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SRI Project 8562

LIQUID HYDROGEN PRODUCTION AND COMMERCIAL DEMAND IN THE UNITED STATES

Prepared for:

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EXECUTIVE SUMMARY

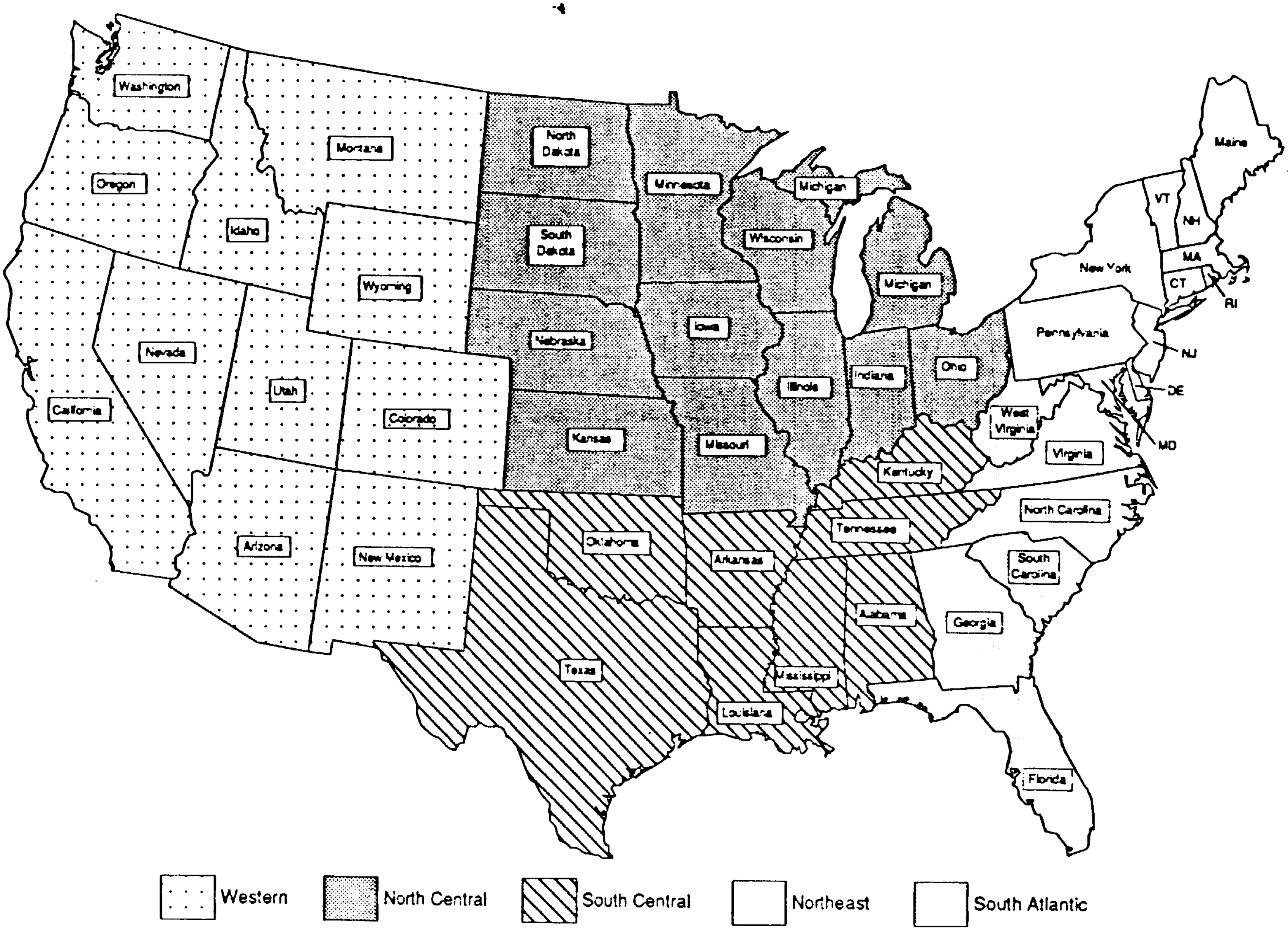
INTRODUCTION AND METHOD OF APPROACH

SRI International (SRI) is pleased to present this final report on liquid hydrogen production and demand, under contract NAS10-11643. Kennedy Space Center (KSC), the single largest purchaser of liquid hydrogen in the United States, manages liquid hydrogen in support of government programs. Increased demand from the commercial sector, as well as NASA's heavy reliance on hydrogen produced from a single hydrogen plant, has prompted KSC to evaluate current and anticipated hydrogen production and consumption in the government and commercial sectors, in order to determine the type of procurement best suited to meeting KSCs hydrogen requirements. The government analysis was conducted by KSC. This study represents SRI's assessment of the commercial sector.

To conduct this study, SRI compiled available information on hydrogen production, trade, consumption and macro-economic trends likely to affect consumption. This information was supplemented by extensive interviews with hydrogen producers, consumers and industry organizations. Specific objectives of the study are as follows:

- Identify liquid hydrogen producers in the United States and Canada during the 1980-1989 period, including:
  - Plant locations, capacities, date on stream and production process used (e.g., burning natural gas or liquefaction of by-product hydrogen)
  - True delivery capability assessed on a best-efforts basis.
- Compile information on expected changes in liquid hydrogen production capabilities in the United States and Canada over the 1990-2000 period.
- Describe how hydrogen is used in each consuming industry and estimate U.S. liquid hydrogen consumption for the chemicals, metals, electronics, fats and oil, and glass industries, and report data on a regional basis as illustrated in Figure ES-1.
- Estimate historical consumption for the years 1980, 1985, 1987, 1988, 1989, and future consumption for 1990, 1995, 2000.
- Assess the influence of international demands on U.S. plants, and in particular, the influence of the Canadian market on Canadian and U.S. production.

Figure ES-1
LIQUID HYDROGEN CONSUMING REGIONS



CONCLUSIONS

As a result of this survey, SRI can present the following observations about the producers of hydrogen, and some projections about the future use.

Liquid Hydrogen Producers

Four companies produce liquid hydrogen at 8 locations in North America. Three of the plants are located in Canada; five are in the United States. A history of producers, plants capacities for the 1980-1990 period is summarized in Table ES-1.

Significant changes that have taken place in terms of liquid hydrogen suppliers over the 1980-1990 period include the following:

- Idle capacity on the West Coast was closed or moved east in order to be closer to the market.
- U.S. based capacity decreased 6.8% while Canadian capacity increased from no capacity in 1980 to 50 tons per day by July 1990. Overall, this corresponds to a 27% increase in North American capacity.
- The number of companies producing liquid hydrogen has expanded. In 1980, Air Products, Airco, and Union Carbide all produced in the United States. In 1982, Airco ceased production and participated in the business as a distributor, leaving Air Products and Union Carbide as the sole producers over the 1983-1988 period. In 1988 the situation changed when HydrogenAL began operating its liquid hydrogen plant in Becancour, Quebec. In June 1990, Airco began operating a plant in Magog, Quebec. Product from HydrogenAl's plant is distributed in the United States by Liquid Air Corporation.
- The newer plants have tended to be smaller than previous plants and to use by-product hydrogen streams.

Industry is still adjusting to the Canadian capacity that has recently come on stream. No company has formally announced plans to construct a new liquid hydrogen plant in North America although there have been rumors of plants being considered for the South Atlantic and the West Coast. Air Products is in the process of debottlenecking its facilities, which will increase the company's North American nameplate capacity to 106-108 tons per day by 1992. No company has announced plans to close capacity, although it is reasonable to believe that Union Carbide will permanently close its Ashtabula plant and add capacity elsewhere by 1995.

Nameplate capacities for any given year are somewhat higher than true delivery capability on an annual basis when factors such as losses and downtime for plant maintenance are taken into account. In general, it is estimated that plants are able to have 92% of nameplate capacity available for delivery. One exception to this may be the Union Carbide plant at Ontario, CA, which is difficult to rate effectively since the plant operates well under capacity due to insufficient demand for product.

Table ES-1
NORTH AMERICAN LIQUID HYDROGEN PRODUCERS
Nameplate Capacity as of January 1 of the Given Year
(Short Tons per Day)

Producing Company and Plant Location	Date on Stream	Production Process or Hydrogen Source	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991p	Remarks
United States															
Air Products and Chemicals Inc. Industrial Gases Division Long Beach, CA	1963	By-product refinery hydrogen purchased from Atlantic Richfield Company, Carson, CA	30	30	15	15	15	15	15	0	0	0	0	0	A 15 ton per day liquefier was moved from this location to Sarnia, Ontario in 1981. The remaining capacity was closed when Air Products opened its Sacramento facility.
New Orleans, LA	1965	Steam reforming of natural gas	30	30	30	30	30	30	30	32.5	32.5	32.5	32.5	32.5	
	1977	Steam reforming of natural gas	30	30	30	30	30	30	30	32.5	32.5	32.5	32.5	32.5	
Sacramento, CA	1986	Steam reforming of natural gas	0	0	0	0	0	0	0	5.6	5.6	5.6	5.6	5.6	
Total, Air Products			90	90	75	75	75	75	75	71	71	71	71	71	By 1992, debottlenecking is anticipated to raise Air Product's total U.S. nameplate capacity by 6-8 tons per day.
The BOC Group, Inc. Airco Distributor Gases Division Airco Gases Division Pedricktown, NJ	1963	Hydrogen was purchased from Sun Olin Chemical Company, which co-produces hydrogen and carbon monoxide by steam reforming of natural gas	6	6	6	6	0	0	0	0	0	0	0	0	Permanently closed.
Union Carbide Corporation Linde Division Ashtabula, OH	1974, 1978	Steam reforming of natural gas; PSA purification	18.8	18.8	12	12	12	12	12	12	12	12	12	12	Plant operates as needed to supplement production from Niagara Falls. A portion of the product from this facility is marketed in gaseous form and not liquified. The facility was initially designed to be capable of producing 18 tons per day of hydrogen, although the actual production capacity was 7 tons per day in 1974. In 1977 the compressors, expanders, and purification unit were modified and a second steam reformer was added, bringing capacity to 18.8 tons per day. The original steam reformer was closed in 1984, bringing capacity to 12 tons per day.
Niagara Falls, NY	1981	By-product of chlorine sodium hydroxide production, cryogenic purification	0	0	22	22	22	22	22	22	22	22	33	33	Facility was built to be easily expanded by an additional 11 tons per day. By-product hydrogen is available from three sources: Occidental Chemical Corporation (with the capacity to generate 23 tons of by-product hydrogen per day), Niachlor Inc. (with the capacity to generate 16 tons of by-product hydrogen per day), and Olin Corporation (with the capacity to generate 6 tons of by-product hydrogen per day). Union Carbide is not the only consumer of hydrogen from these plants.
Ontario, CA	1962	Steam reforming of natural gas; PSA purification installed in 1984	32	32	32	32	21	21	21	21	21	21	21	21	A portion of the product produced from this facility is marketed in gaseous form and not liquified.
Total, Union Carbide			51	51	66	66	55	55	55	55	55	55	66	66	

Table ES-1 (concluded)

Producing Company and Plant Location	Date on Stream	Production Process or Hydrogen Source	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991p	Remarks
Canada															
Air Products and Chemicals Inc. Sarnia, Ontario	1982	By-product hydrogen is purchased from Dow Chemical Canada Inc.'s chlorine-sodium hydroxide plant	0	0	15	15	15	15	15	15	15	22	24	24	Liquefier was moved to this location from Long Beach, CA in 1981. The facility was debottlenecked in 1989 and again in 1990. By 1992, capacity will be increased to 29 tons per day. Dow has the capacity to produce 29 tons per day of by-product hydrogen.
BOC Group, Inc. Airco Industrial Gases, Division Magog, Quebec	June 1990	By-product hydrogen is purchased from Eka Nobel Canada Inc.'s sodium chlorate plant	0	0	0	0	0	0	0	0	0	0	0	15	Plant came on-stream June 1, 1990. Eka Nobel Canada (formerly Quenord, Inc.) has the capacity to produce 19 tons per day of hydrogen.
HydrogenAL Co. Ltd. (A joint venture between Hydro-Quebec and Canadian Liquid Air Ltd.) Becancour, Quebec	1988	By-product hydrogen purchased from C-I-L Corporation's chlorine sodium hydroxide plant (8 tons per day) and electrolytic hydrogen (3 tons per day)	0	0	0	0	0	0	0	0	0	11	11	11	Plant came on-stream in 1988. CIL has the capacity to produce 21 short tons per day of by-product hydrogen. CIL also supplies by-product hydrogen to Oxychem Canada's nearby hydrogen peroxide plant. A steam reformer operates nearby to supply gaseous hydrogen to Norsk Hydro Canada Inc. This hydrogen can reportedly be routed to HydrogenAL.
Total Canadian Nameplate Capacity			0	0	15	15	15	15	15	15	15	33	35	54	
Total North American Nameplate capacity			147	147	162	162	145	145	145	141	141	159	172	191	

Consumption

Although government use typically accounts for only about one fifth of all liquid hydrogen consumed in the United States, it is the only application that requires significant volumes of liquid hydrogen. For commercial consumers, liquid hydrogen is purchased for convenience or, particularly for small volume users, economics. The liquid hydrogen is then vaporized and used in gaseous form. This could change if a new market that consumed hydrogen in liquid form, such as fuel for commercial aircraft, emerged. SRI does not anticipate this occurring before 2000.

The primary commercial markets for liquid hydrogen are in the chemical, metals, electronics, fats and oils, and glass industries. Current, historic, and projected liquid hydrogen consumption for 1990 in each of these industries is presented in Table ES-2.

Table ES-2
U.S. COMMERCIAL MARKET FOR LIQUID HYDROGEN
(tons per day)

	Chemicals, Petrochemicals, and Refining	Metals	Electronics	Fats and Oils	Glass	Other	Total
1980	18.2	14.7	14.6	7.6	4.9	1.1	61.0
1985	21.7	17.2	16.1	6.7	5.0	1.1	67.8
1987	23.5	18.6	16.7	6.4	5.1	2.4	72.8
1988	24.5	19.5	17.5	6.2	5.4	1.9	74.9
1989	30.1	20.5	18.3	6.5	5.4	2.7	83.5
1990	31.6	21.8	19.1	6.1	5.1	3.1	86.8
1995	37-38	30-32	24-25	8	6	4	109-113
2000	43-48	40-44	30-31	9-11	6-8	4-6	132-148

Source: SRI estimates

The commercial market for liquid hydrogen increased at an average annual rate of 2.1% from 1980 to 1985, and at an average annual rate of 3.4% from 1985 to 1988. Consumption increased a dramatic 11.5% in 1989 over the previous year. Reasons for the increase include real growth, efforts by new producers to load their current or planned plants, and temporary market opportunities. For example, when one consumer's source of by-product hydrogen went down for about eight months in 1989 and 1990, the consumer was forced to purchase liquid hydrogen. This single account represented up to 140,000 standard cubic feet per hour (0.36 tons per hour) of demand.

Industry representatives have divergent views regarding future commercial demand for liquid hydrogen, especially over the 1995-2000 period. Representatives have reported anticipated growth rates ranging from 4% to 10%.

SRI forecasts U.S. consumption of liquid hydrogen to increase 4% between 1989 and 1990, then grow at an average annual rate of approximately 4.5% to 5.5% for the next five years. This corresponds to growth at an average annual rate of 4.5% to 5.2% over the 1989 to 1995 period. Demand from 1995 to 2000 is forecast to increase at an average annual rate of 4.0% to 5.5%. Overall, demand is forecast to increase at an average annual rate of 4.3% to 5.3% from 1989 to 2000. SRI believes that growth will increase at the lower end of the range predicted by industry for the following reasons:

- A large part of growth in the industry has been through conversion of captive gaseous hydrogen producers to purchasers of liquid hydrogen. There are expected to be fewer opportunities for this sort of growth in the future.
- In response to increased competition in supplying liquid hydrogen, some gas companies appear to be converting large liquid hydrogen accounts to supplier owned, on-site plants, which are generally longer term contracts.
- As plant loadings increase, gas companies are likely to emphasize servicing more profitable accounts, causing some consumers to convert to captive production.
- Demand in 1989 was unusually high.

Geographically, consumption is concentrated northeast of the Mississippi river. This will continue to be the case through 2000. The following table displays where the major markets for liquid hydrogen are geographically.

Table ES-3
U.S. LIQUID HYDROGEN MARKETS IN 1989 BY GEOGRAPHIC REGION
(tons per day)

	Northeast	North Central	South Atlantic	South Central	West	Total
Chemicals, petrochemicals, and refining	8.4	7.6	5.0	7.6	1.5	30.1
Metals	7.8	7.1	1.8	2.4	1.4	20.5
Electronics	3.6	2.0	1.8	4.6	6.3	18.3
Fats and oils	0.8	2.9	1.0	1.3	0.5	6.5
Glass	0.6	1.6	1.2	1.3	0.7	5.4
Other	0.8	0.7	0.4	0.5	0.3	2.7
Total	22.0	21.9	11.2	17.7	10.7	83.5

International demand has placed and will continue to place insignificant demands on U.S. plants. It is expected that Canadian plants will continue to represent a significant source of liquid hydrogen to the commercial sector.

Canada is reviewing a large scale project to export liquid hydrogen as an energy carrier to Western Europe. Since it is highly uncertain whether the project will come to fruition before 2000, and since the project would include the construction of a new hydrogen plant close to a shipping terminal, it is assumed that offshore demands for Canadian hydrogen will be minimal.

INTRODUCTION

SRI International (SRI) is pleased to present this final report on liquid hydrogen production and demand, under contract NAS10-11643. Kennedy Space Center (KSC), the single largest purchaser of liquid hydrogen in the United States, manages liquid hydrogen in support of government programs. The first liquid hydrogen plants in the United States were built primarily to supply government contracts for liquid hydrogen. With the increased availability of liquid hydrogen, however, producers began to identify accounts in the commercial sector that would benefit from purchasing product in liquid form. Increased demand from the commercial sector, as well as NASA's heavy reliance on hydrogen produced from a single hydrogen plant, has prompted KSC to evaluate current and anticipated hydrogen production and consumption in the government and commercial sectors, in order to determine the type of procurement best suited to meeting KSCs hydrogen requirements. The government analysis was conducted by KSC. This study represents SRI's assessment of the commercial sector.

To conduct this study, SRI compiled available information on hydrogen production, trade, consumption and macro-economic trends likely to affect consumption. This information was supplemented by extensive interviews with hydrogen producers, consumers and industry organizations. Specific objectives of the study are as follows:

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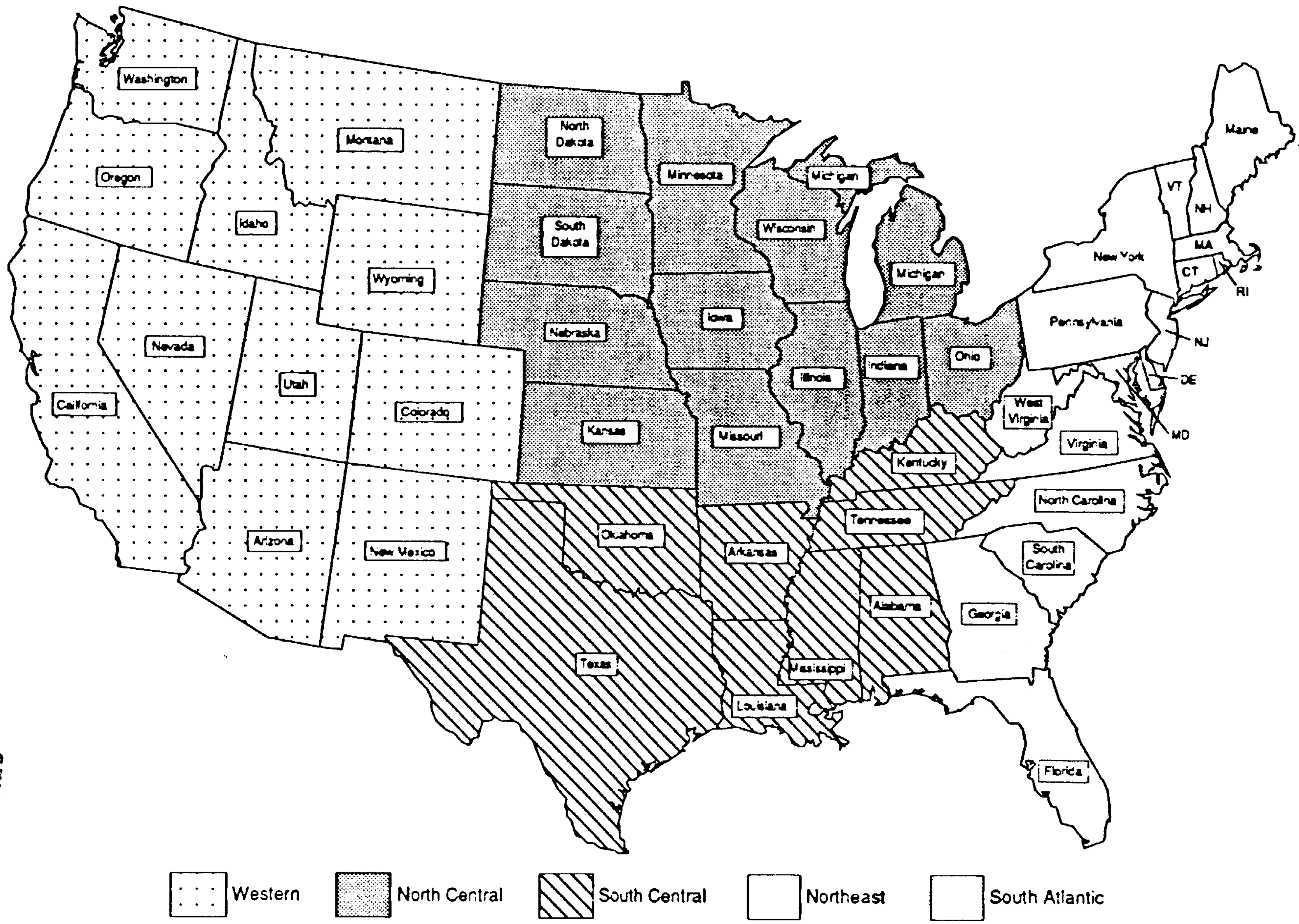
- Estimate historical consumption for the years 1980, 1985, 1987, 1988, 1989, and future consumption for 1990, 1995, 2000.
- Assess the influence of international demands on U.S. plants, and in particular, the influence of the Canadian market on Canadian and U.S. production.

The remainder of this report discusses the current producers and consumers of liquid hydrogen, and suggests trends in consumption for the chemicals, metals, and electronics industries.

Figure 1
LIQUID HYDROGEN CONSUMING REGIONS



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LIQUID HYDROGEN PRODUCERS

In 1980 three companies, Air Products and Chemicals, Inc. (Air Products), the Linde division of Union Carbide Corporation (Union Carbide), and Airco Inc. (Airco, later acquired by BOC Group, Inc.), produced liquid hydrogen in North America. All of the plants were located in the United States. The hydrogen liquified at each of these facilities was hydrocarbon based.

Over the 1980-1985 period, several changes occurred. Air Products and Union Carbide built new plants that took advantage of by-product hydrogen streams in areas with comparatively inexpensive electricity. Airco decided it was not economic to continue to operate its plant but continued to participate in the liquid hydrogen business as a distributor. This left Air Products and Union Carbide as the only North American producers over the 1983-1988 period.

Industry observers perceived the liquid hydrogen business to be profitable. This factor, combined with Canada's interest in utilizing its relatively inexpensive and abundant supplies of electricity, provided the right background for L'Air Liquide and BOC Group to enter the liquid hydrogen business in North America. In 1988 HydrogenAL Co. Ltd., a joint venture between Hydro-Quebec and Canadian Liquid Air (owned by L'Air Liquide SA, France), began operating a liquid hydrogen plant in Becancour, Quebec. On June 1, 1990, Airco (owned by BOC Group) began operating a plant in Magog, Quebec. Table 1 identifies plant locations, capacities, dates on stream, and production processes for liquid hydrogen producers in the United States and Canada during the 1980-1991 period.

True delivery capability is somewhat lower than the nameplate capacity. Factors that are sometimes quoted for converting nameplate capacity to true delivery capability include an on-stream factor (the days per year the plant operates) and a utilization factor (the ratio of product leaving the plant to product produced, which accounts for the losses associated with storing and handling the product before it leaves the plant). Historically, industry observers have estimated true production capacity at about 85% of nameplate capacity. In 1990, is is estimated that all plants are able to produce 92% of nameplate capacity. Air Products is believed to rate its plants closer to their delivery capabilities and may be able to produce at capacity on a short-term basis. Additional product losses take place in delivering the product to the customer. Delivery losses will vary depending on a supplier's delivery system and the number of tanks that must be filled at a customer site. In general, delivery losses are minor, estimated at 2 to 3%.

Not all of the North American plants are currently operating at capacity. The two new Canadian plants in Quebec, Magog and Becancour, are estimated to be running at about 50% capacity. In the United States, the Union Carbide facility at Ashtabula, OH, is run as needed to supplement production from Niagara Falls. Union Carbide's plant at Ontario, CA, is also not fully loaded. Although officially rated at 21-22 tons per day, the Ontario, CA facility is not believed to be ready to produce that amount on demand; industry sources estimate that 17 tons per day may be a more realistic nameplate capacity without modification to the plant or changes in operating procedures. The Ashtabula and Ontario facilities are currently marketing a portion of the gas stream available for liquefaction as gaseous hydrogen.

Table 1
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Total, Air Products			90	90	75	75	75	75	75	71	71	71	71	71	By 1992, debottlenecking is anticipated to raise Air Product's total U.S. nameplate capacity by 6-8 tons per day.
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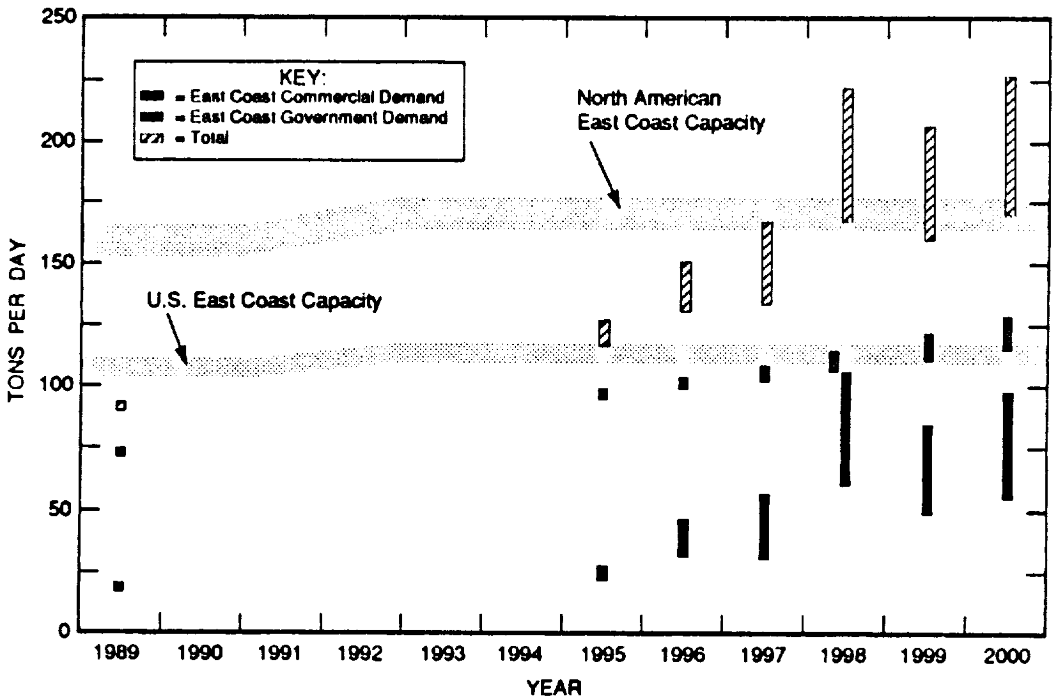
Total Canadian Nameplate Capacity			0	0	15	15	15	15	15	15	15	33	35	54	
Total North American Nameplate capacity			147	147	162	162	145	145	145	141	141	159	172	191	

Industry is still adjusting to the Canadian capacity that has recently come on stream. No company has formally announced plans to construct a new liquid hydrogen plant in North America although there have been rumors of plants being considered for the South Atlantic and the West Coast. Air Products is currently conducting a debottlenecking program that will increase total company capacity by 12 to 14 tons per day in terms of nameplate capacity, or 11 to 12 tons in terms of actual production capability, by 1992 as compared to 1990.

Despite the presence of excess capacity there have been times when extraordinary circumstances have caused supplies to be short, for example, in late May of 1990, Air Products' Sarnia plant was down for scheduled maintenance. Meanwhile, a strike curtailed deliveries from the plants in Quebec, and Union Carbide's Ashtabula plant was down temporarily from fouling of the catalyst. These supply problems, combined with a period of high demand for the space program, caused a temporary problem in meeting demand despite the theoretical excess of capacity as compared to demand. North American capacity is compared to current and future liquid hydrogen demand as projected by SRI in Figures 2, 3, and 4. Figure 4 also shows how SRI's projections compare to more optimistic forecasts.

Figure 2

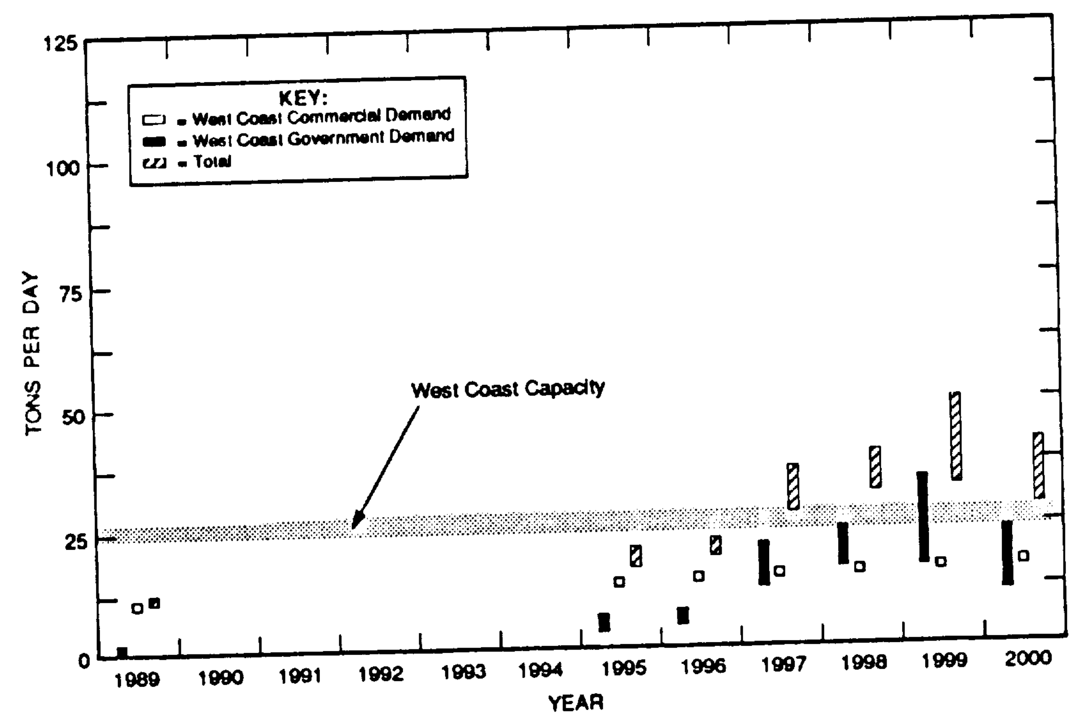
EAST COAST LIQUID HYDROGEN PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

Figure 3

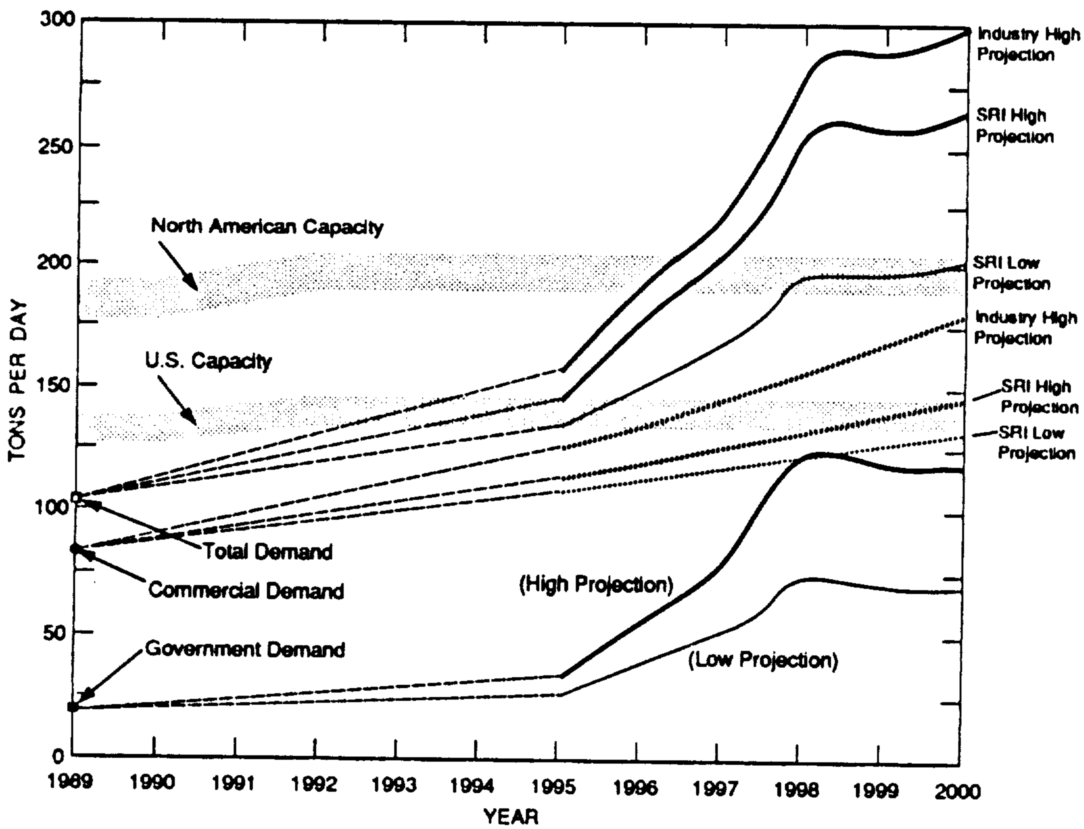
WEST COAST LIQUID HYDROGEN PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

Figure 4

TOTAL U.S. LIQUID HYDROGEN PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

LIQUID HYDROGEN CONSUMPTION

MARKET OVERVIEW

In 1989, an estimated 2,390 billion cubic feet of intentionally produced hydrogen were consumed in the U.S. This figure includes by-product hydrogen intentionally recovered for merchant use, but excludes by-product hydrogen used as fuel or vented, and also excludes large volumes of by-product hydrogen that are produced and consumed captively by refineries. Of the 2,390 billion cubic feet consumed, an estimated 2,324 billion cubic feet were produced captively and consumed in gaseous form primarily by the ammonia, methanol, and petroleum refining industries. Of the remaining 66 billion cubic feet of hydrogen, representing merchant product, an estimated 11.7 billion cubic feet were consumed in liquid form. This is illustrated in Table 2, following, with figures based on SRI estimates. The petroleum refineries consumption does not include hydrogen produced as a by-product of catalytic reforming.

Table 2
U.S. CONSUMPTION OF HYDROGEN–1989

	Billions of Cubic Feet	Tons per Day
Ammonia Producers	1,147	8,180
Refineries[a]	895	6,390
Methanol Producers	172	1,230
Small-Volume Captive Users	110	785
Small-Volume Merchant Users	54 (gas)	385 (gas)
	12 (liquid)	84 (liquid)
Total[b]	2,390	17,054

a. Datum represents hydrogen capacity installed at refineries and does not include hydrogen produced as a by-product of catalytic reforming. In 1989, catalytic reforming generated an estimated 1.4-1.7 trillion cubic feet of hydrogen.

b. In addition to hydrogen that is produced or recovered for consumption, large volumes of by-product hydrogen are generated and used as fuel or vented.

Source: SRI estimates.

In the commercial sector, there are currently no large volume uses that require liquid hydrogen. Liquid hydrogen has achieved widespread use because of the savings in transportation and handling costs for the liquid form compared to the gaseous form for consumers who find it is not economic or otherwise feasible to produce hydrogen captively or purchase it via pipeline.

Some industries that use gaseous hydrogen will be more inclined to purchase it in liquid form than others. For example, applications that need extremely high purity hydrogen will generally prefer to use liquid hydrogen because the process of liquefaction produces an extremely pure product. Thus, the electronics industry has historically tended to use liquid hydrogen.

For the remaining industries–chemicals, metals, fats and oils, and glass–the decision to use liquid hydrogen is primarily based on an individual company's proximity to a source of gaseous hydrogen and the volumes of hydrogen consumed. For distances beyond 100 miles from the source, liquid hydrogen can typically be delivered more economically than gas unless the gaseous hydrogen can be delivered by pipeline. In general, bulk gas and bulk liquid hydrogen costs are roughly the same for consumers purchasing 40 to 50 thousand standard cubic feet of product per month. For larger purchases, gas is generally more expensive on a cost-per-unit basis. However, with liquid hydrogen there are losses due to evaporation. For this reason, liquid hydrogen is generally not recommended for locations where less than 100,000 cubic feet per month are consumed.

When a company's requirements are large enough, it becomes economic to have the hydrogen produced at the consuming location. These plants are called captive plants if owned by the consumer and on-site plants if owned and operated by an industrial gas company. Although on-site hydrogen production costs can vary considerably depending on the price of the feedstock, industry sources state that liquid hydrogen and on-site hydrogen costs are usually equivalent for locations that consume 8 to 10 million cubic feet per month. If consumption is greater, on-site hydrogen is generally less expensive than liquid. This does not necessarily mean that all users of over 10 million cubic feet will have an on-site plant installed. Companies with borderline consumption are often willing to pay a bit more for liquid hydrogen for the following reasons:

- If a company's hydrogen requirements change, the company is not saddled with a plant that it may no longer need.
- The company does not need to worry about plant maintenance or the reliability of its hydrogen supply.
- Liquid hydrogen may be purchased in direct accordance with a company's requirements if use rates are not continuous.

Companies with captive facilities may also purchase liquid hydrogen on occasion. For example, liquid hydrogen may be purchased when the hydrogen plant is closed for scheduled maintenance periods, if the hydrogen plant is not operating properly, or to supplement captive hydrogen during periods of peak demand. Captive plants typically close for maintenance once a year.

No changes in production technology that will significantly alter the economics of captive production are anticipated by industry. However, it is unclear at this time what impact gas separation membranes will have on the merchant hydrogen business. Membranes can be used to clean up a by-product hydrogen stream, displacing demand for generated or purchased hydrogen. Membranes can only be used to concentrate hydrogen, not to produce hydrogen.

In the chemicals, metals, and fats and oils industries, hydrogen is supplied by captive production, purchased gas, and purchased liquid. In the glass industry, all of the users currently purchase liquid hydrogen.

Liquid hydrogen consumption in a given region can vary by large amounts on short notice, particularly in the chemical, petrochemical and refining industries where a large portion of consumption is for servicing accounts that ordinarily have an alternate hydrogen source available. Consumption can decrease dramatically when a company that has been consuming liquid hydrogen decides it would be more economic to have a plant on site.

The commercial market for liquid hydrogen increased at an average annual rate of 2.1% from 1980 to 1985, and at an average annual rate of 3.4% from 1985 to 1988. Consumption increased a dramatic 11.5% in 1989 over the previous year. Reasons for the increase include real growth, efforts by new producers to load their current or planned plants, and temporary market opportunities. Current, historic, and projected liquid hydrogen consumption in each of the major consuming industries is presented in Table 3.

Table 3
U.S. COMMERCIAL MARKET FOR LIQUID HYDROGEN
(millions of cubic feet)

	Chemicals, Petrochemicals, and Refineries	Metals	Electronics	Fats and Oils	Glass	Other	Total
1980	2,555	2,050	2,040	1,060	685	160	8,550
1985	3,040	2,410	2,250	940	700	160	9,500
1987	3,300	2,600	2,340	900	720	340	10,200
1988	3,430	2,730	2,455	870	750	265	10,500
1989	4,215	2,870	2,565	910	760	380	11,700
1990	4,430	3,050	2,680	870	710	425	12,165
1995	5,210-5,370	4,295-4,440	3,340-3,440	1,085-1,185	795-910	495-515	15,220-15,860
2000	6,035-6,695	5,600-6,240	4,160-4,395	1,290-1,480	855-1,055	600-830	18,540-20,695

Industry representatives have divergent views regarding future commercial demand for liquid hydrogen, especially over the 1995-2000 period. Representatives have reported anticipated growth rates ranging from 4% to 10%.

SRI forecasts U.S. consumption of liquid hydrogen to increase at an average annual rate of 4.5% to 5.2% from 1989 to 1995. Demand from 1995 to 2000 is forecast to increase at an average annual rate of 4.0% to 5.5%. Overall, demand is forecast to increase at an average rate of 4.3% to 5.3% from 1989 to 2000.

SRI believes that growth will increase at the lower end of the range predicted by industry for the following reasons:

- A large part of past growth in the industry has been through conversion of captive gaseous hydrogen producers to purchasers of liquid hydrogen. There are expected to be fewer opportunities for this sort of growth in the future.
- In response to increased competition in supplying liquid hydrogen, some gas companies have been converting liquid hydrogen accounts to supplier owned on-site plants, which are generally longer term contracts. Examples include a Union Carbide facility that went on stream in 1989 to supply AT&T's fiber optics plant in Norcross, GA; Air Product's facility to supply FMC Corporation's chemical plant at South Charleston, WV; and Air Product's facility at American Cyanamid's chemical plant in Hannibal, MO
- As plant loadings increase, gas companies are likely to emphasize servicing more profitable accounts, causing some consumers to convert to captive production.
- Demand in 1989 was unusually high.

Geographically, consumption is concentrated in the northeastern states, Michigan, Indiana, and Ohio. This will continue to be the case through 2000. The following tables display data on the major markets for liquid hydrogen by market sectors.

CHEMICALS, PETROCHEMICALS, AND REFINERIES

Table 4 displays consumption in the chemical industry to date, and projections for the next ten years.

Table 4
LIQUID HYDROGEN CONSUMPTION IN THE CHEMICAL, PETROCHEMICAL, AND REFINING INDUSTRIES

Year	Millions of Cubic Feet	Average Annual Growth
1980	2555	
1985	3040	3.5% (1980-1985)
1987	3300	
1988	3430	
1989	4215	8.5% (1985-1989)
1990	4430	
1995	5210-5370	3.6% to 4.1% (1989-1995)
2000	6035-6695	3.0% to 4.5% (1995-2000)

Chemical, Petrochemical, and Refining Applications

Hydrogen, a reducing agent, is widely used in the chemical, petrochemical, and refining industries. In addition to use for its chemical properties, hydrogen is used for cooling during the liquefaction of argon. Chemicals that consume hydrogen in their manufacture are listed in Table 5.

Table 5
HYDROGEN CONSUMING CHEMICALS AND PETROCHEMICALS

acrylamide	hydrogen peroxide
adiponitrile	hydrogenated bisphenol A
alcohols	hydrogenated rosin
p-aminophenol	hydrogenated styrene-butadiene block co-polymer
ammonia	hydrogenated terpene derivatives
aniline (from nitrobenzene)	isobutane
argon (liquid)	isopentane
ascorbic acid	isophorone diisocyanate
1,4-butanediol	lithium hydride
butene-1	methanol
butyrolactam	methylene di-para-phenylene isocyanate (MDI)
butyrolactone	pharmaceuticals
calcium hydride	piperidine
caprolactam	poly alpha-olefins
cyclohexane (from benzene)	polybutene-1
cyclohexanol	polyethylene
cyclohexanone	polypropylene
cyclohexylamine	propylene oxide
ethyleneamines	resins
p-ethyltoluene	sodium hydride
fatty acids	sorbitol
furfuryl alcohol	terephthalic acid
hexamethylenediamine	tetrahydrofuran
hydrochloric acid	tetrahydrofurfuryl alcohol
hydrogen bromide	toluenediamine

In the refining industry, hydrogen is primarily consumed in hydrotreating and hydrocracking.

Hydrogen Sources for Chemical, Petrochemical, and Refining Uses

The majority of hydrogen consumed in the chemical, petrochemical, and refining industries is gaseous hydrogen produced and consumed captively or supplied by pipeline. Hydrogen for this industry sector can be purchased, produced, or recovered.

Regional Consumption

The chemical, petrochemical, and refining industries are concentrated in the Northeast, North Central and South Central regions.

Trends in Consumption for Chemical, Petrochemical, and Refining Uses

This industry sector grew more rapidly than any other from 1985 to 1989, with consumption increasing almost 39%, which corresponds to growth at an average annual rate of 8.5%. This high rate of growth was the result of temporary market opportunities as well as real growth.

Short term, large volume accounts are particularly common in this industry sector. In 1989, there occurred some unusual short term demands for liquid hydrogen. For example, because of an explosion at a by-product producer's plant, a large consumer of by-product hydrogen was forced to purchase liquid hydrogen over an eight month period. This account alone could consume an estimated eight tons per day of product. Another large volume opportunity emerged in response to increased aniline demand which resulted in some companies purchasing liquid hydrogen to supplement captive hydrogen production.

Hydrogen consumption in all forms is expected to increase dramatically in this industry sector over the next ten years, particularly in the refining industry. However, the majority of the growth will be met with gaseous hydrogen produced captively. In the refining industry, increasing quantities of hydrogen will be required because of increased demand for products produced by hydrocracking, the use of increasingly heavy and sour crudes, and increased environmental restrictions. Hydrogen's ability to react with elements such as sulfur and the halogens is likely to lead to new uses in industries where the emission of these elements is or will be restricted.

Growth in this industry sector is particularly difficult to estimate because the sector is composed of many applications which will grow at widely varying rates and because this industry sector has the widest variety of options available to it for obtaining hydrogen. SRI forecasts liquid hydrogen consumption in this industry sector to increase at an average annual rate of 3.6% to 4.1% over the 1989-1995 period. Over the 1995-2000 period, consumption is expected to increase at an average annual rate of 3.0% to 4.5%. The lower end of this range assumes that the rate of growth in hydrogen consumption will slow as is projected for the chemical industry generally. The higher end of the range assumes increased liquid hydrogen consumption primarily for environmental applications.

METALS

Table 6 displays hydrogen consumption in the metals industry, and projected consumption for the next ten years.

Table 6
LIQUID HYDROGEN CONSUMPTION IN METALS

Year	Millions of Cubic Feet	Average Annual Growth
1980	2,050	
1985	2,410	3.3% (1980-1985)
1987	2,600	
1988	2,730	
1989	2,870	4.5% (1985-1989)
1990	3,050	
1995	4,295-4440	7.0% to 7.5% (1989-1995)
2000	5,600-6,240	5.5% to 7.0% (1995-2000)

Metal Applications

In the metals sector, liquid hydrogen is used in both primary metal production and secondary metal processing. Primary operations that consume hydrogen include tungsten, tungsten carbide and molybdenum metal powder production. Secondary operations that consume hydrogen include heat treating, sintering, and brazing. The majority of hydrogen used in the metals industry is for secondary operations rather than primary metal production.

In tungsten and molybdenum metal powder production, hydrogen acts as a reducing agent, to reduce a tungsten or molybdenum oxide to its elemental form. In tungsten carbide production, hydrogen reacts with a hydrocarbon atmosphere generated by the reaction of carbon black and hydrogen to form tungsten carbide powder.

In secondary operations, hydrogen is commonly used as an atmosphere in furnaces that require an atmosphere for reduction or to improve the thermal conductivity of the atmosphere. Small quantities of hydrogen are sometimes used as a backfill gas in vacuum furnaces. Hydrogen is used in large quantities for heat treating; specific heat treating operations that consume hydrogen include normalizing low carbon steel prior to galvanizing, annealing of steel strip and coil, bright annealing of stainless steel, and decarburizing. Types of companies likely to consume hydrogen for heat treating include steel works, finishing mills, and in-house and commercial heat treaters.

Sintering is the process by which loose or compressed powders are bonded by heating at temperatures below the melting points of the major constituents. Because powdered metals undergoing sintering have such a large exposed surface area, hydrogen atmospheres are commonly used to prevent oxidation. Metal compacts that are typically sintered in a hydrogen atmosphere include tool steel, stainless steel, and nickel- and cobalt-base alloys.

Brazing is a technique used largely in the aerospace and electronics industries to join parts. Brazing joins solid materials together by heating them to a suitable temperature and by using a filler metal having a liquidus above 840 degrees Fahrenheit and below the solidus of the base materials.

Hydrogen Sources for Metals Uses

Hydrogen for primary metal production is typically purchased in liquid form or produced captively by steam reforming of natural gas. In secondary operations, a hydrogen atmosphere can be obtained in a variety of ways, including generation from natural gas (endothermic or exothermic atmospheres), dissociation of ammonia or methanol, and purchased hydrogen atmospheres. The largest volume consumers, such as large steel producers, may be located on a pipeline.

Companies that make powdered metal parts have traditionally dissociated ammonia to generate a hydrogen containing atmosphere. At in-house or commercial heat treating operations, generated hydrogen atmospheres have been traditional. Industrial gas companies have targeted powdered metal parts producers and heat treaters as potential liquid hydrogen markets and have been quite successful at persuading many hydrogen users to convert to purchased atmospheres.

Regional Consumption

Consumption in this industry is concentrated in the Northeast and North Central states. The steel industry is primarily located in the north central states, with a large concentration also in the Northeast. Many of the accounts in the North Central region are supplied with pipeline hydrogen. Heat treating operations are more broadly distributed geographically, but tend to be more common in regions with more equipment manufacturing, such as the Northeast and North Central regions. The largest number of powdered metal manufacturers can be found in Pennsylvania. Ranked next in quantity are Michigan, Illinois, California, Ohio and Massachusetts. Primary metal producers that purchase liquid hydrogen are almost all located in the Northeast.

Factors Affecting Consumption for Metals Uses

Liquid hydrogen consumption in the metals industry is expected to increase at an average annual rate of 7.0% to 7.5% from 1989 to 1995. This high rate of growth will be sustained by continued conversion from generated atmospheres to purchased atmospheres, high growth in the powdered metals industry, and higher concentrations of hydrogen being used in bell annealers in the steel industry.

From 1995 to 2000, the average annual rate of growth is expected to slow to 5.5% to 7.0%, to reflect the decrease in opportunities for conversion to purchased atmospheres or high hydrogen atmospheres.

ELECTRONICS

Table 7 displays hydrogen consumption in the electronics industry and projections for the next ten years.

Table 7
LIQUID HYDROGEN CONSUMPTION IN ELECTRONICS

Year	Millions of Cubic Feet	Average Annual Growth
1980	2,040	
1985	2,250	2.0% (1980-1985)
1987	2,340	
1988	2,455	
1989	2,565	3.3% (1985-1989)
1990	2,680	
1995	3,340-3440	4.5% to 5.0% (1989-1995)
2000	4,160-4395	4.5% to 5.0% (1995-2000)

Electronic Applications

The largest volumes of hydrogen used in the electronics industry are used in integrated circuit (IC) manufacture. Other segments of the electronics industry that consume hydrogen include semiconductor grade polycrystalline silicon manufacture via the Siemans process, optical fibers manufacture for communications, and fused quartz manufacture.

Specific applications that use hydrogen in wafer fabrication (integrated circuit manufacture) are presented in Table 8. The largest volumes of hydrogen are believed to be used in epitaxy, where the reactive gases dichlorosilane and hydrogen chloride are diluted with hydrogen, which functions as both the reactive gas and carrier gas. Epitaxy is common to all integrated circuit manufacturing processes. Chemical vapor deposition of compound semiconductors such as gallium arsenide also consumes significant volumes of hydrogen; however, this industry is currently a small fraction of the silicon industry as a whole.

The remaining uses of hydrogen in wafer fabrication are comparatively minor. Ion implantation, for example, is a high vacuum process using little material. Oxidation involving pyrogenic steam generation is growing in popularity, but is only one of a number of processes than can be used. In diffusion annealing and bonding operations, hydrogen is a minor component mixed with nitrogen and argon to inhibit oxidation in carrier gases used . Hydrogen is a minor etchant and is primarily used with halogenated solvents to produce the etchants anhydrous hydrogen chloride and hydrogen fluoride on site.

In polysilicon production, silicon is produced by the pyrolytic decomposition of trichlorosilane or silicon tetrachloride. Hydrogen is also consumed as an atmosphere when growing single crystals from a melt of polycrystalline starting material. In the fabrication of optical fibers and quartz chambers and fixtures, hydrogen is used as a clean burning fuel.

Table 8

APPLICATIONS FOR HIGH-PURITY HYDROGEN IN SEMICONDUCTOR MANUFACTURING

Process	Process Description	Hydrogen Use
Polysilicon Production	Silicon is produced by the pyrolytic decomposition of trichlorosilane or silicon tetrachloride by the following reaction: $$H_2(g) + SiHCl_3(g) \rightarrow Si(s) + 3HCl(g)$$	Reducing agent
Crystal Growth	The production of single crystals (usually silicon) from a melt of polycrystalline starting material. The two most common crystal growth methods are the Czochralski method and the Float Zone method.	Atmosphere
Epitaxy	The process of depositing a crystalline layer having the same structure as the substrate. Impurities such as diborane or phosphine are often added to the epitaxial layers to change the electrical conductivity of the crystalline silicon.	Reducing medium and/or carrier gas
Etching	Removing unwanted material from a surface.	Atmosphere
Oxidation	Growing a layer of silicon dioxide on a silicon surface.	Hydrogen and oxygen are combined to make pyrogenic steam
Diffusion	A high-temperature process in which dopants are introduced into the surface layer of the semiconductor material to change its electrical characteristics.	Carrier gas
Chemical Vapor Deposition	The process of forming a thin film on a substrate by the chemical reaction of a gaseous species (epitaxy is a special form of chemical vapor deposition).	Carrier gas and reducing atmosphere when the substrate is polycrystalline silicon or one of the III-V elements
Ion Implantation	A technique for doping impurity atoms into an underlying substrate by accelerating the selected dopant ion toward the silicon target through an electrical field.	Dilution of dopant bearing gases
Annealing	The slow regrowing of a crystal from amorphous material through the application of heat. This process is commonly used to relieve stress after the substrate has been bombarded by accelerated ions.	Atmosphere
Bonding	Attachment of an integrated circuit's electrical circuits to the external environment.	Atmosphere

Hydrogen Sources for Electronics Uses

Because of its high purity, liquid hydrogen has traditionally been the form of choice for consumers purchasing hydrogen for wafer fabrication and polysilicon production.

Purity requirements for hydrogen for fuel use are not as stringent, which means that a company's procurement decision will be based primarily on production and transportation economics. Quartz fabricators tend to be small volume consumers that will purchase gas in tube trailers. AT&T is the largest fiber optic manufacturer that uses hydrogen. AT&T purchased liquid hydrogen at its Norcross, Georgia facility until its requirements grew large enough to justify having Union Carbide operate an on site system at the site.

Regional Consumption

The electronics industry, in particular integrated circuit manufacture, tends to be concentrated in the Western states, the South Central region and the Northeast. Fiber optics has been a large end use in the South Atlantic states, polysilicon production in the Western and North Central states, and quartz production in the North Central and South Atlantic states.

Factors Affecting Consumption for Electronics Uses

Liquid hydrogen consumption has not grown as rapidly as the electronic industry segments that consume hydrogen, primarily due to increased efficiency of use. For example, polysilicon production used to be a large market for liquid hydrogen, but unit requirements were vastly reduced in the early 1980s by the introduction of hydrogen recycling. It is believed that unit hydrogen consumption for wafer fabrication will increase slightly because of the trend toward CMOS and BiCMOS structures that are heavily dependant on epitaxy in their processing. Hydrogen has also been proposed as part of a system to replace CFCs used in cleaning solutions. Liquid hydrogen consumption in electronics is projected to grow at an average annual rate of 4.5% to 5.0% from 1989 to 2000.

FATS AND OILS

Table 9 displays consumption in the fats industry, and projections for the next ten years.

Table 9
LIQUID HYDROGEN CONSUMPTION IN FATS AND OILS

Year	Millions of Cubic Feet	Average Annual Growth
1980	1,060	
1985	940	-2.4% (1980-1985)
1987	900	
1988	870	
1989	910	-0.8% (1985-1989)
1990	870	
1995	1,085-1,185	3.0% to 4.5% (1989-1995)
2000	1,299-1,480	3.5% to 4.5% (1995-2000)

Fats Applications

Hydrogenation increases the ratio of saturated to unsaturated bonds, which in turn affects the chemical and physical properties of fats and oils. Hydrogenated products are less susceptible to oxidation and subsequent spoilage. Hydrogenation raises the melting point of a fat or oil, so oils that are normally a liquid at room temperature can remain as solids at room temperature.

The U.S. fats and oils industry can be divided roughly into two segments: the segment classified under SIC code 207 that is primarily involved hydrogenating vegetable oils for use in products such as shortening, margarine, baking fats, and frying fats, and the segment manufacturing chemical products such as fatty acids from tallow or vegetable oils for use in shampoos, industrial lubricants, household cleaners, and other applications. Consumption for fatty acid manufacture is discussed in the chemical industry sector.

Hydrogen Sources for Fats Uses

An estimated 8 to 9 billion cubic feet of hydrogen are consumed annually in the hydrogenation of fats and oils. The vast majority of hydrogen is produced captively. Companies with captive facilities typically produce enough hydrogen for all their needs, so hydrogen purchases are limited to supplying demand when the hydrogen plant is closed for maintenance once or twice a year. Maintenance is usually scheduled for slow periods, and generally does not take more than two days. During this time, most captive producers will purchase one or two truckloads of liquid hydrogen. Most of the plants that do not produce hydrogen purchase liquid hydrogen, although one plant in the Northwest is known to purchase by-product gas.

Regional Consumption

Demand for this end use is concentrated in the North Central region, which accounted for an estimated 45% of liquid consumption in 1989.

Factors Affecting Consumption for Fats Uses

Production of hydrogenated fats and oils has increased at an average annual rate of about 2.7% over the past 10 years and should continue to grow at an average annual rate of about 1.5-2.5% from 1990 to 2000. Liquid hydrogen consumption in this industry has not followed trends in fats production. From 1980 to 1985, several larger companies expanded their market share and consolidated production at large facilities with on-site generators. Although a few companies with smaller hydrogen plants, generally based on ammonia dissociation or electrolysis, converted to purchased gas or liquid product, this did not compensate for the decline in liquid hydrogen consumption that took place as large liquid accounts converted to on-site production and some smaller liquid hydrogen accounts ceased production.

From 1985 to 1990, consumption has fluctuated between 870 and 940 million cubic feet. In any given year, demand is less likely to reflect industry growth than one-time incidents, such as whether a fats processing plant has opened or closed or switched between captive and purchased product. For example, the primary factors influencing the the change in consumption between 1989 and 1990 were the installation of a captive hydrogen plant at the Ag Processing Inc., St. Joseph, MO, facility, combined with the construction of the new Aarhus Inc. facility in Port Newark, NJ, that will use purchased hydrogen.

It is expected that liquid hydrogen consumption in the fats and oils industry will grow at an average annual rate of 3.0% to 4.5% from 1989 to 1995, and at an average annual rate of 3.5% to 4.5% from 1995 to 2000. Assumptions behind this projection include the following:

- The trend toward industry consolidation, and in turn toward large plants with captive hydrogen, has slowed.
- Hydrogen consumption per unit product will not decline and may increase.
- Recently developed fat substitutes, such as Simplesse from Monsanto Co. and Olestra from Proctor & Gamble, will remain comparatively small volume specialty products and will not erode the market for natural fats.

Hydrogen consumption per unit product is difficult to predict since several factors, often contradictory, influence the amount of hydrogen consumed per unit of product. These factors include changes in the degree of hydrogenation desired as well as changes in the efficiency of the hydrogenation process.

One major factor that affects the degree of hydrogenation required is change in the types of oils processed, which is in turn influenced by world vegetable oil prices and consumer preferences. For example, in the mid-1980s comparatively low prices for palm oil led to large increases in its use. Because palm oil was more saturated than most of the oils it replaced, less hydrogenation was required.

In recent years, health concerns have led to a consumer preference for unsaturated fats; this can lead to an increase in hydrogenation levels since unsaturated fats in many instances require partial hydrogenation to obtain necessary physical characteristics. The fast food industry, which has historically used large quantities of fats that are naturally highly saturated, is considering converting to less saturated vegetable oils which will need to be partially hydrogenated for use.

In theory, developments in biotechnology could make it possible to breed plants from which oils of the proper degree of saturation would be produced without further modifications but this is not likely to impact hydrogen consumption by 2000.

GLASS

Table 10 displays consumption in the glass industry, and projections for the next ten years.

Table 10
LIQUID HYDROGEN CONSUMPTION IN FLOAT GLASS

Year	Millions of Cubic Feet	Average Annual Growth
1980	685	
1985	700	0.4% (1980-1985)
1987	720	
1988	750	
1989	760	2.1% (1985-1989)
1990	710	
1995	795-910	0.8% to 3.0% (1989-1995)
2000	855-1,055	1.5% to 3.0% (1995-2000)

Glass Applications

Hydrogen is used as an oxygen scavenging atmosphere in the manufacture of flat glass by the float process. In the float process, a continuous ribbon of glass is floated on a bed of molten tin. Because tin is highly sensitive to oxidation, the glass is held in a controlled atmosphere of nitrogen and hydrogen while the irregularities in the glass even out and the glass becomes flat. The glass is then cooled while it advances across the molten tin until the glass surface is hard enough for the glass to be removed. A typical float atmosphere is 5 to 6% hydrogen and 94 to 95% nitrogen, although the hydrogen concentration can vary between 3% and 8%. Hydrogen concentrations as high as 10% have been used on occasion.

Hydrogen Sources for Glass Uses

Because their annual requirements are below the point where it is economic to produce hydrogen, all consumers in this industry currently purchase liquid hydrogen. In the early 1980s, Guardian Industries purchased by-product gaseous hydrogen from a chlorine-sodium hydroxide plant near its Carleton, Michigan facility. Since the closure of that plant in early 1985, Guardian has purchased liquid product.

During the next five to ten years it is expected that glass consumers will continue buying liquid hydrogen from industrial gas suppliers. Consumers report that even if technology were available to produce hydrogen captively in the quantities consumed in this industry, that they would be reluctant to invest the capital necessary to build, operate, and maintain a hydrogen plant.

Regional Consumption

Most hydrogen for float glass production is consumed in the North Central region (30% of 1989 consumption), followed by the South Central and South Atlantic regions (24% and 22%, respectively), and then the West and Northeast (13% and 11%, respectively).

Float glass tanks tend to be located near glass markets. For example, glass demand for the automotive industry is concentrated in the North Central region. The newest float glass plants have been built in the Western and South Atlantic states to supply demand associated with increased construction. In the South Atlantic region, half of the U.S. mirror glass manufacturing industry is located within approximately 150 miles of the Libby Glass's North Carolina plant.

Factors Affecting Consumption for Glass Uses

Hydrogen consumption tends to vary with two factors: float glass production and the concentration of hydrogen in the controlled atmosphere. Float glass production levels are by far the most important factor.

Float glass production reached record levels in 1987 and 1988 and several new plants came on stream; (PPG Industries in Chehalis, WA, in late 1986; AFG Industries in Victorville, CA, in late 1987; Guardian Industries in Richburg, SC, in late 1988; AFG Industries Inc. in Spring Hill, KS, in January 1989; PPG Industries in Cumberland, MD, in late 1989). In 1989, production levels remained flat. Because capacity grew more rapidly than demand, some older facilities were temporarily closed in 1990 for maintenance (e.g., one of Ford's tanks at Tulsa, OK and Libbey's unit at Lathrop, CA) or to avoid building up excessive inventories (e.g., AFG Industries at Cinnaminson, NJ, and one of three tanks at Ford's Nashville, TN facility). Float glass tanks tend to operate near capacity or not at all.

In general, companies try to minimize hydrogen consumption to control costs. Since 1980, companies have become more efficient in their hydrogen use. It appears unlikely that significant further reductions in hydrogen consumption will take place.

Between 1989 and 1995, liquid hydrogen consumption in float glass production is expected to increase at an average annual rate of 0.8% to 3.0%. Between 1995 and 2000 consumption is forecast to increase at an average annual rate of 1.5% to 3.0%.

Regional growth is not expected to vary significantly from the national trend. None of the major U.S. companies have announced new plant construction over the next five years, although it is expected that the lines that are currently not operating will come back on stream. Currently the West and South Atlantic are the regions least likely to build new plants since these are the areas where new plants were most recently constructed. The West is especially experiencing overcapacity currently. The West also has strict environmental regulations regarding furnace emissions which increase the costs associated with operating a plant in the region. In Pennsylvania, a study was done for a new float glass facility by a group of investors not currently in the float glass business, but plans for building an actual plant have not been initiated.

OTHER USES

Table 11 displays hydrogen consumption for other, marginal users of hydrogen.

Table 11
OTHER CONSUMPTION OF HYDROGEN

Year	Millions of Cubic Feet
1980	160
1985	160
1987	340
1988	265
1989	380
1990	425
1995	495-515
2000	600-830

This category includes consumption at public utilities for generator cooling, and controlling stress corrosion cracking at nuclear power plants with boiling water reactors. Other applications include calibration gas for instrumentation, and a variety of processes requiring a controlled atmosphere, including in various research activities. As in other industry sectors, some of the demand consumption is attributed to unusual short term requirements. For example, one producer reported selling liquid hydrogen for its fuel value over a five day period during a cold spell last winter when fuel supplies were unusually tight. Because consumption in this category (which accounts for less than 5% of total consumption) is obtained by difference, fluctuations in the data reflect any imprecision in the records of consumption in the individual market sectors, as well as actual changes in consumption.

In the long term, there are tremendous opportunities for hydrogen as an alternate energy source or energy carrier. Despite ongoing research in this area, it is not anticipated that energy will become a significant market for hydrogen in the U.S. by 2000. Even if hydrogen should achieve widespread use as an alternate energy source or energy carrier, it is unclear in what form the hydrogen would be consumed. For example, a vehicle powered by a hydrogen fueled fuel cell could generate the hydrogen on board from methanol. Alternatively, gaseous hydrogen could be stored in metal hydrides or other materials, such as the activated carbon being studied by Syracuse University. Most sources involved in development of alternate fueled vehicles report that the fear of consumer rejection of a system based on hydrogen has limited the development of vehicles fueled directly by hydrogen. It is thought that many individuals are only aware of hydrogen for its role in the Hindenburg disaster, and would be unlikely to want a hydrogen tank on their car. In general, liquid hydrogen is most likely to be required for projects that involve large scale or nonterrestrial transport, such as the proposed project for sending energy from Quebec to Western Europe, and studies concerning hydrogen for use as an aircraft fuel.

The province of Quebec in Canada and the European Community are currently studying the feasibility of shipping hydrogen to Hamburg, West Germany. Under the current proposal, the hydrogen would be produced electrolytically at a 100 megawatt plant in Quebec on the St. Lawrence Seaway. The hydrogen could be shipped as liquid hydrogen, ammonia, or methylcyclohexane. The initial phase of the project, which is nearing completion, will estimate the cost of the concept with an accuracy of about 15%. On a preliminary basis, industry sources indicate that shipping liquid hydrogen currently appears to be the most promising alternative. However, it also appears that transporting hydrogen from Quebec to Hamburg, as opposed to producing hydrogen in Hamburg, is unlikely to be justifiable on purely economic grounds. Once the initial studies are complete, there is no funding mechanism in place for implementing the program. Because it is highly uncertain whether the idea will be implemented, and because hydrogen for the project would be produced from a dedicated plant, it is assumed that this project will not impact the North American market for liquid hydrogen between now and 2000.

Industry sources indicate that development of hydrogen as a fuel for commercial aircraft is unlikely to take place before development of the National Aerospace Plane, since expertise gained from development of the aerospace plane could be transferred to commercial aircraft. This would push development of commercial hydrogen fueled aircraft beyond 2000. It is possible that small scale aircraft, such as the unmanned aircraft for atmospheric research applications proposed by Aurora Flight Sciences Corporation, could consume liquid hydrogen by 2000. Current estimates put hydrogen consumption at 300 pounds per flight for the Aurora. If the concept is in fact developed, it is unlikely that more than one or two flights would take place before 2000.

International demand has placed and will continue to place only minor demands on U.S. plants. It is expected that Canadian plants will continue to represent a significant source of liquid hydrogen to the commercial sector.

In 1989, trade with Canada is estimated to have resulted in the net import of 2,700 million cubic feet (19.3 tons per day) of liquid hydrogen. This hydrogen primarily served liquid hydrogen demand in the Northeast and North Central regions.

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16. Abstract
Hydrogen, particularly liquid hydrogen, will continue to be an integral element in virtually every major space related program as well as numerous aeronautical programs and a variety of research projects throughout the United States. Liquid hydrogen has also become a significant merchant product to serve certain commercial markets requiring bulk hydrogen for providing many consumer goods and services.

Liquid hydrogen is not a universally available commodity (production) as compared to other commonly used cryogens and industrial gases. The number of supply sources historically have been limited to regions having concentrated consumption patterns. Namely this has been the Southwest, Southeast, and Northeast regions. Except for the Northeast, which is predominantly a commercial demand area, production plant location and size were typically gauged by needs contemplated by the government.

With the increased space program activity and the possible reality of new programs it becomes necessary to assess all future programs on a collective and unified basis to assure that proper planning and contractual commitments are timely to meet everyone's needs. This report is an initial attempt to identify projected requirements on a long range basis.

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