings and information sessions. Construction, pressure vessel, and electrical advisors, as well as the fire inspector will be involved throughout the final design and licensing process. The reformer will have all appropriate air permitting and emission monitoring provisions. This analysis will includes consideration of low potential 'catastrophic' risks such as security (e.g. vandalism, sabotage, terrorist activities, explosives) as well as large vehicle collisions.

The overall design of the station was done consulting the Canadian National Fire Code, which is consistent with American codes. Special attention was paid to the sections regarding chemical reactors. By locating the station components outdoors the station conforms to NFPA 50A siting conditions. The materials of construction will be chosen such that relevant sections are made of non-flammable material. Some of the other important standards that future design iterations would include are listed below [13]:

ASME Boiler and Pressure Vessel Code (BPVC)
ASME B31.3 (2002) Process Piping
CGA C-7 (2000) Guide to Preparation of Precautionary Labeling and Marking of Compressed Gas Containers
CGA G-5 (2002) Hydrogen Physical Properties,
CGA G-5.4 (2001) Standard for Hydrogen Piping Systems at Consumer Locations ,
CGA G-5.5 (1996) Hydrogen Vent Systems ,
CGA S-1.1 (1994) Pressure Relief Device Standards-Part 1-Cylinders for Compressed Gases ,
CGA S-1.3 (1995) Pressure Relief Device Standards-Part 3-Stationary Storage Containers for Compressed Gases ,
ANSI/CSA NGV2 (2000) Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers ,
DOTn 49 CFR, Parts 171-180 Regulations for Transportation Equipment and the Transport of Hazardous Materials ,
2003 International Building Code (IBC) ,
2003 ICC Electrical Code™ (ICC EC),
2003 International Fire Code (IFC) ,
2003 International Fuel Gas Code (IFGC) ,
2003 International Mechanical Code (IMC) ,
2003 International Residential Code (IRC) ,
2002 National Electric Code (NFPA 70) ,
2003 NFPA 30A – Motor Fuel-Dispensing Facilities and Repair Garages ,
1999 NFPA 50A – Gaseous Hydrogen Systems at Consumer Sites,
2002 NFPA 52 – Compressed Natural Gas (CNG) Vehicular Fuel Systems ,
2002 NFPA 54 - National Fuel Gas Code Natural Gas Systems ,
2003 NFPA 5000 Building Construction and Safety Code

5.2 Hazardous Operation (Hazop) Analysis

A hazop analysis was done on each of the identified nodes. Table 5.2 summarizes some of the hazards and their implications as well as overall hazard.

Table 5.2: Modified Hazop analysis of proposed hydrogen retail station

Deviation	Failure Mode	Result	Action	S	P	H
No Power	Power Failure	Control systems fail, safety compromised	Fail to a safe position	3	2	B
No Hydrogen in the tanks	Leak in the storage tanks	Fire/explosion hazard	Leak detection, maintenance and inspection program, IR fire detectors, remove all ignition sources, use appropriate seals and gaskets	1	3	C
	Leak in the Piping			1	1	D
No Dispenser	Car has Rammed into it	Ignition of hydrogen	Barriers and curbs, dispensers with automatic isolation. ERAP.	1	4	A
No Dispenser Hose	Car has driven away with it.	May cause a hydrogen leak	Use hoses that are detatchable, customer/employee training , clear instructions ERAP.	4	4	A
More pressure in the tanks (past 6000 psi)	Due to heating in the sun	May go past the design pressure. Cause stresses on tank, may cause leaks	Pressure relief valves, Ensure that the tanks can handle a wide range of pressures with some over design Have a good maintenance and inspection program	2	2	C
Static Electricity	Movement of gasses and friction against pipes and such Lightning	May build up enough voltage to cause the hydrogen to ignite.	Ensure that the car and dispensers (as well as other equipment) are grounded properly (through the nozzle), use a lightning rod, ERAP.	1	2	D
Less mass flow to the car	Leak in the piping	Fire/explosion hazard	Have sufficient leak detection, Strong maintenance and inspection program, IR fire detectors, remove ignition sources	1	1	D
	Hose is not hooked up properly	H2 leak , Fire/explosion hazard	Customer Training, Software control, unique Nozzle design	2	1	D
Station Collapses	Act of God (e.g. Earthquake)	Compromised station integrity, leaks, fire/explosion hazard	ERAP, Isolation of all systems, improved station construction	1	4	A
S = Severity, P = probability (Scale 1 – 4, very – not very), H = Hazard (A – D, Acceptable risk – Unacceptable Risk)						

Three broad areas of risk from Table 5.2 are identified as being particularly significant. They can be put in the following categories in order of decreasing risk.

1. Customer error resulting in accidents (all nodes)
2. Loss of integrity of system compounds, resulting in leaks and fires (piping node)
3. Ignition from static, lightning, and stray currents

Other failure modes include

4. Over pressure of system lines and vessels (including onboard storage)
5. Loss of power
6. Corrosion of the storage tanks (resulting in loss of integrity)
7. Reformer meltdown
8. Acts of God

5.3 Customer Error

Customer will be a major source of hazard, because this error includes a wide variety of failures. Such failures include accidents between customer vehicles and the station, improper use of the station equipment when refueling, and filling leaking or faulty vehicle storage tanks. Though no one deviation caused by customer error has a very high hazard rating, the shear number of incidents that can be caused by customers warrants this error to be ranked as the highest hazard.

In order to prevent customers from hitting any of the components, barriers have been put in place around the dispensers (NFPA 50A, 5000). The design of the station also follows a natural flow that resembles a normal gas station. The reformer and the storage tanks have been located away from traffic zones. The reformer is located in a walled enclosure and the storage tanks are located on a roof section accessible only to employees and inspectors. Dispensing procedures should be composed in accordance with NFPA 52 [14]. These include items such as prohibiting smoking on site as well as filling a vehicle that is experiencing leaks. Informing the customer of, and enforcing the rules is the duty of well-placed signs and station employees.

Immediately following the station opening, the customer may not completely know how to use the equipment. It is the intention that the station be self-service, therefore the risk that the customer may use the equipment improperly exists. The FTI hydrogen dispensers are able to communicate with the fuel cell vehicles. As such, the dispenser will not fill the car unless the car is completely ready. Filling of a running car will be locked out by control electronics. Nevertheless, for the first year of station operation, as well as whenever called upon, special-duty station employees will be required to train drivers on how to use the station filling equipment. These additional employees are part of the education and awareness program. The use of additional special-duty employees at the station helps to educate the public as well as trains an new workforce for future stations.

In the case of an accident, emergency response action plan (ERAP) are in place to ensure that the situation can be dealt with. The document will touch on the following subjects [14]:

- How to identify the emergency
- What actions need to be taken
- Who to notify
- Evacuation procedures
- Safety systems

5.4 Loss of integrity resulting in accidents

In addition to customer errors that can result in accidents, there is also the regular usage wear on the station that will eventually result in hydrogen leaks. This is especially important in the system piping. It runs overall throughout the station, thus has the highest probability of being near an ignition source.

There are several ways to prevent and detect any integrity problems in the system. Prevention can be effectively accomplished with regular maintenance. The station should be checked for leaks (ASME B31.3) and signs of wear by employees, as well as by professionals as required by the state laws and codes. Items to be inspected will include all piping, storage containers, hoses, pressure relief devices, vent systems, as well as the safety system. Inspection should include weekly sweeps of the piping with portable combustible gas sensors while at the same time completing a visual inspection of the piping. All piping systems were designed to be fully accessible. Fire prevention is also accomplished by removing all sources of ignition from sensitive areas (using intrinsically safe equipment).

A state-of-the-art detection system will alert employees and the necessary ERS services of any leaks or fires. This is accomplished by both combustible gas detectors (NFPA 50A), as well as IR fire detectors located throughout the station. The sensors status is continuously monitored by the overall control system. Special attention was paid to the reformer area and the pump heads. The control system both alerts the employee of any problems, as well as to automatically shuts off and isolates affected sections of the station. Manual shutoff is also possible. In either case, the employees will refer to the ERP.

5.5 Ignition from static, lightning, and stray currents

Static electricity and lightning pose significant dangers to the hydrogen refueling station. This is a result of the low ignition energy of hydrogen. The static electricity that can build up when hydrogen flows through a pipe can cause the ignition of the hydrogen. Lightning poses a similar risk. One publication indicated that lightning could ignite hydrogen from several miles away. This is a significant hazard because there is a high probability of many lightning storms during the operation of this station. There are existing stations that do not fill busses when there is a risk of lightning. This is not an option for a functioning hydrogen economy, because people will definitely need to fill cars on rainy days. The risk of lightning needs to be managed and not avoided. The natural gas industry and traditional gas stations have successfully tackled this issue.

In the specific case of lightning and static electricity issues, all cars as well as the entire system will be well grounded according to NFPA 50A s.2-4.6 and API RP 2003 as well as other applicable codes. The station also includes a lightning arrestor (rod) to further reduce risk of a build-up of voltage that could lead to ignition. The distribution system from FTI contains a build-in static dissipation and grounding system.

5.6 Other failure modes

Accidents involving overpressure are mitigated using pressure transducers and pressure release valves in key locations. In case of system power failure, the power-off position of any actuators, valves, and other devices is in their safest position. Most importantly, feed to the reformer will be stopped and the storage tanks will be isolated if a power failure occurs. The reformer shutdown is managed internally by the Hydrogenics control systems. Management of corrosion in the storage tanks resulting from water in the hydrogen feed as well as hydrogen embrittlement will be done through a rigorous inspection and maintenance program. To deal with acts of God as well as random acts of terrorism and vandalism, the station operators will rely on the ERP and the intrinsic shutdown and isolation controls.

5.7 General safety

Other practices to be observed during the operation of this station include [14]:

- Working with local authorities and experts to advise on the station risks
- Extensive training of personnel in the safe operation and maintenance of the station
- Provision of all necessary safety gear to employees and public, including fire extinguishers and emergency exits
- No automobile maintenance activities are permitted on site (except for minor activities such as checking tire pressure)

5.8 Summary

Operating the proposed station in a safe manner is very important. By following the codes and standards that are available, as well as the codes that will be released in 2006, the station will operate as safely as possible. This section has demonstrated that the proposed station design will be able to avoid or detect and mitigate the most serious risks posed. This will be accomplished through constant attention to safety in design, inspection, as well as emergency response and maintenance programs.

6.0 Economic Analysis

6.1 Introduction

The economic analysis of the hydrogen retail station is very important to the overall promotion of hydrogen fuel as an alternative to gasoline. It is important for retail stations to be economically viable while at the same time have a hydrogen selling price that is competitive with gasoline. Until hydrogen fuel cells become widely commercialized, however, early adopters of fuel cell vehicles will have to pay more per kilometer driven.

In order to perform an economic analysis, the station was approximated as a small chemical plant and the appropriate costing procedures made. The procedure in question was from M.S Peters & K.D. Timmerhaus, Plant Design and Economic for Chemical Engineers [15]. This section will explain the different aspects of the economic analysis including the various assumptions that were taken. This analysis is an order of magnitude analysis, typical of the analysis performed to determine feasibility early in the design. The true cost of the station is expected to fall between +/- 30% of the cost reported here, as is typical in such an analysis.

The price of hydrogen is determined using an after tax internal rate of return (ROR) of 10% after 10 years. In order to cost the hydrogen it was assumed that construction of the station would take place in 2005 and the station would begin generating revenue in 2006.

6.2 Equipment Costing

The three major pieces of equipment needed to construct the station, the natural gas reformer, the hydrogen storage tanks, and the distribution system were tendered to suppliers for detailed quotations. In order to protect confidentiality, the exact cost of the individual components cannot be disclosed. Table 6.1 provides the basic information of the equipment cost [10,11,12]. These costs formed the basis of the overall economics of the station.

Table 6.1: General equipment information

Equipment	Supplier	Location
Natural Gas Reformer	Hydrogenics	Installed cost Rochester NY
Storage Tank (per unit)	CP Industries	FOB PA USA
Hydrogen Dispenser (Two hoses, plus nozzles)	Fueling Technologies Inc	FOB Toronto Canada

Note that the cost of smaller items such as the safety and control equipment are not included as a major cost item, however their costs are available in the bill of materials. Their costs are included in the direct costs. In order to obtain the installed costs of the storage tanks and dispensers in Rochester NY, delivery and installation factors from Peters& Timmerhaus [15] were applied to the numbers as shown in Table 6.2.

Table 6.2: Installed equipment cost

Equipment	Delivery Factor	Installation Factor	Installed Cost, 2004 (USD)
Natural Gas Reformer	1	1	XXXX
Storage Tanks (3)	1.1	1.4	XXXX
Hydrogen Dispenser (2)	1.1	1.3	XXXX
Total Purchased Equipment Costs			1,963,200

The installation factors assume that the storage tanks can be approximated as metal tanks and the dispenser has similar installation costs as a mixer. Note that the above number does not account for inflation between 2004 and 2005 (the year when the station would be constructed). Inflation over one year is insignificant in this order of magnitude estimate.

6.3 Capital Costing

Table 6.3 shows the breakdown of capital costing for the refueling station. The literature values for each of the components were taken from Peters& Timmerhaus [15].

Table 6.3: Breakdown of total capital costs for the station

Component	**Literature guidelines (% of FCI)**	**Actual % FCI**	**Cost (USD)**
Purchased Equipment (installed Costs)	15-40	60	1,963,180
Instrumentation and Controls (Installed)	2-8	2	65,980
Piping (Installed)	3-20	3	98,970
Electrical (installed)	2-10	2	65,980
Buildings (including Services)	3-18	10	329,900
Yard Improvements	2-5	3	98,970
Service facilities (installed)	8-20	1	32,990
Land	1-2	1.5	49,490
TOTAL DIRECT COST			**2,639,470**
Engineering and Supervision	4-21	4	131,960
Construction Expense	4-16	8	263,920
Contractors Fee	2-6	3	164,950
Contingency	5-15	5	164,950
TOTAL INDIRECT COST			**659,800**
TOTAL FIXED CAPTIAL INVESTMENT			**3,299,000**
Working Capital	10-20	10	329,900
TOTAL CAPTIAL COST			**3,628,900**

From the Table 6.3 it can be shown that the majority of the cost of the refueling station would come from the initial capital investment on the purchased equipment.

The hydrogen refueling station total capital investment is 3,628,900. Several assumptions have been made. The first is that due to the extremely high cost of the equipment relative to an installation of the proposed size, the equipment cost was assumed to represent 60% of the fixed capital investment (FCI), not 15-40%. Percentages between 60% – 80% are more common for natural gas refueling stations as suggested by the literature [16]. The second is that many of the other items are assumed to be on the lower side of the suggested literature values. Again, this is skewed by the large installed costs of the equipment. As well, for a small operation such as the proposed station, the costs should be lower than a full chemical plant that would have a more complicated design and hence higher costs. The third is that due to the design of the station, service facilities will be minimal and therefore their cost-fraction is much lower than the literature guidelines.

6.4 Operating Costs

Table 6.4 below shows the outlined calculated values for the yearly operating costs. The natural gas requirements and electricity were calculated based on values obtained from NY State.

Table 6.4: Station yearly operating costs

Component	Literature Value (%)	Actual %	Cost (USD)
Manufacturing Cost			
Natural Gas	Process Dependant		295650.0
Electricity			
Reformer	Process Dependant		100740.0
Kiosk	Process Dependant		8400.0
Maintenance Year 1-5	2-6 of FCI	3	49470.0
Maintenance Year 6-9	2-6 of FCI	3	114,000
Operating Labour	NA	NA	88,700
Operating Supplies	15 % of Maintenance	15	7,420
Total Year 1-5			166,940
Total Year 6-10			231,470
Fixed Costs			
Depreciation	10-20 FCI	10	329,900
Property taxes	1-4 FCI	1	32,990
Insurance	0.5-1 FCI	2	65,980
Operating Overhead	5-15 TPC	0.5	4566.6
General Expenses			
Marketing	2-20 of TPC	2	18266.6
TOTAL OPERATING AND PRODCUTION COST			**913328**

The natural gas cost was calculated based on the reformer requirement of 1350 SCFM at a price of 0.025 USD per SCF of natural gas [17]. The electricity cost for the reformer was calculated based on the price of premium wind power being utilized at 0.10 USD per KWh and the reformer using 2,760 KWh per day [17]. The operating labour cost was calculated based on paying minimum wage for one daytime supervisor, plus at least one daytime attendant and two nighttime attendants. The maintenance costs were calculated for two different periods. The first period, years 1-5, did not include any maintenance costs for the reformer, because a 5-year warranty was included in the capital cost. For years 6-9, the maintenance costs for the reformer was included. A depreciation of 10% was used for the equipment. Land and the buildings were assumed not to depreciate. Note that the cost of water was not included. As will be shown in the sensitivity analysis, this omission will not significantly impact the final price of hydrogen.

6.5 Tax credits and incentives

There are several opportunities to obtain outside funding from government agencies, which will help reduce the capitol costs and therefore improve the overall profitability of the station. These typically take the form of tax credits or direct funding. Three examples of the types of resources available are:

- The New York State tax credit for clean-fuel vehicle refueling property: This tax credit pays for 50% of the cost of the property including property for storing or dispensing a clean-burning fuel into the fuel tank of a motor vehicle propelled by that fuel (26 U.S.C.A. §179A, subsection d) [18].
- New York State Clean Cities Challenge Program (PON) No. 834: This program delivered by the New York State energy Research and Development Authority (NYSERDA) can provide funding to cost-share up to 75% of the cost of installing alternative fueling and recharging equipment.[19]
- Department of Energy (DOE) "Grand Challenge": This DOE initiative has a total funding up to $80 million over a four-year period for 28 projects (average of 2.85 million dollars per project) including projects involved with distributed production of hydrogen and hydrogen delivery [20].

Other such incentives exist to help kick start the large scale use of hydrogen . For the purposes of the costing study, the selling price for hydrogen will be determined with and without the use of incentives.

6.6 Hydrogen Pricing

The price of hydrogen was calculated using a present value (PV) analysis based on a 10 year breakeven period as outlined in the contest rules and a production rate of 54750 kg of hydrogen per year. The tax rate was assumed to be 30% [15]. The PV analysis included the following costs and revenues shown in Figure 6.1 (not including tax credits and other incentives).

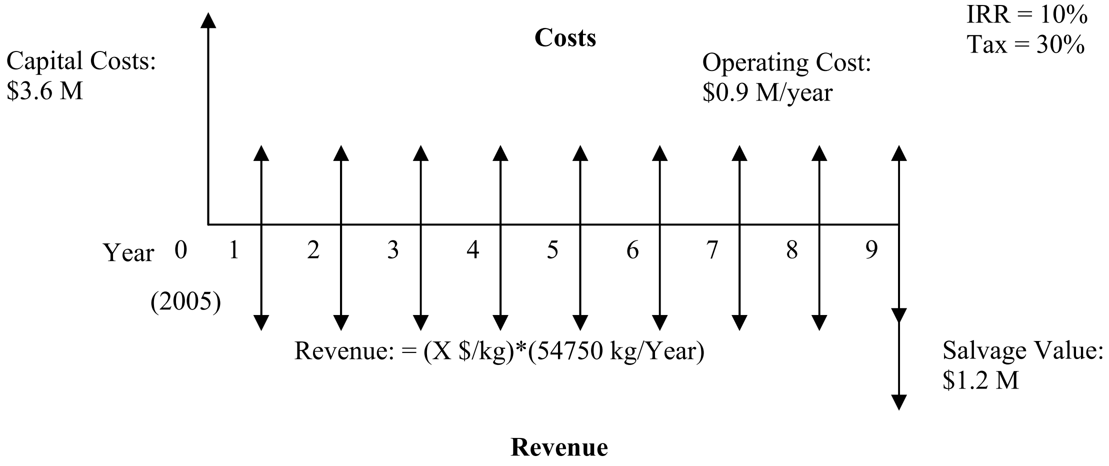


Figure 6.1: Cost and revenue streams for the proposed hydrogen retail station.

In order to achieve a 10% after tax IRR, the selling price of hydrogen was determined to be $39.14 (USD)/kg hydrogen, resulting in a driving-price of $0.65 (USD)/mile. This is a very high price, even for early adopters. In comparison, an ordinary gasoline ICE can achieve a driving-price of 0.06 USD/mile. Judging by the capital costs of the station, it is not a surprise that the raw cost/kg of H_2 is so high. Outside sources confirm the cost of hydrogen as being between $15 - $22 /kg [21].

In order to be competitive with gasoline prices, the cost of hydrogen would have to reach $3.50 /kg H_2. If tax credits and other incentives are maximized, the capitol costs of the station can almost be eliminated. If the incentives described above are exploited, the price of the hydrogen reduces to $25.5 /kg, or $0.43/mile which is more reasonable for an early adopter.

Sensitivity Analysis

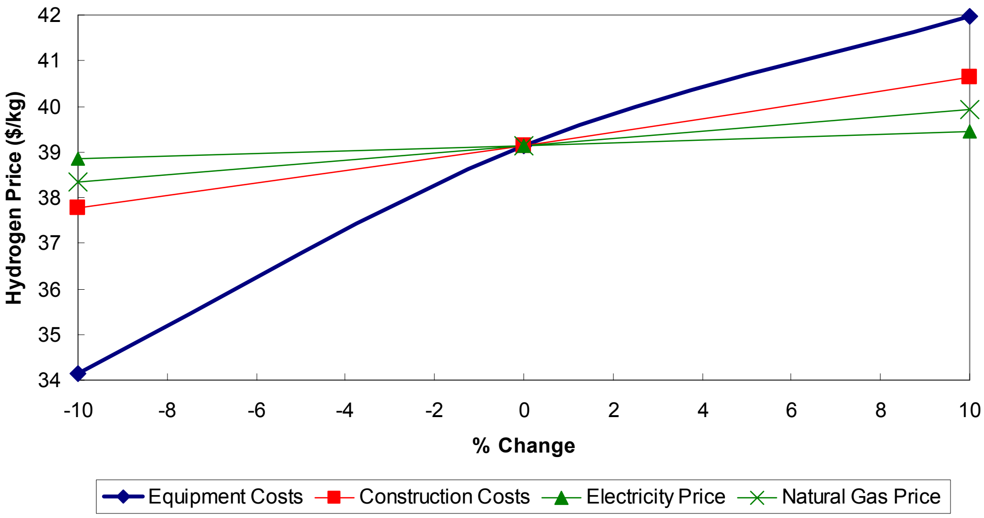


Figure 6.2: Sensitivity of hydrogen selling price to equipment costs, construction costs, electricity price, and natural gas price.

Hydrogen sensitivity analysis was completed based on a 10% variation in four variables: the equipment cost, price of electricity, price of natural gas, as well as the construction costs. As expected, reducing the cost of the equipment has the greatest impact on the cost of hydrogen. It is very important to find ways of subsidizing the equipment costs in order to make hydrogen more economical for users.

Interestingly, the sensitivity analysis shows that the final price of the hydrogen produced by the station is not as sensitive to the utility costs or the natural gas feed costs. This indicates that the hydrogen price can remain constant with the natural increases or decreases of these prices. The analysis also shows that the omission of water costs would not have had a significant impact on the final selling price of hydrogen. Further investigation also showed that revenue generated from the concession or from the car wash would have little impact. In light of these facts, it may be appropriate in future design iterations to limit the space of the kiosk and eliminate the car wash to save on the construction costs. These are both factors that have a significant impact on the final price of H_2).

6.7 Summary

The hydrogen retail station as designed will require capital expenditures of $3 628 900 U.S. and has a yearly operating cost of over $900 000 U.S. In order to achieve a 10% after tax IRR on the investment, the selling price for hydrogen will have to be $39.14 U.S./kg H_2. If tax credits and other government incentives are taken advantage of, the price can fall below $26 U.S./kg H_2. For early adopters the latter price will prove more encouraging to increase hydrogen use in the country. In either case, the price of hydrogen is an order of magnitude higher per kilometer than gasoline. This is mostly die to the high capital costs of the station, due to the high capital costs of the equipment.

7.0 Environmental Analysis

One of the main advantages of fuel cells are that they are supposed to be more environmentally responsible than internal combustion engines. However, the impact that a fuel cell vehicle has on the environment largely depends on the methods used to produce the hydrogen fuel. This section seeks to determine the amount of environmental impact of the hydrogen produced from the proposed hydrogen retail station in terms of the amount of CO_2 emissions from the hydrogen's entire life cycle. Figure 7.1 illustrates the different aspects of the hydrogen and the station's life cycle that will be considered here.

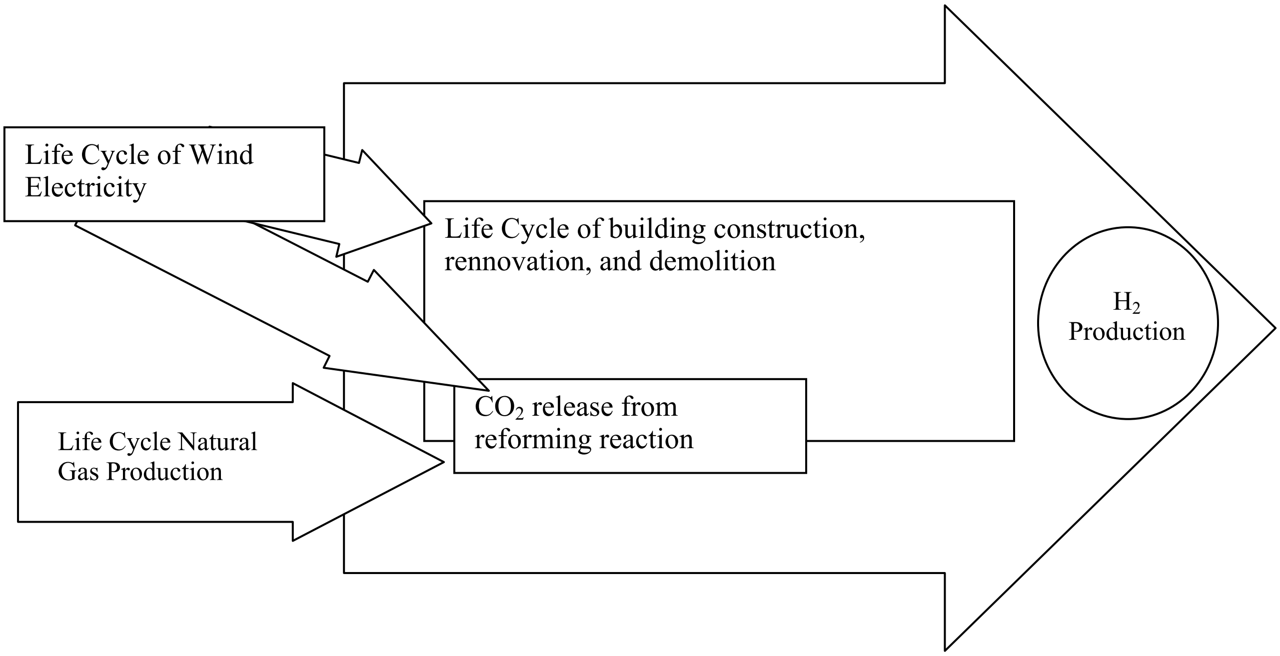


Figure 7.1: Components of the life cycle analysis.

During the design and construction and operation of the "Chex0" hydrogen refueling station, every effort to determine and minimize environmental burdens was made. The environmental analysis of the proposed hydrogen refueling plant consists of four major areas where emissions are generated:

1) Natural Gas CO_2 Burden: This includes the CO_2 emissions from extracting natural gas from the ground and delivering it to the station.
2) Reformer Operation: This involves the electricity needed to operate the reformer as well as the CO_2 generated from the reforming reaction.
3) Building Use: This includes the general electricity use of the station including operation of the concession as well as the car wash.
4) Building Construction: This includes the CO_2 generated from the construction (including building materials), future renovations, and eventual deconstruction of the retail station.

For standardization purposes, emissions have been calculated as grams of CO_2 burden. Note that not all of the components have been accounted for, for example the CO_2 contribution from water use as well as from the construction of the storage tanks and dispensers have been neglected. Preliminary research indicated that the other parts would have a relatively small contribution to the overall CO_2 burden of the station [5].

Once the CO_2 burden of each of the components was determined, the amount of CO_2 generated for each kg of hydrogen (well to tank) as well as the overall CO_2 emissions for each kilometer driven by a fuel cell car (well to wheel) were be calculated.

7.1 Natural Gas CO_2 Burden – Ground to Station

Natural gas production requires energy through many different steps. Table 7.1 from [22] lists the Carbon emitted as a consequence of the different processes. Note that the numbers used here are based on Japanese natural gas, which is transported as a liquid in some cases. This it not likely to be the case with the US supply, therefore the tabulated data likely overestimates of the emissions of the processes.

Table 7.1: Carbon emissions from natural gas production steps

Process Step	Carbon Emission (g-C/Mcal)
Production	1.1
Liquefaction	9.2
LNG Transportation	1.6
Regasificaiton	0.6
Sum	**12.5**

The above sum of 12.5 g-C/Mcal is approximately equivalent to 137 g-C/m^3, or 502.3 g-CO_2/m^3. The reformer uses approximately 38.2 m^3/h of natural gas. Using these numbers we find that the total CO_2 emitted to supply the station with natural gas is approximately **460890.5 g-CO_2/day**.

7.2 Reformer Operation

The second aspect of hydrogen production considered for environmental CO_2 emission analysis is the operation of the reformer. The CO_2 emissions from the reformer can be broken up into two parts. The first is the electricity requirement to operate the reformer and the second is the CO_2 released in the reforming of natural gas.

Only electricity generated by renewable resources was considered in this report. This electricity is available, at premium prices, via many different distributors and energy brokers in the area. Rochester power utility offers green energy using a mixture of conventional sources and wind power. The customer can select for different packages which vary in the amount of wind they are composed of. For this station, 100% wind generated electricity was selected. From [23] the data in Table 7.2 was given on the life cycle CO_2 emissions from wind generated electricity.

Table 7.2: 'green power' CO_2 emissions

Technology	Life Cycle Range of CO_2 Production g-CO_2/kWh
Wind	7 – 9

For the purposes of this study the highest value was taken to create a conservative estimate of the emissions, thus the CO_2 production per kWh is 9 g-CO_2/kWh. From the specification of the reformer, provided by Hydrogenics Inc., we know that the reformer will consume 2760 kWh every day, this includes the energy needed to compress the hydrogen to 6000 psi. Thus, the CO_2 generated from electricity use is **28428 g-CO_2/day**.

The second aspect of reformer operation is the CO_2 generated from the reforming reaction. The catalytic reaction between natural gas (which can be approximated by methane) and water in an overall reaction as follows:

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

For the purposes of this study it is assumed that all of the methane introduced into the system is converted to an equimolar amount of CO_2. From an input CH_4 rate of 1350 ft^3/h at 15°C and 1 atm, a CO_2 discharge of **1689008.0 g-CO_2/day** was calculated.

7.3 Building Use

Station electricity use not associated with the reformer was calculated in order to provide an estimate of the daily CO_2 emissions as a result of building operation. An average of the electricity cost of other stations in the area was determined as a means of estimating our stations cost. There was a significant range of costs, from $300/month to $700/month [24]. In order to produce a conservative estimate, $700/month was chosen as being closest to a station that also operates a car wash. Assuming an electricity cost of $0.03/kWh the amount of energy used by the station is 778 kWh/day. Using the same numbers for the CO_2 impact as with the reformer, 10.3 g-CO_2/kWh, the total estimated CO_2 burden of the station operation is **8011.1 g-CO_2/day**.

7.4 Building Construction, Renovation, and Demolition

The CO_2 emissions from construction of the buildings were also estimated. They were estimated based on numbers used for houses in the UK [25]. This report examined the construction, operation, renovation, and final demolition of the houses and determined their individual contribution to the overall CO_2 emissions. Table 7.3 shows the various contributions as a percentage of the total CO_2 emissions.

Table 7.3: Carbon Dioxide Emissions from different project phases

Construction	Operation	Renovation	Demolition
5.5%	93.9%	0.45%	0.15%

Assuming that these percentages will also hold for the hydrogen retail station, the CO_2 burden can be calculated by using the estimate on the building operation CO_2 emissions from the previous section. A value of **520.1 g-CO_2/day** was obtained.

7.5 Well to Tank Analysis

Table 7.4 summarizes the CO_2 emissions from the different sources considered:

Table 7.4: Carbon Dioxide Emissions from different sources

Source	g-CO_2/day	% of Total	NREL Estimate [5]
Natural Gas Production and Distribution	460890.5	20.9	25%

Reformer Electricity	28428.0	1.3	74.8%
Reforming Reaction	1689008.0	77.4	
Building Operation	8011.1	0.36	
Building Construction	520.1	0.02	0.4%
Total	2205977.5	100	
Well to Tank (g-CO_2 /Kg H_2 Produced)	**14579.1**		11888

Table 7.4 shows that the largest contributor to emissions from the station is the reforming reaction. This analysis is validated by a similar study done on a large-scale hydrogen production plant.

From the information in Table 5 the well to tank CO_2 emissions per kilogram of hydrogen was calculated to be **14579.1 g-CO_2/kg H_2**. This agrees well with the NREL study that proposed CO_2 emissions of 11888 g-CO_2/kg H_2. The CO_2 emissions from hydrogen production are **102.7 g-CO_2/MJ** on a higher heating value basis.

In comparison, literature values for the well to tank CO_2 emissions for gasoline are approximately **17.97 g-CO_2/MJ** [26]. The difference between the two values is largely due to the reforming reaction, which produces a significant amount of CO_2. The environmental significance of the large discrepancy between H_2 and gasoline on a well-to-tank basis is minimal, because a significant portion of the CO_2 generated from gasoline use stems from its combustion.

7.6 Well to Wheels comparison

In order to compare the quantity of CO_2 released per km driven between an internal combustion engine car and a fuel cell car it was assumed that similar amounts of energy were used to produce the raw materials and to build the car frames and engines.

The combustion engine obtains 11.7 km/L, which translates into an energy demand of 2.98 MJ/km, assuming that gasoline has a energy density of 131.9 MJ/gallon. This is comparable to literature value of 2 MJ/km [26]. During combustion 1 liter of gasoline will release 2.5 kg-CO_2 equivalent emissions [27]. This value agrees with the assumption that gasoline is made up of only octane, for which the CO_2 released is 2.17 kg-CO_2/l. Combining these values with the well-to-tank numbers results in a total CO_2 emission value for internal combustion engines of **267.6 g-CO_2/km** on a well-to-wheel basis. This agrees well with literature values, which range from 126 g-CO_2/kg to 337 g-CO_2/km [28,29,30].

On the other hand, hydrogen fuel cell cars do not emit any greenhouse gasses when being used in the car. The fuel cell vehicles tanking at this station are able to obtain 60 miles/kg-H_2. Combining this fuel economy with the total hydrogen production CO_2 emission of 14707 g-CO_2/kg-H_2 yields a CO_2 emission rate of **151.0 g-CO_2/km**.

Natural Resources Canada (NRCAN), using their GHGenius CO2 modeling system, [31] performed the well-to-wheels CO2 production analysis independently. The values that we calculated using our independent assumptions agree very well with the model results, which predicted an emission rate of 184.9 g-CO_2/km based specifically on the system proposed for this competition.

In total, well-to-wheel CO_2 emission savings amount to 116.7 g-CO_2/km/Car. If 50 cars are replaced, then the total emission saving would be **5832.6 g-CO_2/km**. Operating at a maximum capacity of 50 fills per day, a savings of **383622.075 kg CO_2** is enjoyed per year.

7.7 Sensitivity

Of the different CO_2 emission sources considered in this report, only two are able to be influenced by the station design. The first is the efficiency of the reformer and the second is the method of electricity generation. The station designers cannot control the emissions from natural gas production and shipping, nor can the building CO_2 emissions to any appreciable degree.

Selecting a different system can change the yield of the reformer. The current system produces 2 mol-H_2/mol-CH_4 instead of the theoretically possible 4:1 ratio. This is largely because a fraction of the natural gas feed is used to create steam to drive the reaction. If a non polluting (electrical) resource was used to create steam and if the reaction was ideal (the current system has near-ideal steam reforming) the well to tank emissions could fall below 9000 g-CO_2/kg-H_2 and the well to wheels emissions would drop to less than 100 g-CO_2/km/car. This would increase the CO_2 savings over 50 cars to almost 9000 g- CO_2/km.

The type of electricity source used by the station will also have a large impact on the well-to-tank and well-to-wheel emissions from the station. For this project, premium power prices are being paid for green electricity that is generated from 100% wind. On the other hand, Rochester's power utility has the power generation makeup shown in Table 7.5 [32] along with the resultant CO_2 emissions [23].

Table 7.5: Carbon Dioxide Emissions from Rochester's power utility

Generation Type	Capacity (MW)	% of Capacity	g-C/kWh
Hydro	2.6	1.4	11.6
Gas	83	44.7	192.3
Coal	100	53.9	514.5

From the capacity percentages an estimate on the emissions is 707 g-CO_2/kWh. This would increase the well-to-tank estimation to over 3000 g-CO_2/kg-H_2 and hence increase the well-to-tank emissions past those of the internal combustion engine to over 320 g-CO_2/km. This would make gasoline a more environmentally friendly option. The economic analysis reflects the usage of 100% renewable technology through the purchase of premium "green" electricity from Rochester Gas and Electric.

8.0 Public Awareness/Marketing and Education Plan

In order for hydrogen technologies, specifically a hydrogen filling station, to gain public acceptance, the following barriers need to be overcome.

1. The public is wary of unfamiliar and new technology.
2. Sufficient refueling/service infrastructure do not exist to make people feel confident that upon buying H_2 vehicles they can be reliably fuelled.
3. Few hydrogen vehicle options are available on the market.

Hydrogen made a poor first impression on the general public, with the Hindenburg Zepplin disaster in Lakehurst NJ, in 1937. With time, science exonerated hydrogen as the culprit, however the damage done to hydrogen's image by this accident persists to this day. The goal of the proposed familiarization strategy is to overcome the perception of hydrogen as a dangerous fuel.

People are familiar with the internal combustion engine, and familiar with the gasoline/diesel fuel that powers this technology. The gasoline infrastructure is well established, with vast investments in its construction and maintenance being made yearly. People are far less familiar with hydrogen and its use as a transportation fuel. Our marketing strategy will familiarize the citizens of Rochester with hydrogen over three to six months, starting in September 2005 leading up to March 2006. By the time the station opens the public will have a basic understanding of hydrogen as a fuel, and it is hoped that many citizens will be willing to make the leap to a hydrogen powered vehicle.

The public acceptance plan starts with small advertisements that provide easily digestible facts about hydrogen that the public can read, comprehend, and assimilate into their general understanding of the world. Six months later, when considering buying a car, a hydrogen vehicle will not be immediately dismissed as unfamiliar and therefore unthinkable. People are not expected to see every advertisement, so for seventeen weeks from September 2005 to January 2006 we will run two small advertisements per week in the Rochester Democrat & Chronicle with information that will be selected to linger in the minds of future customers.

These small "Did you know" advertisements will also contain a web address, which will direct interested parties to a web page consisting of hydrogen facts, and have sections on distributed electricity generation, fuel cell-based backup power, hydrogen fuel cell vehicles, and an outline of hydrogen safety information. This way, when someone brings up hydrogen and the Hindenburg in conversation over pints at the local watering hole, the facts will be available to make an educated argument on the side of hydrogen!

In February, these small advertisements will continue to be printed, but will be supplemented with larger color advertisements leading up to our grand opening. At the grand opening, various promotional items will be distributed, including travel coffee mugs, bumper stickers, key chains, and the rare 'early adopter' window decal to create pride in the decision to move to hydrogen ahead of the majority and give early-adopters credit for the smart decision. The 'early adopter' decal will be given away free to cars filling at the station within twelve months of opening. It is anticipated that the key chain will become the subtle 'status symbol' for those technologically and environmentally progressive, and will be designed as such.

Once people are familiar with Hydrogen, we begin to explain the role that Rochester can play in this energy future. We build on the fast ferry that is starting to carry people across Lake Ontario to and from Toronto, which will be building its own Hydrogen Village in the near future (11). The site for our station is on the main road in from the ferry terminal, and people with fuel cell cars will be able to visit Toronto without worrying about being able to find hydrogen there.

The site location was selected due to its extremely high visibility, and the large volume of traffic that passes through the intersection every day (63750 cars per day, based on a 2001 study (9)). Before the opening, signs on the construction site will remind people that a hydrogen filling station is coming. Once it is open, people driving past the station will integrate it into their perception, and the image of H_2 as a safe fuel will be perpetuated.

Our association with Piehler Pontiac will also provide leverage for promotion. Having a dealership that will be selling hydrogen-powered vehicles right next to the station provides an ideal sales climate. Customers can buy, maintain, and fuel the vehicles all in the same area- with each aspect of the automotive economy conveniently co-located. With each sale and refueling, the goal of a hydrogen economy is brought closer.

The small advertizements will run Sunday with a pick up on the following Wednesday. With a 150-column inch bulk contract with the Rochester Democrat & Chronicle, these ads will cost $919.60 per week, or (52/12) $3984.93/month.

There would be additional advertising ahead of the March 25/26 grand opening. A quarter page color ad in the Rochester Democrat & Chronicle will cost $4945.50, with our 150-column inch contract-advertising rate.

A one page advertisement has been created for this competition and can be found on the next page

We're planning your roadtrip to the future.

It's time to go!

Chex0 Hydrogen Filling Station GRAND OPENING CELEBRATION March 25-26, 2006.
Lake Ave & Ridge Road, Rochester NY. Across from Kodak Park.

Hydrogen.
The fuel of the future.
www.rochesterhydrogen.org

Chex0
In Association with:

HYDROGENICS

FTI Fueling Technologies Inc.

9.0 References

1. "Powerful potential seen in fuel cells", Democrat and Chronicle, Website. http://www.democratandchronicle.com/biznews/1021Q524MT3_Fuel21_business.shtml, 2003

2. Nicoletti, G. 1995. "*The Hydrogen Option for Energy: A Review of Technical Environmental and Economic Aspects.*" Hydrogen Energy, Vol. 21, No 10. Pp. 759-765.

3. NREL, 2001. *Life Cycle Assessment of* H_2 *Production via NG Steam Reforming.*

4. "Rules and Guidelines for the First Annual University Student Hydrogen Design Contest:

5. Hydrogen Fuelling Station" National Hydrogen Association, 22 December, 2003

6. "Annual Energy Outlook 2002, with Projections to 2020" US Energy Information Administration, 21 December, 2001

7. "West Ridge Road Final Design Report" December 2002, for the City of Rochester NY

8. "Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System For transportation Applications: Hydrogen Infrastructure Report" US DOE, July 1997

9. www.hydrogenus.org/Press%20releases&H_2V.PresssRelease.December9.pdf (need help with this site.. does not come up)

9. Lewin, D.R., Lecture 11: Hazard and Operability (HAZOP) Studies, Course Notes, Department of Chemical Engineerng, Technion, Haifa, Israel

10. Hydrogenics Reformer Proposal document

11. CP Industries Storage Tank Quote

12. FTI Hydrogen Dispenser Quote

13. "Permitting Hydrogen Motor Fuel Dispensing Facilities", US DOE (2004)

14. "Clean Air Program: Design Guidelines for Bus transit Systems Using Hydrogen as an Alternative Fuel", US Department of Transportation (1999)

15. Peters, M.S., and Timmerhaus, K.D., "Plant Design and Economics for Chemical Engineers", 4th ed., McGraw-Hill Inc, USA, 1991

16. Case Studies of Cost Effective Natural Gas Refueling Stations, Gas Research Institute (2000)

17. Email correspodents Joe Rizzo of Rochester Gas and Electric. February, 2004.

18. New York State Energy Research and Develpoment Athority, Alternative-Fuel (Clean Fuel) Vehicle Tax Incentive. Website. http://www.nyserda.org/afvtax.htm, (2004)

19. New York State Energy Research and Develpoment Athority, New York State Clean Cities Challenge, Website. http://www.nyserda.org/834pon.html, 2004

20. Fuel Cells Today, US DOE Has $200 Million for H2 Research, Website, 2003 http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/Legislation/DisplayLegislation/0,1626,641,00.html

21. United States Council for Automotive Research, Creating an Infrastructure for Hydrogen a Major Challenge in the Transition to Fuel Cells, Website. 2003. http://www.uscar.org/Media/2002issue2/hydrogen.htm

22. Toyko Gas, Is city gas evaluated by LCA (life cycle assessment)?, Website, 2002. http://www.tokyo-gas.co.jp/env/clean/e_text/q6.html

23. ESMAP, "Energy Services for the World's Poor", The World Bank (ESMAP), Washington D.C., U.S.A., 2000.

24. One-Reality, Gas Stations for Sale in New York State, Website, 2004. http://www.one-realty.com/gasstation.htm

25. „Environmental Impact of Buildings, European Commission", Directorate General XII for Science, Research and Development, Progran APAS (1997).

26. NREL, 2001. *Life Cycle Assessment of* H_2 *Production via NG Steam Reforming*

27. Weiss, M.A., Heywood, J.B., Drake, E.M., Schafer, A., AuYeung, F.F., „On the Road in 2020: A Life Cycle Analysis of New Automobile technologies", Energy Laboratory MIT (2000)

28. National Round Table on Environment and Economy, 1997.

29. Transportation Technology R&D Center, Powering the Next Generation of Vehicles - Fuel Cells or Internal Combustion Engines?, Website, 2004. http://www.transportation.anl.gov/assessments/ct22-FCV.html

30. Energy Independence Now, How do Hydrogen Fuel Cell Vechiles in Terms of Emmission and Energy Use? A Well to Wheel Analysis. Web site. 2003. http://www.energyindependencenow.org/pdf/fs/EIN-Well-to-Wheel-Analysis.pdf

31. http://teikougaisha.mlit.go.jp/wsdocs/full/8

32. Rodchester Public Utilities, Power. Web site. 2004. http://www.rpu.org/about/facilities/power/

APPENDICES

Appendix A: Bill of Materials

Bill of Materials (BOM)

Hydrogen Refuelling S

Updated Mar-01-04
By: Erik

Part Number	Name	Description	Supplier (s)	Cost/Unit (USD)	Num Units	Total Cost
FRO1769	HySTAT Refueler Unit	Natural Gas Reformer	Hydrogenics Corp	XXX	1	#VALUE!
C-29534	High-pressure Hydrogen Storage Tanks	Seamless pressure vessel to ASME UPV Code Section	CP Industries	XXX	1	#VALUE!
H131229	Hydrogen Dispensor	Pump stands	FTI	XXX	2	#VALUE!
H131229b	Second delivery hose	auxliary hose for faster filling	FTI	XXX	2	#VALUE!
H131229c	Car Nozzle	standardized connection nozzle with breakaway ports	FTI	XXX	2	#VALUE!
61-0126C	LEL-1000 Combustible sensor	H2 gas detectors	Thermo Electron Corp	225	6	1350
SS4-AS2	Digital Fire Detection System	IR flame detectors	Fire Sentry Corp	1705	3	5115
SM4	Swivel mount for SS4	IR flame detectors	Fire Sentry Corp	130	3	390
FT-2045	Test Lamp for SS4	IR flame detectors	Fire Sentry Corp	1500	3	4500
777517-00	FP-1000 RS-232/RS-485 Network Module	E-stop/fill control system	National Instruments	395	1	395
777518-100	FP-AI-100 Analog Input Module, 8-Channel, 12-Bit	E-stop/fill control system	National Instruments	350	1	350
777518-110	FP-AI-110 Analog Input Module, 8-Channel, 16-Bit	E-stop/fill control system	National Instruments	350	1	350
777519-01	FP-TB-1 Universal Terminal Base, Screw Terminals	E-stop/fill control system	National Instruments	95	2	190
776671-03	LabVIEW	E-stop/fill control system	National Instruments	995	1	995
KMQSS-125G-6	Subminiature quick-disconnect probe, type-K	E-stop/fill control system Temperature Element	Omega Corp	24	2	48
FM1000	Plug-on Display, Pressure Transducer	E-stop/fill control system Pressure Transmitter	Omega Corp	125	2	250
830581U	IBM NetVista	DAQ/Safety Computer System	IBM Corp	999	1	999
8291 Series	Angle-body piston valves	Hydraulic valves	ASCO Valve Inc	109	11	1199
26-1700 Series	High Pressure / Back Pressure	Pressure release valves	Tescom Corp	149	1	149
M-6104	Model 6104 Flash arrestor	Flash arrestors	Matheson	30	5	150
SS-V5NBF8	Stainless 5-Valve Manifold, 1/2 in. FNPT, Ball Tip	Flow selector assembly, manifold with 4 valves	Swagelok	245	4	980

Appendix B: Industry quotes and sizing information

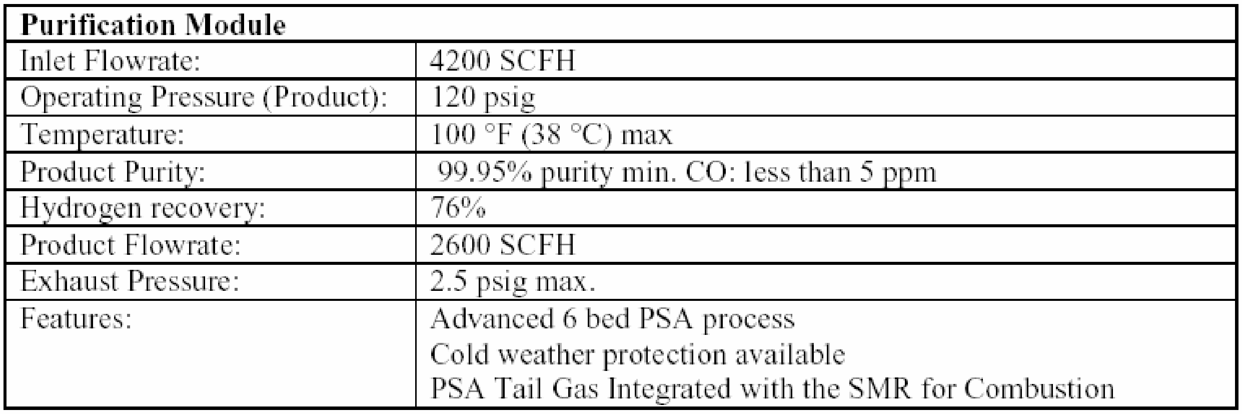
1. Hydrogenics Reformer System (Excerpts from Hydrogenics Proposal No. 1769)

Housing Dimensions	102" wide X 360" long X 114" high
Weight in Operation	~ 25,000 kg
Noise Level	< 65 dB measured at 1 foot distance
Gas Generation Rate	4200 SCFH of SynGas Maximum (~77% (vol.) Hydrogen Content)
Final Purified Gas Delivery Rate	2600 SCFH of Hydrogen Maximum (99.95 + % purity)
Gas Delivery pressure	6000 psig Maximum.
Electric Power IN / OUT	575 VAC, 3 ph, 60 Hz
Cooling Water	None Required (Closed Loop)
Feed Water	Municipal water (6 USGPH nominal, 10 USGPH max)
Natural Gas Supply	1350 SCFH @ **5-7.5 inch H_2O** (Residential Option) 1350 SCFH @ **20 psig** (Industrial / Commercial Option)
Note: All stated gas volumes refer to dry gas at 60 °F and 14.696 psia.	

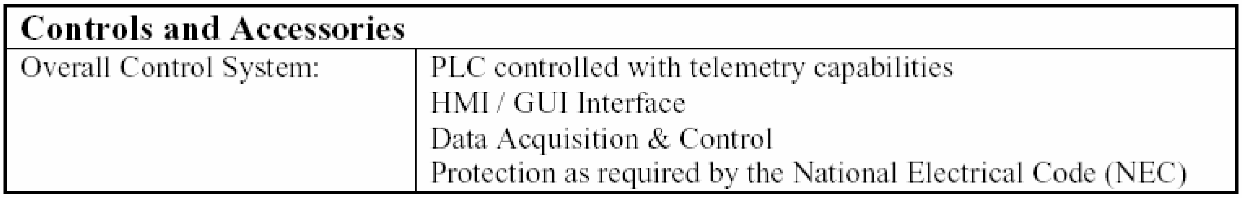
GAS PROCESSING SYSTEM: Steam Methane Reformer	
Gas Generation Rate (SynGas):	4200 SCFH of SynGas Maximum (~77% (vol.) Hydrogen Content)
SynGas Product Purity (Based on 150 psig dew point pressure):	Hydrogen ~77%, Carbon Monoxide ~2.0%, Carbon Dioxide ~18.5%, Methane ~1%, Nitrogen ~ 0.4%, Water: Balance
Reformate Delivery Pressure:	5 psig (max)
Reformate Delivery Temperature:	40°C (max)
Reformate %RH:	100%

SynGas Compression Module	
Hydrogen Supply Pressure:	150 psig
Hydrogen Suction:	1.3 psig
Compressor Speed:	960 rpm (nominal)
Compressor Capacity:	4200 SCFH – SynGas
Installed Motor Power:	TBS

High Pressure Compression Module	
Hydrogen Supply Pressure:	6000 psig
Hydrogen Suction:	6.3 psig (12 max at compressor suction)
Compressor Speed:	960 rpm (nominal)
Compressor Capacity:	4200 SCFH
Installed Motor Power:	TBS



Purification Module	
Inlet Flowrate:	4200 SCFH
Operating Pressure (Product):	120 psig
Temperature:	100 °F (38 °C) max
Product Purity:	99.95% purity min. CO: less than 5 ppm
Hydrogen recovery:	76%
Product Flowrate:	2600 SCFH
Exhaust Pressure:	2.5 psig max.
Features:	Advanced 6 bed PSA process Cold weather protection available PSA Tail Gas Integrated with the SMR for Combustion



Controls and Accessories	
Overall Control System:	PLC controlled with telemetry capabilities HMI / GUI Interface Data Acquisition & Control Protection as required by the National Electrical Code (NEC)

2. FTI Dispenser system (Quotation reference 2004-592)

Hydrogen Dispenser Model # HD5411 D52

General Specifications
- High profile cabinet with single delivery hose.
- Maximum Working Pressure: 447 bar
- Meter Maximum Flow Rate: Up to 20 kg/minute
- Codes and standards:
  - NEC for Class 1, Division 2, Group B Hazardous Location
  - ASME B31.3
- Electrical Requirements: 110 VAC, 60 Hz
- Dimensions (W*D*H): 33” W x 22” D x 92” H
- Approximate Weight: 500 lbs
- Operating temperature ranges: -40°F to +160°F

Standard Equipment
- Standalone fill computer for temperature compensated fills.
- Coriolis mass flow meter with internal transmitter.
- Electronic computer for sale, volume with 1” high, price per unit display is 0.7” high. All displays are back-lit and intrinsically safe.
- Internal gas detection system that alarms at 20% LEL and 40% LEL.
  - At 20% LEL the disables electrical power to dispenser, sends a signal to an external alarm. In addition, a sounder and red flashing lamp mounted on the dispenser are triggered. (NOTE: The sounder and flashing lamp are both intrinsically safe). At 40% LEL the alarms are the same as at 20% LEL with an additional trigger to signal a station emergency shutdown.
- 3/8” stainless steel piping and fittings on pressure lines.
- Inlet valves are pneumatically operated valves (external air or nitrogen supply required).

- Pressure relief valve to protect the vehicle against overpressure. Note: This is only a backup protection method, the electronic control system will serve as the primary means for controlling the filling pressure and preventing an overfill.
- Internal vent line combined with nozzle vent line. This line is piped to base of dispenser for connection to vent line away from dispenser.
- Filter on dispenser hydrogen inlet, with coalescing element to remove oil, water and particulate.
- Liquid filled, panel mounted pressure gauges for dispenser line pressure
- Nozzle holster to fit 350 bar car configuration hydrogen nozzle.
- Weh breakaway system for pressure and vent line on hose.
- Twin-line delivery hose designed for hydrogen service.
- Vibration/knock-down sensor connected to field wiring junction box
- Intrinsically safe Emergency Shutdown Button mounted on dispenser
- Ground cable reel integrated into dispenser.
- Vehicle communication cable and interface electronics for communicating with vehicle sensors. This option can match the California Fuel Cell Partnership Interface Specification (Rev. 6). Please confirm protocol type.
- Nozzle price is not included in the price of the dispenser.

3. CP Industries Hydrogen Storage Tanks (PCI Inquiry C-29532)

ITEM 1: One (1) 6-vessel assembly (3 wide x 2 high)
SPEC: Seamless pressure vessel to ASME UPV Code Section VIII, Division 1, Appendix 22, Safety Factor 3:1 for dry gas, non-corrosive service. Design temperature -20 °F to +200 °F. Vessel material is SA372 Grade J Class 70.
Vessel Size: 16" OD x 1.250" MW x 30' 0" Long
Design Pressure: 6667 psig
Assembly Water Volume: 162.0 cu. ft.
Assembly Capacity: 123.7 kg / 52,158 scf H_2 @ 6000 psig
Est. Assembly Weight: 45,720 lbs.

The assembly vessels are horizontally mounted in I-beam supports. Each vessel includes a ½” stainless steel ball valve on the front end, a safety relief valve with ¾” isolation ball valve on the opposite end, a ½” NPT drain valve and 5% notch ultrasonic inspection. The entire assembly will be painted with one coat of epoxy primer and a finish coat of white urethane enamel. Seismic bracing is not included.

Appendix C: Storage Tank connection overview

Figures C.1, C.2, and C.3 detail the connections and piping between each of the station components

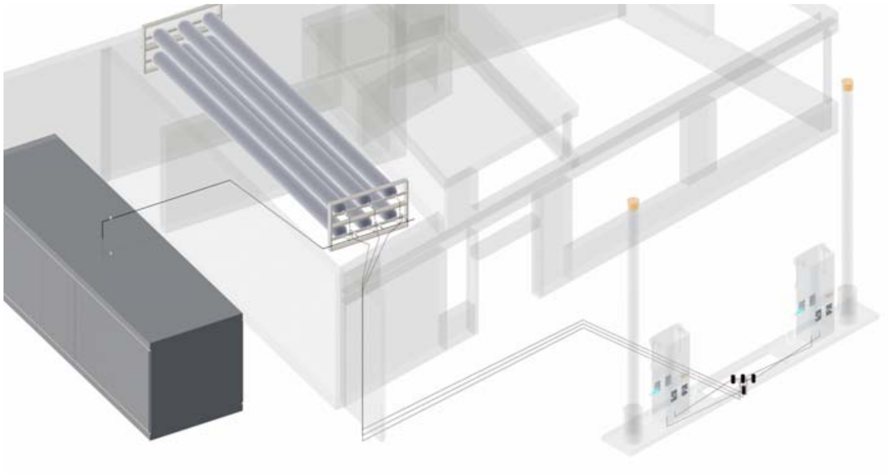


Figure C.1: Rendering of connections between reformer, storage, and dispensers.

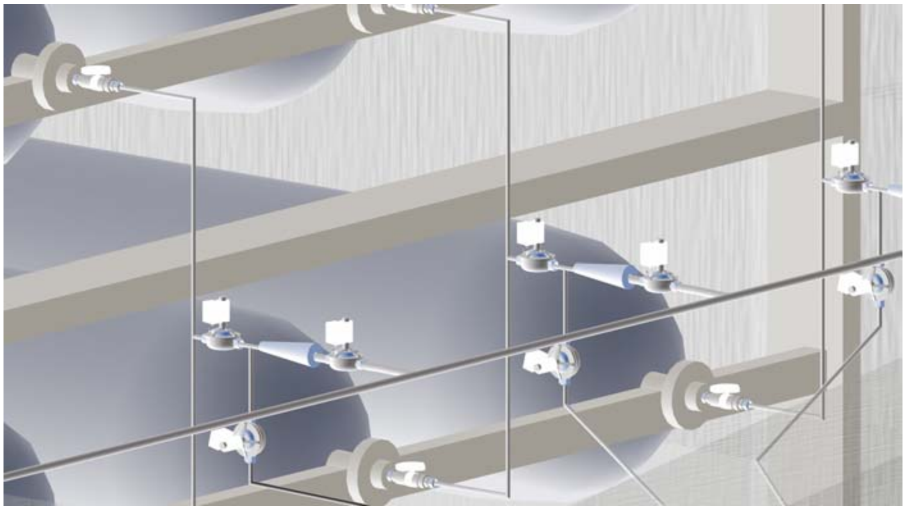


Figure C.2: Close up of the storage manifolding system

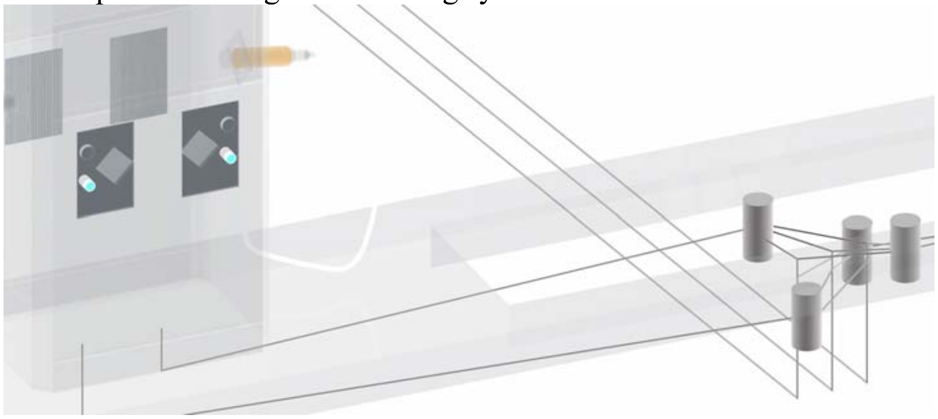
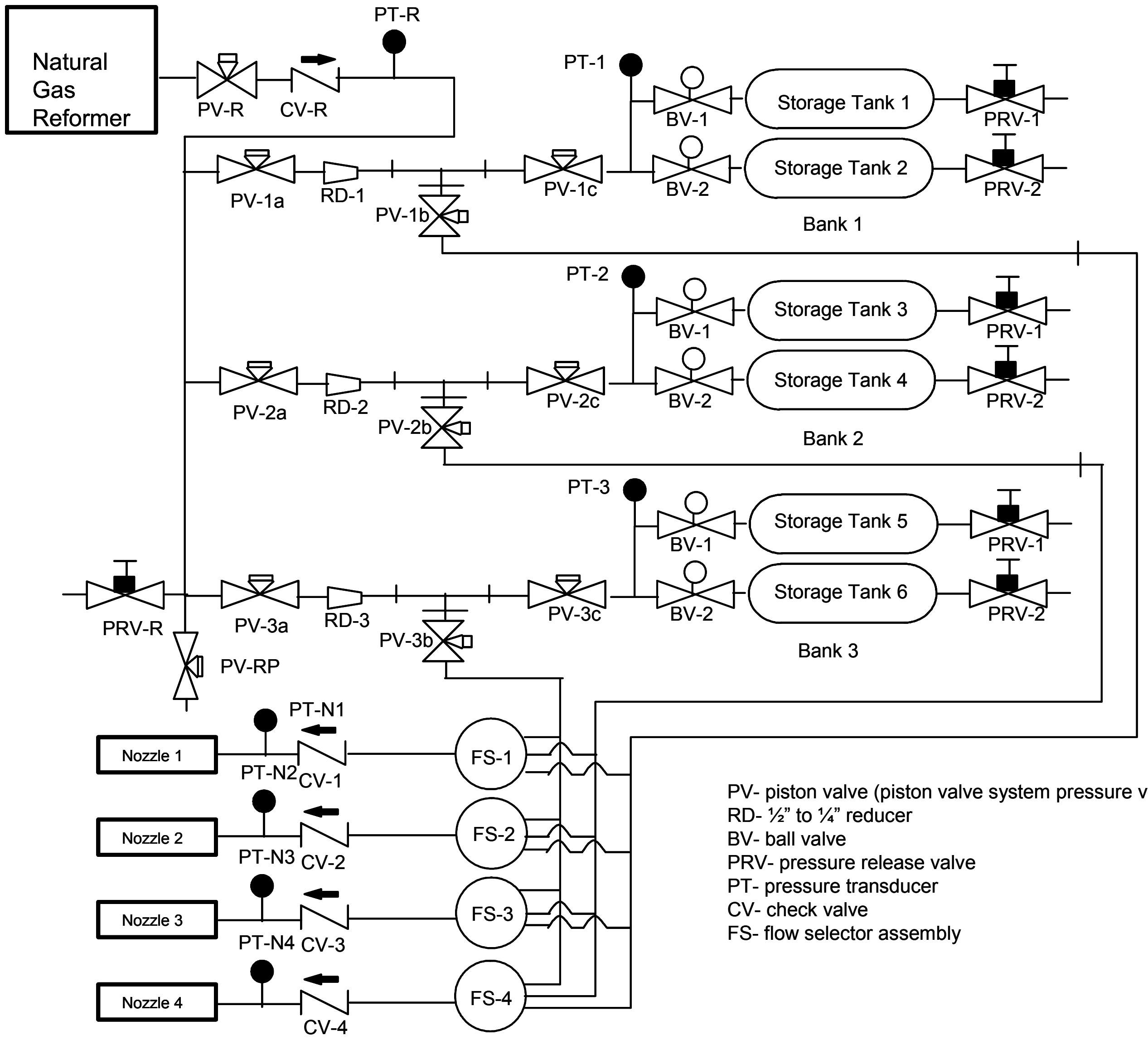


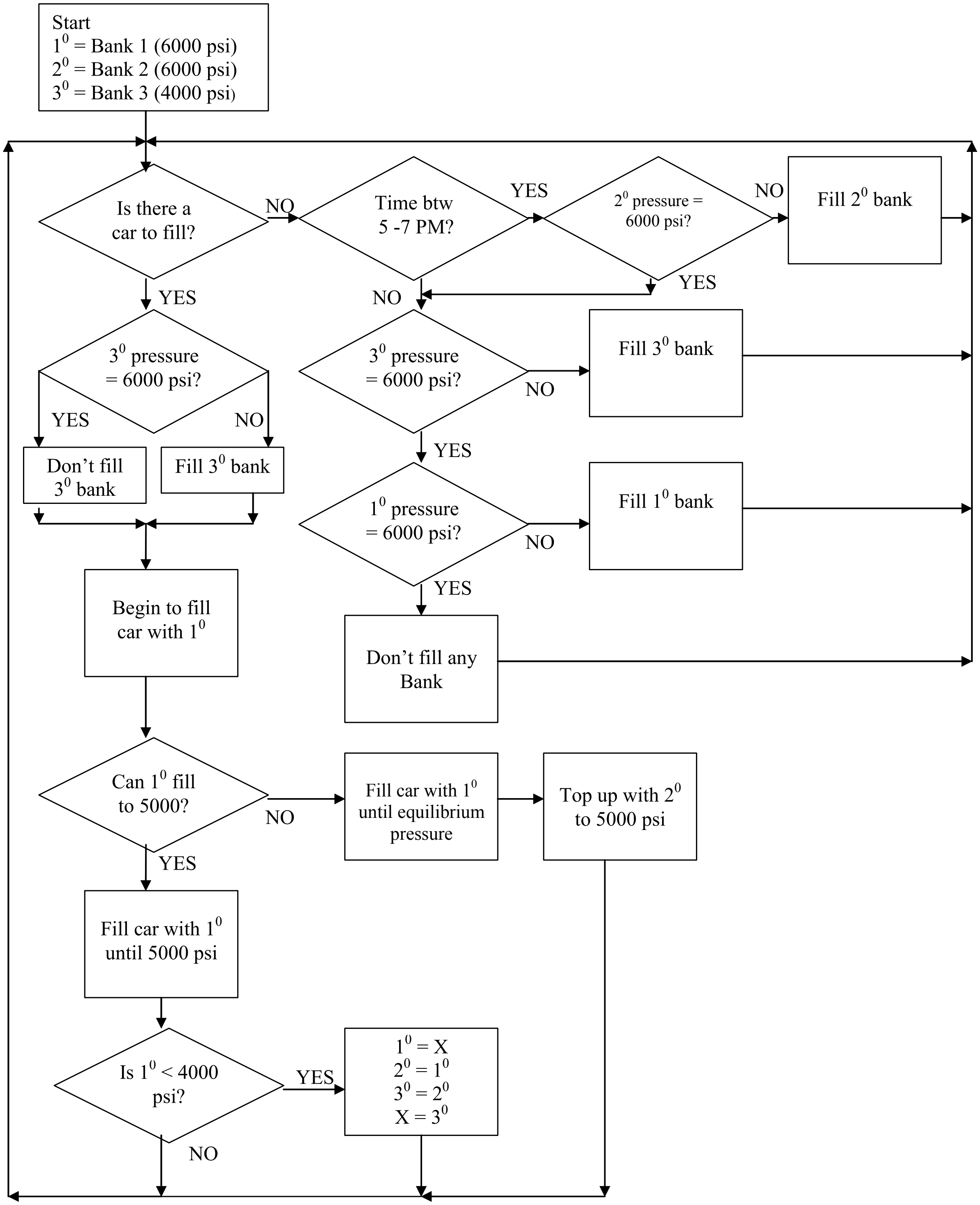
Figure C.3: Close up of piping to dispensers

Appendix D: Piping and Instrumentation diagram

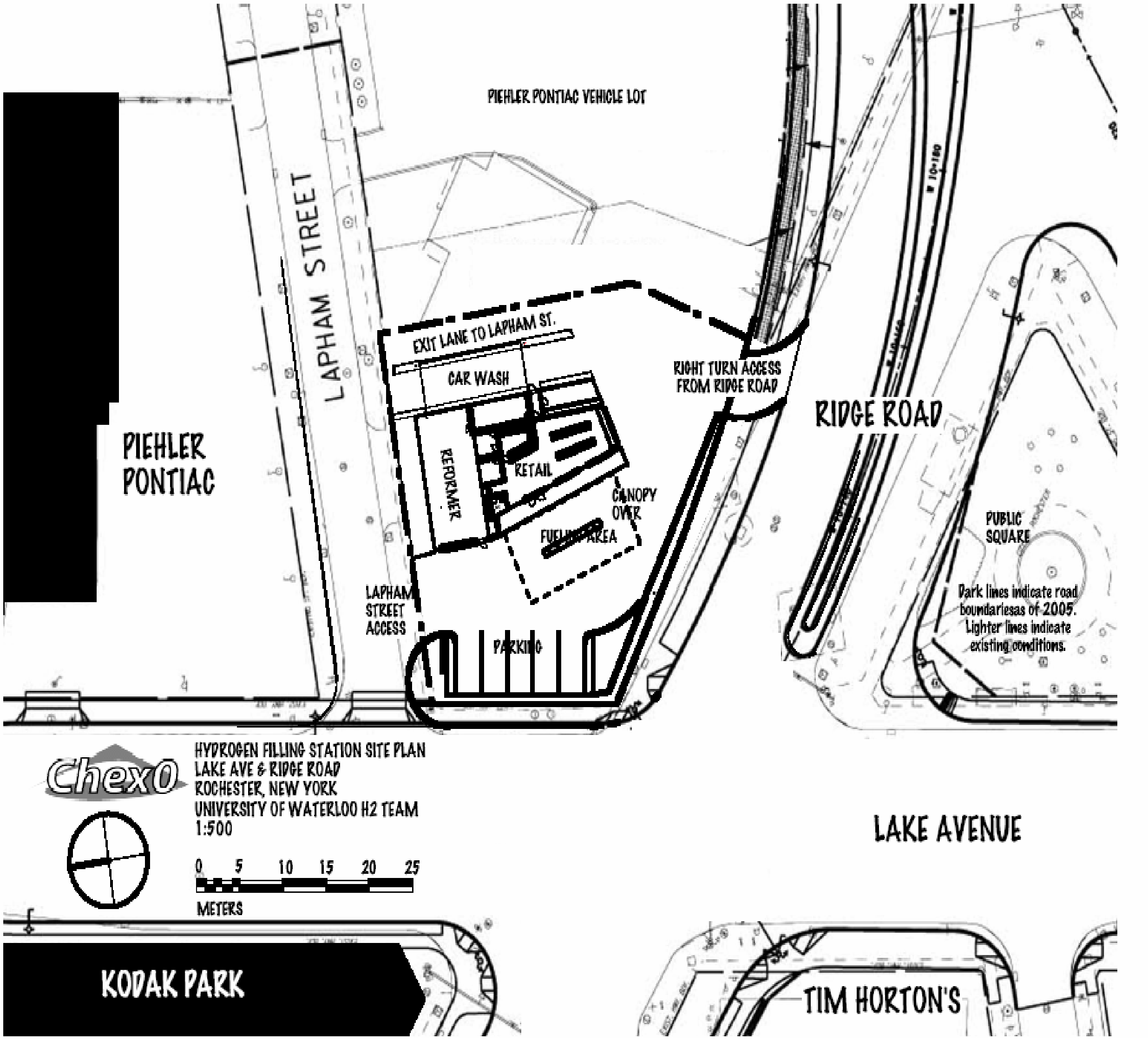


PV- piston valve (piston valve system pressure vessel not shown)
RD- ½” to ¼” reducer
BV- ball valve
PRV- pressure release valve
PT- pressure transducer
CV- check valve
FS- flow selector assembly

Appendix E: Control strategy for hydrogen storage management



Appendix F: Site Plans



Appendix G: Building Plans