HYDROGEN FUEL DISPENSING STATION FOR TRANSPORTATION VEHICLES

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Abstract

A technical and economic assessment is being conducted of a hydrogen fuel dispensing station to develop an understanding of the infrastructure requirements for supplying hydrogen fuel for mobile applications. The study includes a process design of a conceptual small-scale, stand-alone, grassroots fuel dispensing facility (similar to the present-day gasoline stations) producing hydrogen by steam reforming of natural gas. Other hydrogen production processes (such as partial oxidation of hydrocarbons and water electrolysis) were reviewed to determine their suitability for manufacturing the hydrogen. The study includes an assessment of the environmental and other regulatory permitting requirements likely to be imposed on a hydrogen fuel dispensing station for transportation vehicles.

The assessment concludes that a dispensing station designed to produce 0.75 million standard cubic feet of fuel grade (99.99%+ purity) hydrogen will meet the fuel needs of 300 light-duty vehicles per day. Preliminary economics place the total capital investment (in 1994 U.S. dollars) for the dispensing station at $ 4.5 million and the annual operating costs at around $ 1 million. A discounted cash-flow analysis indicates that the fuel hydrogen product price (excluding taxes) to range between $1.37 to $2.31 per pound of hydrogen, depending upon the natural gas price, the plant financing scenario, and the rate of return on equity capital.

A report on the assessment is due in June 1995. This paper presents a summary of the current status of the assessment.

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DISCLAIMER

Introduction

The transportation sector is a major consumer of fossil-derived fuels. For example, in 1993, in the United States (U.S.), this sector was responsible for 27 percent of the energy consumed and 66 percent of the petroleum used in the country (Patil and Zegers 1994, Gross 1994). The transportation sector is also a major contributor to the total U.S. emissions and is responsible for the increasing level of petroleum imports to the country. In the future, unless an alternate fuel significantly penetrates the transportation market, petroleum imports are expected to increase significantly to meet the transportation sector needs. These imports will have a major impact on the national well-being by being a drain on the national wealth and a national security concern. To staunch this drain on the national wealth, to decrease our dependence on imported fuels, and to decrease the environmental insult due to the continued use of petroleum-derived fuels, hydrogen is being evaluated as a desirable replacement for fossil-derived fuels.

Hydrogen as a fuel for transportation applications has several desirable attributes. Hydrogen can be converted to energy either thermally (for example, in an internal combustion engine) or chemically (for example, in a fuel cell). Unlike fossil-derived fuels (such as gasoline) hydrogen, when converted, produces water and no toxic, noxious, or hazardous emissions such as carbon and nitrogen oxides, particulates, aldehydes, and other non-methane hydrocarbons (NMHCs). Because hydrogen is very light and a gas at ambient conditions, any accidental open release will result in the hydrogen rapidly diffusing into the atmosphere and, unlike petroleum-derived fuels, will not result in any soil or water pollution. Hydrogen potentially has a very much larger and globally widely distributed resource base than petroleum. For example, hydrogen can be readily manufactured from water, fossil fuels, biomass, or other hydrocarbon resources. Hydrogen as a fuel has three times the energy content of gasoline, on an equivalent mass basis. When used as a fuel in fuel cell powered vehicles, it can provide 2 to 3 times the energy conversion efficiency of conventional gasoline-fueled, internal combustion engine powered vehicles because fuel cells being electrochemical conversion devices are not limited by the Carnot heat cycle. Hydrogen fuel cell vehicles operate quietly and produce no emissions other than water. They are environmentally benign and can be considered to be true "zero emission vehicles" unlike electric powered vehicles which are, in reality, "transferred emission vehicles".

One of the obstacles to the increased use of hydrogen in transportation is the lack of the supply infrastructure needed to make fuel hydrogen readily available to the public, similar to the present-day ready availability of motor fuels such as gasoline. To help surmount this obstacle, Oak Ridge National Laboratory (ORNL) was tasked by the U. S. Department of Energy to conduct an evaluation of a hydrogen fuel dispensing station for light-duty vehicles. The objective of this work is to perform technical and economic assessments to develop the infrastructure requirements to facilitate the introduction of hydrogen as an environmentally-desirable replacement for present day petroleum-derived transportation fuels. The work includes the development of design requirements for a conceptual hydrogen fuel dispensing facility similar to the present-day gasoline dispensing stations. This facility will be designed as a stand-alone plant to produce hydrogen from natural gas using conventional steam reforming and water gas shift processes. Other hydrogen production processes (such as partial oxidation of hydrocarbons and water electrolysis) would be reviewed to determine their suitability for manufacturing the hydrogen for the stand-alone dispensing station. The study will also include an assessment of the environmental permitting and other regulatory requirements likely to be imposed on building and operating a hydrogen dispensing station for fueling light-duty transportation vehicles.

This paper provides a summary of the current status of the assessment and preliminary results. A draft report (Singh and Richmond 1995) on the assessment is due to be issued in June 1995. This report will contain a review of the fuel hydrogen production technologies, an economic assessment for a conceptual, small-scale, stand-alone, grassroots hydrogen fuel dispensing station, and an assessment of the environmental and permitting requirements for the hydrogen fuel dispensing station.

Technology Assessment

Hydrogen can be produced by numerous methods from a wide range of resources such as fossil fuels, water, biomass, and other organic raw materials. Industrial hydrogen production processes include steam reforming (of natural gas and light hydrocarbons), partial oxidation (of heavy oils and tars), electrolysis (of water), gasification (of coal and biomass), and plasma conversion of natural gas or other hydrocarbons. Of all these processes, steam reforming of natural gas is the most widely used process because it is considered to be the most economic route for hydrogen production (Bochow 1995, Khurana 1994, Tindall and King 1994, McKetta and Cunningham 1987, and Baird 1983). Large quantities of hydrogen are produced as an intermediate stream for captive use in petroleum refineries and petrochemical plants for product upgrading operations. However, very little is sold as merchant or commodity hydrogen. Because of economics, most non-captive hydrogen for commodity sales is produced by the steam-reforming of a hydrocarbon (usually natural gas).

The hydrogen fuel dispensing station was designed as a grassroots facility with on-site production of hydrogen from natural gas. Steam reforming of natural gas was chosen as the conversion process because of economics and the ready availability of natural gas in the U. S. The process design of the production facility was performed using the ASPEN PLUS™ process simulator. The production plant was sized to produce 0.75 million standard cubic feet per day (MMscfd) of fuel grade (99.99%+ purity) hydrogen from 0.34 MMscfd of pipeline quality natural gas. The dispensing station was designed to produce and deliver gaseous fuel hydrogen at 3700 psia delivery pressure at the dispensing pumps to service an average of 300 light-duty vehicles per day.

The design premises for the dispensing station are summarized in Table 1. These premises were developed based on the following:

- The vehicle fuel requirements were developed to meet Goal 3 given in the ***Partnership for a New Generation of Vehicles (PNGV) Program Plan*** (U.S. Department of Commerce 1994).
- The light-duty vehicles would likely be powered by a proton exchange membrane (PEM) fuel cell stack requiring high purity (99.99%+) hydrogen as fuel.
- The fuel hydrogen would be stored on the vehicle in appropriate gas cylinders as high pressure (3600 psia) gas.
- The dispensing station would be staffed around the clock by trained operators.

Table 1. Basic Premises for Designing the Stand-alone, Small-scale, Grassroots Hydrogen Fuel Dispensing Station

Given below are the basic premises used for designing the small-scale, stand-alone hydrogen fuel dispensing station with on-site hydrogen production:

- Station capacity = 300 light-duty vehicles per day.
- Vehicle hydrogen requirements = 5 kg (11 lbs) for 640 km (400 mi) range at 38 km/L (90 mi/gal) of gasoline equivalent.
- Fueling station design capacity = 1800 kg/day (3970 lbs/day) or 21×10^3 std. m^3 /day (0.75 MMscfd) (at 60°F and 14.7 psia) of hydrogen.
- Fueling station designed to produce and dispense 99.99%+ pure hydrogen gas at 3700 psia.
- The hydrogen is to be produced by steam-methane reforming from pipeline quality natural gas.
- Number of fueling bays at the station = 4.
- Average fueling time per vehicle = 15 minutes.
- The fueling facility will be capable of dispensing fuel 24 hours per day.
- Fueling station staffing level = 3 operators per shift or 13 operators total for the facility. This staffing level does not include the administrative and maintenance staff that may be required for the facility.
- All cost estimates are to be in 1994 U. S. dollars.

Further details of the process design of the dispensing station are given in Singh and Richmond (1995). A block flow diagram of the dispensing station is shown in Figure 1 and Figure 2 is an artist's view of the conceptual stand-alone, small-scale, grassroots hydrogen fuel dispensing station.

Economic Assessment

An economic assessment was conducted of the conceptual hydrogen fuel dispensing station to estimate the price of the hydrogen produced at the facility and to evaluate the station's profitability under different financing scenarios. Briefly, the economic assessment consisted of developing the total capital investment for the facility, the estimated annual operating costs, and performing a discounted cash flow economic analysis under different financing scenarios to build the facility. The financing scenarios examined included 100 percent equity capital, 70 percent equity and 30 percent

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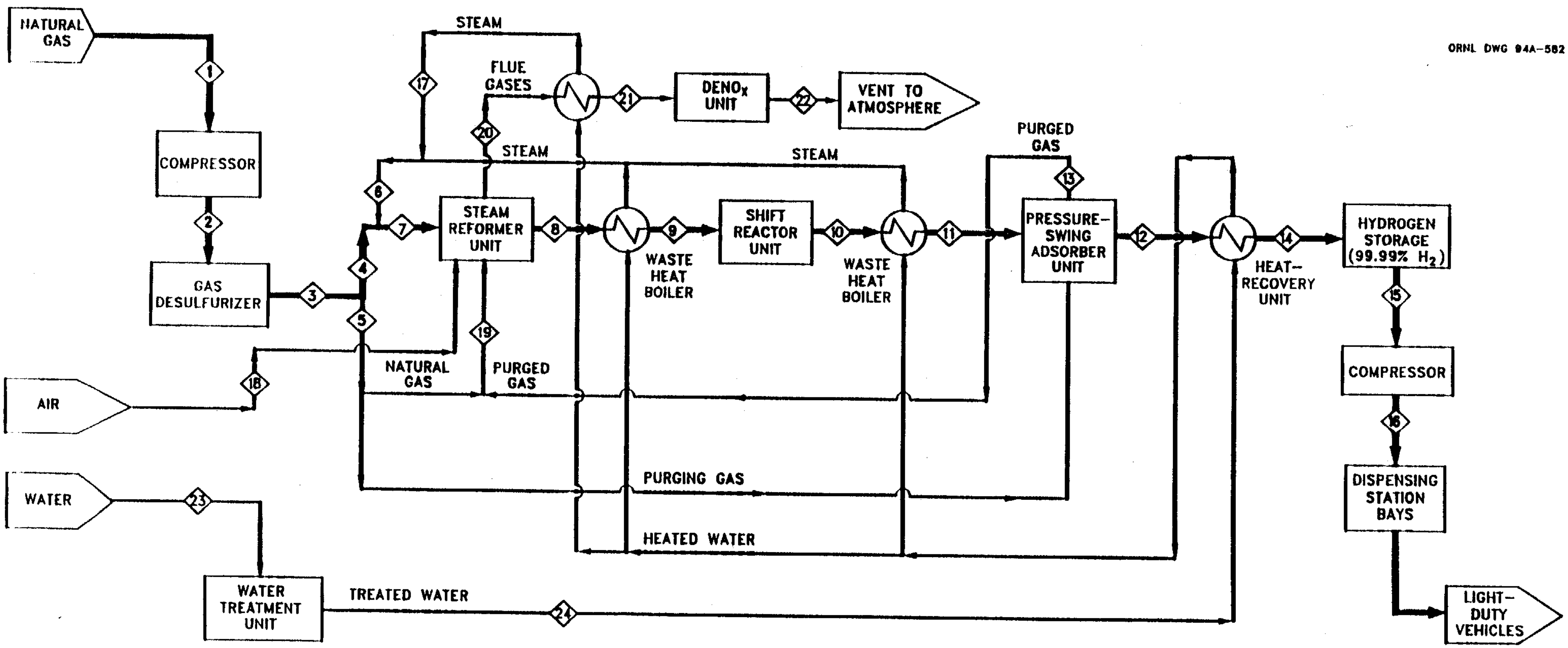
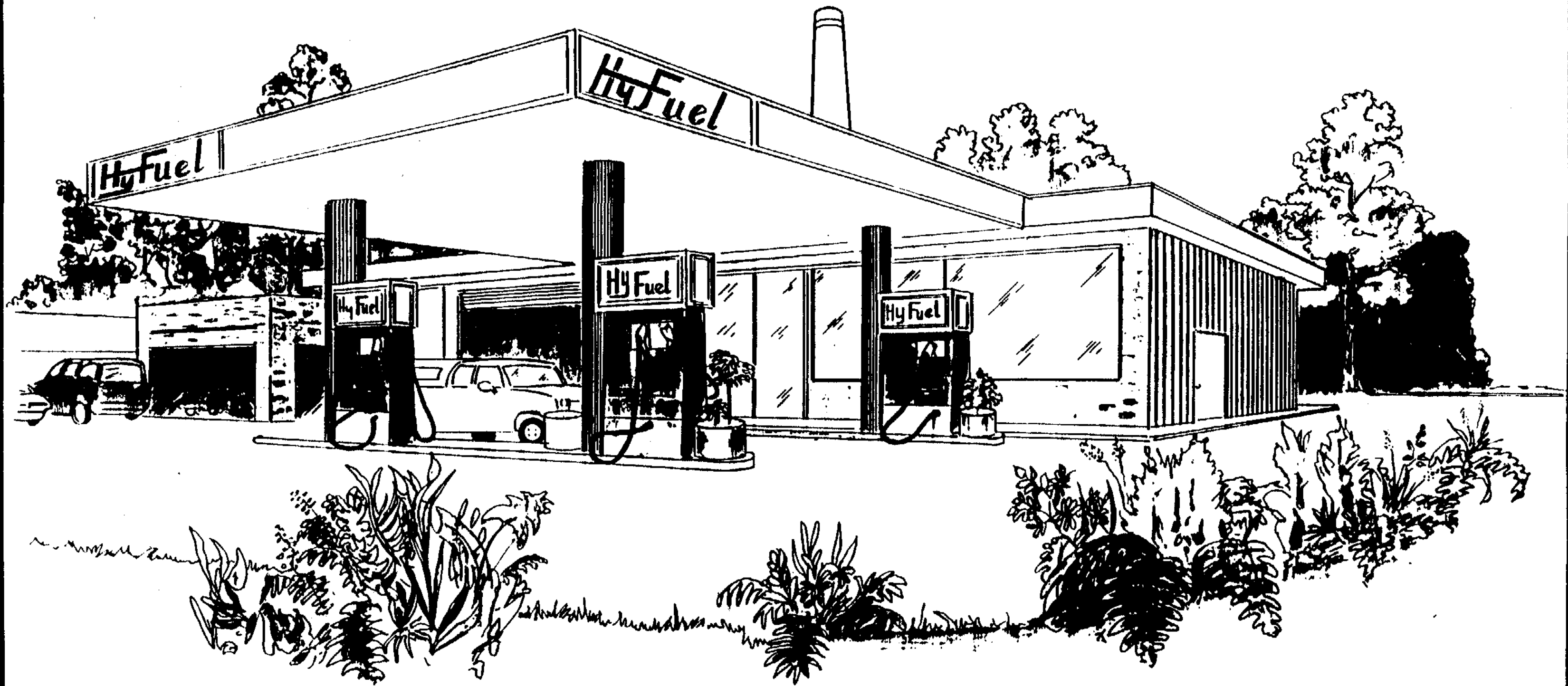


BLOCK FLOW DIAGRAM FOR DISPENSING STATION WITH ON-SITE HYDROGEN GENERATION USING CONVENTIONAL TECHNOLOGY



ARTIST'S VIEW OF CONCEPTUAL HYDROGEN FUEL DISPENSING STATION debt capital, 50 percent equity and 50 percent debt capital, and 30 percent equity and 70 percent debt capital. All costs in the economic assessment were developed in terms of 1994 U. S. dollars.

The estimated plant capital investment is given in Table 2. The capital investment was developed using plant costs obtained from various sources including King (1995) and Ogden, Dennis, and Strohbehn (1994). The estimated annual operating costs for the dispensing station are given in Table 3. Data to develop the annual operating costs were obtained from various sources such as King (1995) and Brown (1995). The economic analysis was performed using an ORNL-developed discounted cash flow analysis computer program called "PRP" (Salmon 1983). Briefly, this program determines the product price from a production plant given the economic parameters associated with building and operating the plant. The PRP program was used to determine the product or selling price for the hydrogen from the dispensing station given the capital investment, estimated annual operating costs, financing scenarios, and other cost accounting parameters such as taxation rates and depreciation schedules. The results of the economic analysis are summarized in Table 4 and are plotted in Figure 3 for different natural gas feed prices. From Table 4 and Figure 3, it can be seen for example, that the product price of the hydrogen for, say, $ 2.00 per thousand standard cubic feet (Mscf) of natural gas and for 100 percent equity financing, ranges between $ 1.47 and $ 2.04 per pound of fuel hydrogen, for a rate of return on equity capital ranging between 10 and 20 percent. The hydrogen product price shown is exclusive of taxes that may be imposed on the hydrogen fuel.

Sensitivity studies are being conducted to determine the impact on the fuel hydrogen price of changes in several economic parameters such as changes in the plant capital investment and the annual operating costs. The results of these sensitivity studies will be available in the technology assessment report by Singh and Richmond (1995).

Environmental Assessment

The environmental assessment consisted of determining the environmental and regulatory permitting requirements likely to be imposed on the conceptual small-scale, stand-alone, grassroots hydrogen fuel dispensing station. These regulatory and permitting requirements were developed assuming that the dispensing station was to be located in an industrial area in the Los Angeles Basin in southern California. The above assumption was made for the following reasons:

- Hydrogen fuels for transportation are most likely to be first introduced in the Los Angeles Basin in the U. S. as this area of the country has a chronic air pollution problem and has taken the lead in the introduction of alternate, clean-burning transportation fuels.
- The environmental permitting regulations for siting industrial plants are most stringent in this location. If a production facility is designed to meet these strict regulations, then such a facility will readily be able to meet the permitting regulations in other parts of the country.

Table 2. **Estimated Plant Capital Investment for Hydrogen Fuel Dispensing Station with On-Site Hydrogen Production Using Steam Methane Reforming**

	$ (1994)
• Installed cost for 0.75 MMscfd H_2 production plant	2,900,000
• Installed cost for 6-h GH_2 production storage tank	120,000
• Installed cost for GH_2 product compressor	150,000
SUBTOTAL installed cost of modular plant equipment	3,170,000
• Installed cost of buildings and structures (5%)	160,000
• Installed cost of interconnecting electricals, piping, instrumentation and controls between modules	150,000
• Installed cost of dispensing bays	100,000
• Land costs (1 acre @ $ 20,000/acre)	20,000
SUBTOTAL direct plant costs	3,600,000
• Allowance for permitting and other regulatory costs	150,000
• Allowance for other indirect plant construction costs	200,000
SUBTOTAL installed plant cost	3,950,000
• Contingency (at approximately 10% installed plant cost)	350,000
SUBTOTAL fixed capital investment	4,300,000
• Working capital (@ approximately 5% of fixed capital investment)	200,000
TOTAL plant capital investment	4,500,000

Table 3. **Estimated Annual Operating Costs for Hydrogen Fuel Dispensing Station with On-Site Hydrogen Production Using Steam Methane Reforming**

	$ (1994)
• Direct labor–13 operators @ $50,000/person-year	650,000
• Supervision and maintenance labor @ 25% of direct labor	163,000
• Supplies and chemicals	30,000
• Insurance @ 1% of depreciable capital cost	36,000
• Power @ 6 ¢/kWh	15,000
• Water @ $2/1,000 gallons	5,000
• Waste disposal	5,000
TOTAL annual operating costs	904,000

Table 4. Summary of Economic Analysis for Hydrogen Fuel Dispensing Station

Natural Gas Price $/Mscf[a]	Return on Equity %	Hydrogen Product Price, $/lb. Debt[b] /Equity Ratio, Percent 0/100	30/70	50/50	70/30
	10	1.47	1.43	1.40	1.37
	12	1.57	1.50	1.46	1.41
2.00	15	1.74	1.63	1.55	1.48
	20	2.04	1.85	1.72	1.60
	10	1.56	1.56	1.48	1.46
	12	1.66	1.59	1.54	1.50
3.00	15	1.82	1.71	1.64	1.57
	20	2.13	1.94	1.81	1.69
	10	1.64	1.60	1.57	1.54
	12	1.75	1.68	1.63	1.59
4.00	15	1.91	1.80	1.73	1.66
	20	2.22	2.03	1.90	1.77
	10	1.73	1.69	1.66	1.63
	12	1.83	1.77	1.72	1.68
5.00	15	2.00	1.89	1.82	1.74
	20	2.31	2.11	1.99	1.86

[a]Mscf = thousand standard cubic feet.
[b]Interest rate on debt = 9%

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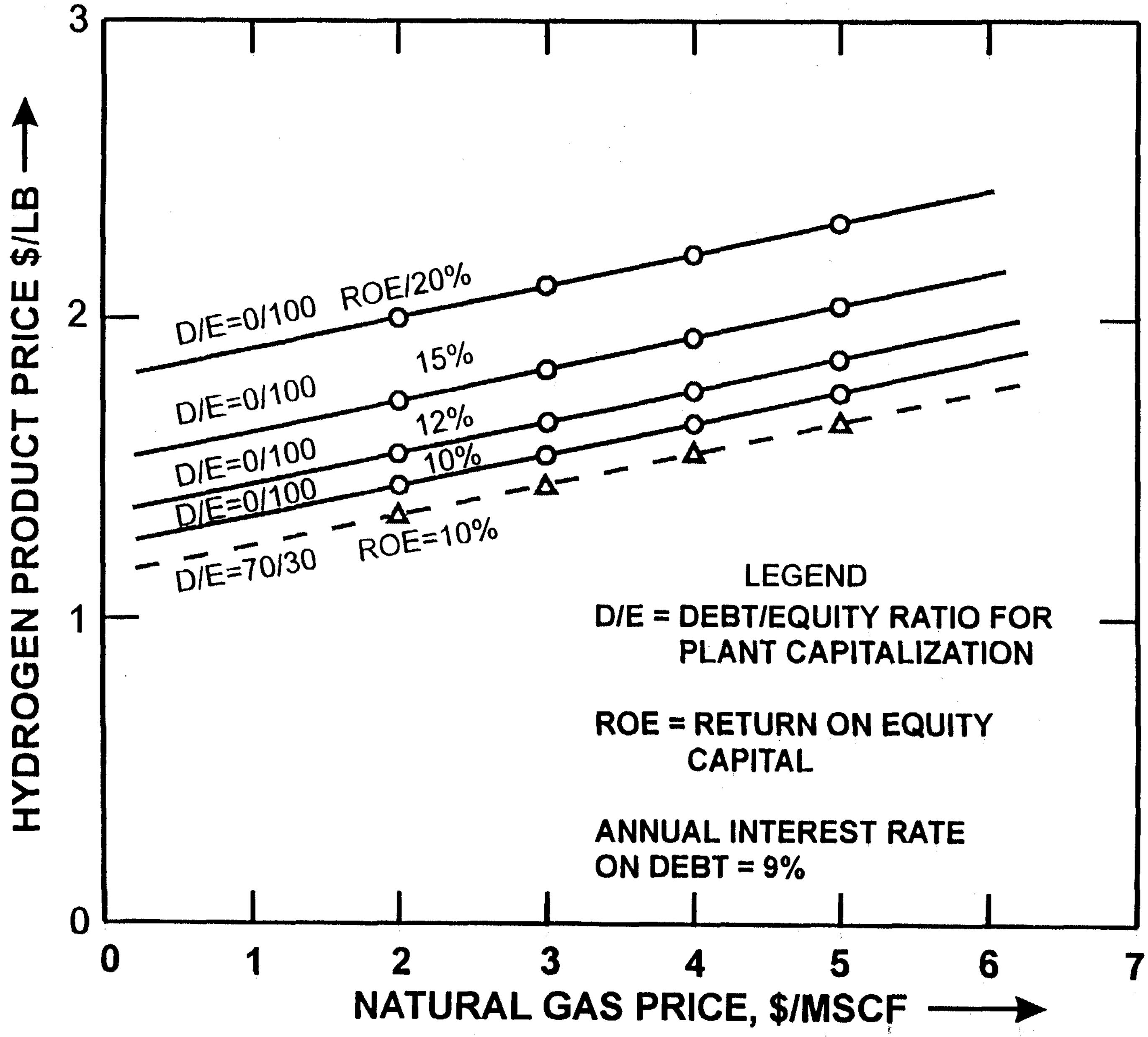
HYDROGEN PRODUCT PRICE FROM CONCEPTUAL DISPENSING STATION



The likely effluents from the conceptual hydrogen fuel dispensing facility evaluated in this assessment will consist of the following:

- Combustion flue gases from the steam-reformer heater. An analysis of the flue gas from the hydrogen production plant at the dispensing station is given in Table 5. The principal components present are nitrogen, water vapor, and carbon dioxide. The flue gas contains no noxious components [other than up to 20 parts per million (ppm) of nitrogen oxides].
- Blowdown water from the water treatment operations and domestic sewage from the dispensing station. This wastewater should contain no hazardous or toxic components and could be discharged to, for example, a municipal wastewater treatment facility for treatment and disposal.
- Solid wastes consisting principally of domestic trash and debris (e.g., waste paper, cardboard, plastics, and glass). The solid wastes should normally not contain any hazardous or toxic compounds requiring special disposal. These wastes could be sent to the local solid waste disposal facility for destruction and/or disposal. Spent catalysts which are periodically removed from the production plant are expected to be returned to the catalyst manufacturer for recycling.

The innocuous nature of the dispensing station effluents and wastes suggests that the station should not have to obtain any special permits other than those required for conducting normal manufacturing and distribution operations. Nonetheless, the dispensing station will likely have to comply with several federal and/or state environmental regulations and local permitting ordinances. The likely permits, regulations, and ordinances that the dispensing station will have to comply with are listed in Table 6. Because the dispensing station is basically a small chemical production plant, the equipment used at the station will have to be designed to comply with accepted industrial codes. A list of these potential codes is given in Table 7. Tables 6 and 7 present the potential regulatory requirements for the dispensing station; the actual codes, permits, and regulations will be decided when the conceptual plant moves into the detail design phase.

California has published a handbook entitled 1994 California Permit Handbook (Holanda 1994) which is an excellent guide to the permitting process involved in siting a production plant in the state. This handbook (or an update) would need to be consulted when the conceptual hydrogen fuel dispensing station moves into reality.

Conclusions

Some of the conclusions from the assessment are as follows:

- Fuel hydrogen likely will be produced from natural gas in the near-term as a transition fuel until the commercial production of hydrogen using solar energy can be demonstrated.
- Hydrogen production from natural gas by steam-methane reforming is an accepted commercial process in the petrochemical industry and dispensing station sized facilities can be built.
- Dispensing facilities producing fuel-grade (99.99%+ purity) hydrogen are feasible however, no such stations have been built to demonstrate and validate this conclusion.

Table 5. Flue Gas Analysis from the Hydrogen Production Plant at the Conceptual Dispensing Station.

Components	Molecular Weight	Flow Rate (moles per day)	Composition (mole percent)
CH_4	16.04	—	—
C_2H_6	30.07	—	—
C_3H_8	44.10	—	—
H_2	2.016	—	—
CO	28.01	—	—
CO_2	44.01	919.06	16.41
N_2	28.02	3,360.58	60.01
O_2	32.0	81.04	1.45
Ar	39.94	38.21	0.68
Mercaptans	48.11	—	—
H_2O	18.02	1,201.21	21.45
NO_x	46.02	0.11	0.002
Totals	—	5,600.21	100.00
Stream mol. weight	—	28.64	28.64
Vol. flow rate MMscfd	—	2.13	—
Mass flow rate, (lb/d)	—	160390	—
Temperature, °F Pressure, psia	—	180 20	—

Table 6. Summary of Federal, State, and Local Regulations and Permits for Hydrogen Fuel Dispensing Station.

- **<u>Federal Regulations</u>**

  - Energy [Title 10 Code of Federal Regulations (CFR)]
    - Department of Energy (Chapters II, III, and X)
  - Commerce and Foreign Trade [Title 15 (CFR)]
    - Department of Commerce (Chapters II, VIII, IX, and XI)
  - Commercial Practices [Title 16 (CFR)]
    - Federal Trade Commission (Chapter I)
    - Consumer Product Safety Commission (Chapter II)
  - Conservation of Power and Water Resources [Title 18 (CFR)]
    - Federal Energy Regulatory Commission (Chapter I)
  - Employees' Benefits [Title 20 (CFR)]
    - Department of Labor (Chapters I. IV-VII)
    - Department of Health and Human Services (Chapter III)
  - Highways [Title 23 (CFR)]
    - Department of Transportation (Chapters I-III)
  - Internal Revenue [Title 26 (CFR)]
    - Department of the Treasury (Chapter I)
  - Labor [Title 29 (CFR)]
    - Department of Labor (Chapters I, II, IV, V, IX, XIV, and XXV)
    - Occupational Safety and Health Administration (Chapter XVII)
    - Occupational Safety and Health Review Commission (Chapter XX)
  - Protection of Environment [Title 40 (CFR)]
    - Environmental Protection Agency (Chapter I)
    - Council on Environmental Quality (Chapter V)
  - Public Health [Title 42 (CFR)]
    - Public Health Service (Chapter I)
  - Emergency Management and Assistance [Title 44 (CFR)]
    - Federal Emergency Management Agency (Chapter I)
    - Departments of Commerce and Transportation (Chapter IV)
  - Transportation [Title 49 (CFR)]
    - Department of Transportation (Chapters I, III, and V)
    - Interstate Commerce Commission (Chapter X)

- **<u>State Regulations</u>** (e.g., for California)
  - Title 4 Business Regulations
  - Title 5 Environmental Review Process
  - Title 8 Industrial Relations
  - Title 22 Social Security
  - Title 23 Waters

- **<u>Regional Permits</u>** (e.g., for California)[a]
  - Public Utilities Commission Permit
  - Development Permit
  - Industrial Works Department Permit
  - Public Works Department Permit
    - Conditional Use Permit
    - Building Inspection Permit
    - Land Development Approvals
  - Hazardous Materials Risk Management: A Prevention Plan (HMPP)
  - Hazardous Waste Generation Permit
  - Air Permits/Air Toxics Regulations
  - Wastewater Discharge Permit
  - Solid Wastes Disposal Permit
  - General Construction Permit
  - Site Occupancy Permit

[a]Source: Koner, H.C., W. D. Gaulett, and J. Abbott, November 29–December 2, 1992. Pages 336-339 in "Licensing and permitting considerations for fuel cell project," *Fuel Cell Programs and abstracts 1992 Fuel Cell Seminar*, Tucson, Arizona.

Table 7. Potential Codes for the Equipment Design and Construction of the Hydrogen Fuel Dispensing Station.*

- American Gas Association (AGA): Report No. IS 100-1.
- American Society of Mechanical Engineers (ASME): Boiler and Pressure Vessel Code, Section VIII.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE): ASHRAE/IES 90.1-1089.
- American National Standards Institute (ANSI) Codes: A4.3, B31.3, B31.5, B93.5, B93.9, D56, D1018, Z48.1
- American Society for Testing and Materials (ASTM) Standards: A193, B57.1, B849, D1018, E136, E162, F113, F1129, F1459, Z11.7.
- American Petroleum Institute (API): Standards 620 and 750, Bulletins 6FA, 6FB, and Publications 910 and 2009.
- Chemical Manufactures Association (CMA) Guides: 018026, 018030, 057003, 024041, 047024, 047023, 024010,022002, 022008.
- Compressed Gas Association (CGA) Codes: B96, C4, C6-8, C10, C14-16, C341, E1, E6, G5.3, G5.4, P1, P8, P12, P19, S1.1-S1.3, S3, S4, S7, TB9, V1, V6, V7, V9.
- Fluid Controls Institute (FCI): 68.1, 69.1, 70.1, 70.2, 73.1, 79.1, 81.1, 85.1, 87.1, 87.2, 89.1.
- Gas Processors Association (GPA) Standards: 2140, 2261, 2265, 2337, 3132, 8173, 8182.
- Instrumentation Society of America (ISA): Recommended Procedures (RP) 7.1, 12.6, 12.13, and Standards 51, 12.13, 20.
- National Fire Protection Association (NFPA) Codes: 30, 30A, 50, 50A, 50B, 51, 51B, 53, 54, 70, 90A, 497A, 497M.

- A steam-methane reforming hydrogen fuel dispensing station demonstration facility needs to be built and operated to demonstrate the commercial viability of producing hydrogen fuel for vehicles thereby increasing the public acceptability of environmentally superior hydrogen as a transportation fuel.
- Preliminary cost estimates (in 1994 U. S. dollars) place the total capital investment for the stand-alone dispensing station at $ 4.5 million and the annual operating costs around $1 million.

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