

The Economics of Small to Medium Liquid Hydrogen Facilities

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Although the consumption of hydrogen has continued to grow in the United States at the rate of nine percent per year, no new liquid hydrogen production has been added since 1997 and liquid hydrogen capacity (Table 1) is still greater than demand.

The early U.S. tonnage hydrogen plants were built with the NASA program usages as their base. Later plants were built to serve industrial clients. A few tonnage plants exist in Europe and are dedicated to commercial and Ariannospace requirements. Small liquefiers have been brought online in Asia and in South America to serve either research or space related programs.

Onsite generators (natural gas reformers) provide hydrogen for most of the growth; while hydrogen liquefaction plants in the U.S. and Europe are operating at less than capacity. Papers have been published that discuss concepts and costs for the "hydrogen economy" utilizing liquefiers that are six times larger than the largest existing liquefier^{1,2}. However, some users and industrial gas companies around the world wish to evaluate the economics of small and medium size hydrogen liquefaction systems. The information presented here describes these smaller liquefiers; that is, up to five tpd or 700 MMSCFY.

Liquid hydrogen production plants have usually been described in terms of tons per day (tpd) of production, as are air separation and carbon dioxide plants. To those in the industrial gas industry not familiar with liquid hydrogen facilities, this terminology makes it difficult to put things into perspective since most air separation plant capacities are also expressed in tons per day, and are orders of greater magnitude in size. Describing liquid hydrogen plants in terms of tons per day does not adequately convey to most people either the magnitude of the investment, or the volume of the product. A better method is to compare liquid hydrogen plants to liquid helium plants. Liquid helium production plants are generally described in terms of million standard cubic feet per year (MMSCFY) or liters/hour (l/hr). Liquid hydrogen production plants in the U.S. range from five tpd to 30 tpd. A five tpd plant, the largest considered here, produces a yearly volume of 700 MMSCFY (2,720 liters/hr) — about the capacity of the largest single train commercial liquid helium plant and the largest hydrogen liquefier considered in this article, as can be seen in Figure 1.

A very important difference when liquid helium production costs are compared with hydrogen costs is the value of the feed gas. Contrary to the production of hydrogen; helium is in every

case, produced great distances from most market places and has to be liquefied to minimize the transportation costs. Helium is commercially available only through recovery from natural gas. Hydrogen gas production can be much closer to the market place due to feedstock (natural gas) availability and even generated onsite. In some cases, it is recovered as a waste gas from chlorine production or petrochemical operations and value-based on its BTU content plus a premium. As such; it provides very attractive pricing. However, as older chlor alkalai

Classifying Hydrogen Liquefiers in MMSCFY

Hydrogen liquefiers are more appropriately compared to helium liquefiers than to air separation liquefaction plants. Helium liquefaction plant investments and operating costs compare closely with hydrogen liquefiers even though the size of existing U.S. hydrogen liquefiers are on the high side of commercial helium liquefiers. Helium refrigerator/liquefiers are in use at numerous research centers around the world, and a good deal of cost data is in the public domain.

WorldWide Liquid Hydrogen Plants			
Owner	Location	Size, T/D ¹	Onstream
APCI	Sacramento, CA	6	1986
APCI	Pace, FL	30	1994
APCI	New Orleans, LA	35	1963
APCI	New Orelans, LA	35	1978
APCI	Sarnia Ontario, Canada	30	
Praxair	East Chicago, IN	30	1997
Praxair	Ontario, CA	22	Shutdown
Praxair	Niagra Falls, NY	40	1988
Praxair	Ashtabula, OH		Shutdown
Praxair	McIntosh, AL	29	1995
BOC	Magog, Quebec, Canada	15	1989
Air Liquide	Becancour Quebec, Canada	12	1988
Asiatic Oxygen	India	600 l/hr	
Linde	Ingostadt, Germany	4.8	1992
MHI	Tashiro, Japan	0.6 (350 l/hr)	1984
CALT	Beijing, CHINA	0.6 (300 l/hr)	1995
Japan Liquid Hydrogen	Tane-Ga-Shima, Japan	1.4 (730 l/hr)	1986
APCI	Rosenburg, Holland	6	1990
Air Liquide	Waizers France	11.5	
Iwatani	Amagaski, Japan	1.4	
Pacific Hydrogen	Oita, Japan	1.9	
Air Liquide	Kouru F. Guiana	2.3	

Notes 1. Tons/day are short tons

Table 1

plants shutdown and the use of chlorine declines, hydrocarbons have become the major source of hydrogen. It has always been difficult to justify a major investments such as a hydrogen liquefier since there would be no guarantee the chlor alkali plant would operate long enough to recover the investment.

Hydrogen liquefaction becomes a practical alternative to shipping hydrogen gas under the following circumstances:

when the distance is great enough, onsite gaseous production is not viable, quantities to be stored are large, very high purity is required, or the hydrogen is used in the liquid state.

The cost to produce pure hydrogen gas from a reformer is mostly determined by the cost of the hydrocarbon feed stock. In the case of natural gas the unit cost is half of the cost of the natural gas per 100scf including the reformer furnace fuel(i.e for \$0.40/100scf natural gas, the added unit cost to the hydrogen is \$0.20/100scf). Except in special cases, electrolysis of water is not economical since the power consumed is 12 to 13 kwh/100scf.

The cost of pure helium gas, when estimated at \$5 to \$6/100scf, is almost 20 times greater than the cost of hydrogen. While hydrogen liquefaction will increase the cost of hydrogen by magnitudes, helium liquefaction will increase the cost of helium by only percentages.

Producing & Purifying Hydrogen and Helium

In addition to liquefaction there are also similarities in the purification schemes for helium and hydrogen. Some hydrogen is recovered as a by-product from the production of chlorine and some from electrolysis. However, except for these special situa-

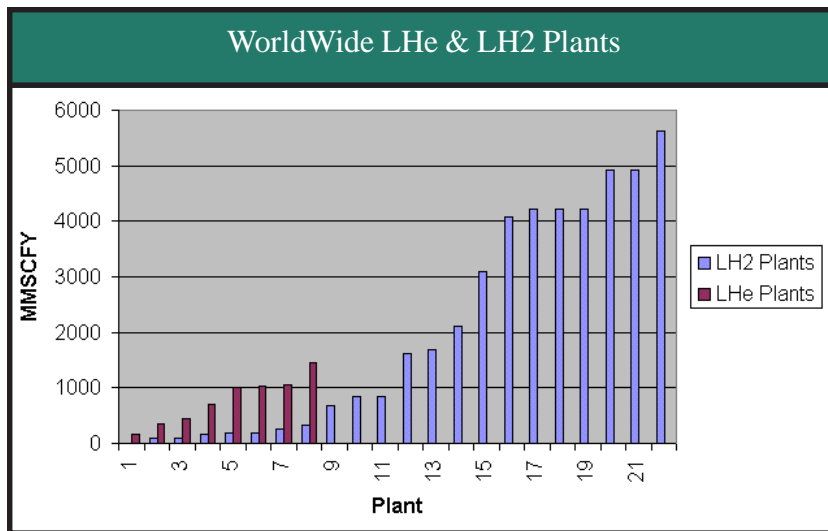


Figure 1

tions, most hydrogen these days is produced from hydrocarbons. Helium, on the other hand, is solely recovered from natural gas.

Helium and hydrogen are typically purified by pressure swing adsorption (PSA). The optimum feed pressure to a PSA is about 350 psi. Some trace impurities usually remain and are taken out in the liquefiers by adsorption on activated carbon. The major difference in the purification

trains is the processing of the waste gas that contains about 30 percent of the helium or hydrogen. The blowdown gas from hydrogen PSA systems consists mostly of carbon dioxide and hydrogen which is directed into the fired side of the reformer furnace, recovering its fuel value (Figure 2).

For a helium PSA, the high value of helium justifies recovery of the blowdown gas consisting of helium and nitrogen. It is recovered by recompressing to feed pressure where the total stream passes through a -320°F cryogenic condenser before entering the PSA. The major costs associated with PSA purification are the capital cost of the PSA, and the energy to recover of the helium or hydrogen in the blowdown gas. The extra step needed for helium purification doubles the capital cost as compared to the hydrogen purification system (Figure 3).

Liquefying Hydrogen and Helium

The capital equipment used to liquefy hydrogen is similar to helium liquefaction systems. Both use vacuum insulated cold boxes with turbine expanders, usually liquid nitrogen pre-cooling, and mostly oil flooded screw compressors, sometimes in combination with reciprocating compressors. A typical process used for the lique-

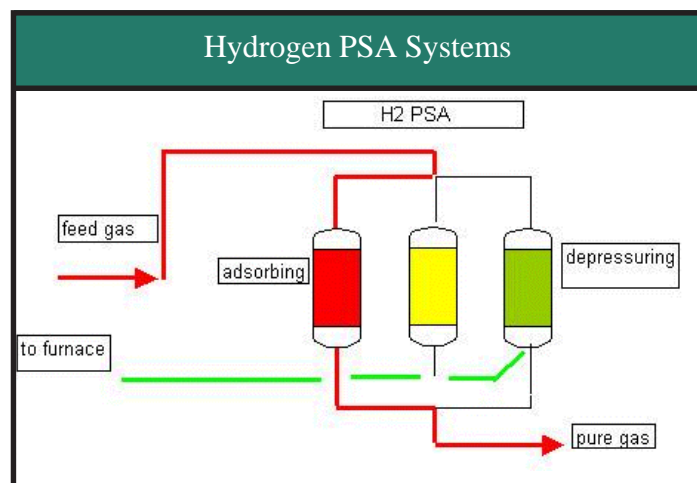


Figure 2

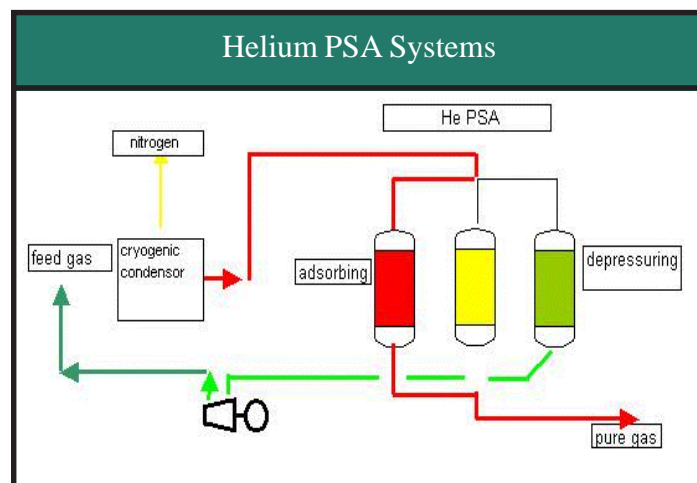


Figure 3

faction of helium and adapted to hydrogen liquefaction is a Brayton cycle as shown in Figure 4.

The larger hydrogen plants use more complex cycles as the improvement in power consumption outweighs the increased capital. For the smaller plants (less than 200 MMSCFY), a standard helium liquefier is often adapted to the liquefaction of hydrogen. One important difference is the need to convert the ortho molecular form of hydrogen to the para form. This is accomplished in multiple beds of catalysts which in turns generates heat, an additional refrigeration load. Typical costs for helium liquefiers, can be adjusted for the extra cost of ortho to para conversion in order to bring into focus the unit investment for hydrogen liquefaction. As discussed later, the amount of power to liquefy hydrogen per 100 scf is similar to helium liquefaction. In T. Strobbridge's often quoted survey³, he demonstrates a direct relationship between the input power of low temperature refrigerators and cost.

Figure 5 shows the unit cost of the liquefaction capital cost over the range of small to medium size hydrogen liquefiers. The scope included in the capital cost is an installed liquefier with some storage. It does not include the reformer or PSA purification. The unit costs used for the chart are based on an installed cost for a pure hydrogen gas liquefier using a 75 percent debt at five percent interest rate, 25 percent equity financing, a 15 percent internal rate of return on the investment, double declining depreciation over five years, and a 15 year plant life. It assumes the liquefier is added to an existing plant and does not include costs for land, building, and storage. The investment for the distribution

due to its greater specific heat, the liquefaction of hydrogen will consume a third more liquid nitrogen per scf than the liquefaction of helium. Other than cost of the pure gas, liquid nitrogen consumption is a the major variant when comparing liquid hydrogen with liquid helium on a scf basis. Another factor increasing the quantity of liquid nitrogen is an ortho to para conversion step at -320°F. A reasonable unit cost use estimate for the quantity of liquid nitrogen, used is 67 scf of liquid nitrogen per 100 scf of hydrogen. Whether to produce liquid nitrogen at the hydrogen facility or import it, will depend on the local availability and cost of liquid nitrogen. Some processes improve the variable costs with more investment by consuming the liquid nitrogen at lower temperatures using vacuum compression.

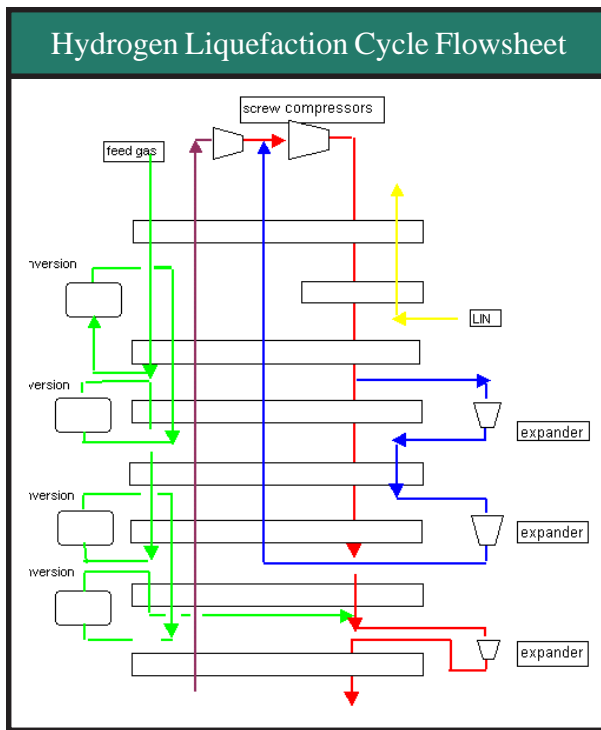


Figure 4

equipment and customer storage tanks (usually recovered as a facility fee) can exceed the investment in the liquefier.

Hydrogen Liquefaction Variable Costs

The major variable costs to liquefy hydrogen are the cost of liquid nitrogen for pre-cooling and electrical energy for compression. Labor and overhead costs will depend on staffing and if the liquefaction system is integrated with the operation of other onsite units such as a natural gas reformer or ASU.

Liquid Nitrogen Consumption

Many liquid helium and liquid hydrogen production facilities use liquid nitrogen to provide refrigeration down to temperatures of -320°F to -340°F. The consumption per unit of liquefaction does not vary much over a wide range of plant sizes. But

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Compression Costs

The theoretical work to liquefy helium should be greater than hydrogen because of its colder liquefaction temperature. However, hydrogen must be converted to the para molecular form during liquefaction, since ortho form will vaporize rapidly when liquefied. The conversion is accomplished in a series of catalyst beds and is a heat producing change. This is explained in an article by G. Kinard⁴. This conversion adds to the work consumed to liquefy hydrogen liquefaction. Therefore when hydrogen liquefaction and helium liquefaction compression are compared on a kwh/100scf basis, they are close enough for conceptual cost estimating.

Since it is assumed liquid nitrogen is provided for refrigeration for both hydrogen and helium liquefiers, the remaining energy below -320°F is removed by

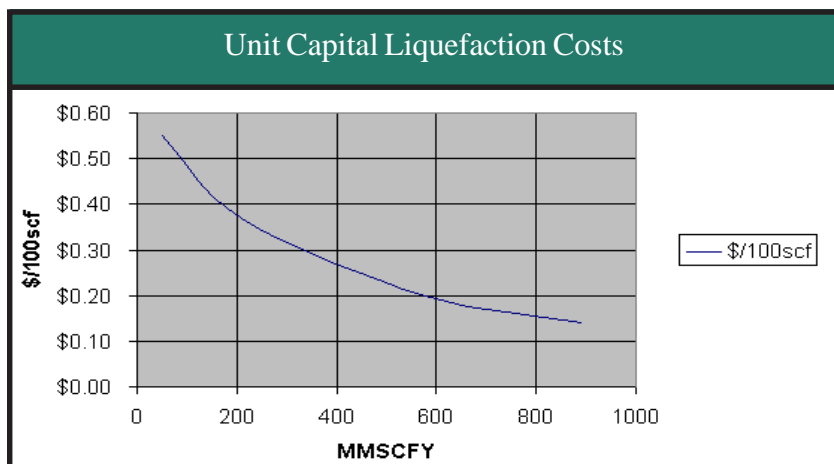


Figure 5

compression of recycle gas and expanders. The theoretical work per 100scf, below -320°F to liquefy hydrogen is less than helium liquefaction. The hydrogen theoretical work assumes that the ortho to para conversion occurs incrementally as the hydrogen is cooled. In practice though, the conversion is done in a few steps, at different temperature levels and this inefficiency almost closes the power consumption gap. The actual electric power consumption will depend on the efficiency of the specific liquefier and is usually expressed as Carnot efficiency. The efficiency does improve as systems become larger because the cycles become more complex and efficiencies of expanders and compressors usually get better as they become physically larger.

A useful rule of thumb to estimate the power required, is to assume 3 kwh/100scf for the smaller liquefiers and 2 kwh for the mid sized units. Note that it is assumed the hydrogen gas fed to the liquefier has been compressed prior to the PSA unit.

In conclusion, the Rough Order of Magnitude (ROM) factors presented here can be used to bring into focus the liquefaction costs for small to medium size hydrogen liquefiers. These costs added to the cost of hydrogen gas can be compared to the typical wholesale price F.O.B. the large U.S. production plants of \$ 0.50/100scf. Since liquefaction is such a large portion of the total cost of liquid hydrogen a much more detailed analysis would be necessary to prove the economics of a potential project. ■

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