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Hydrogen Technologies in Canada:

A preliminary Assessment

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Hydrogen Technologies in Canada:

A preliminary Assessment

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MOSST
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FOREWORD

The energy policies of most developed countries have demonstrated an urgent need to attain energy self-sufficiency and reduced dependence on foreign oil supplies. In addition to extensive conservation, the search for alternative energy forms has figured prominently in many of these policies. Within this last category, hydrogen has emerged as a serious subject for study as an indirect and direct energy carrier.

Traditionally, hydrogen gas has been used in Canada and in most industrialized countries as a chemical input for the production of ammonia, methanol and upgraded fuels, as well as a reducing agent in metallurgy. However, in its proposed role as an energy vector it can be used in many applications ranging from off-peak electrical energy storage to extensive use as an automotive fuel.

The rationale behind the current "hydrogen movement" is hinged on its socially desirable characteristics, as well as its versatility as a fuel. The production, storage and consumption of hydrogen is virtually pollution free and is, therefore, viewed as an excellent substitute to fossil fuels, should the present pollution problems remain unresolved and become socially unacceptable.

Cannot accurately [illegible] this.

Because hydrogen is not available in nature in pure form, it must be manufactured from a primary or secondary energy form. It can be produced from any renewable energy source such as solar, wind, thermal, tidal, hydraulic or biomass, in addition to conventional sources such as fossil fuels and nuclear power. In regions which have access to abundant water and hydroelectric resources, hydrogen can be produced continuously with no supply restrictions.

N.B.

In Canada, the potential for hydrogen as part of a future energy base seems excellent on the supply side. We have abundant reserves of renewable energy sources such as hydraulic, biomass and tidal, together with free access to unlimited fresh and salt water resources. We also have our own indigenous nuclear technology which is highly compatible with hydrogen gas production. On the demand side, however, the need for hydrogen as an alternative fuel is not strong relative to other countries. Our current energy program places a great deal of emphasis on developing vast reserves of non-conventional petroleum and continuing the search for conventional fossil fuels in frontier areas.

Ultimately, however, supply restrictions of conventional fuels will lead to an increased demand for acceptable substitutes.

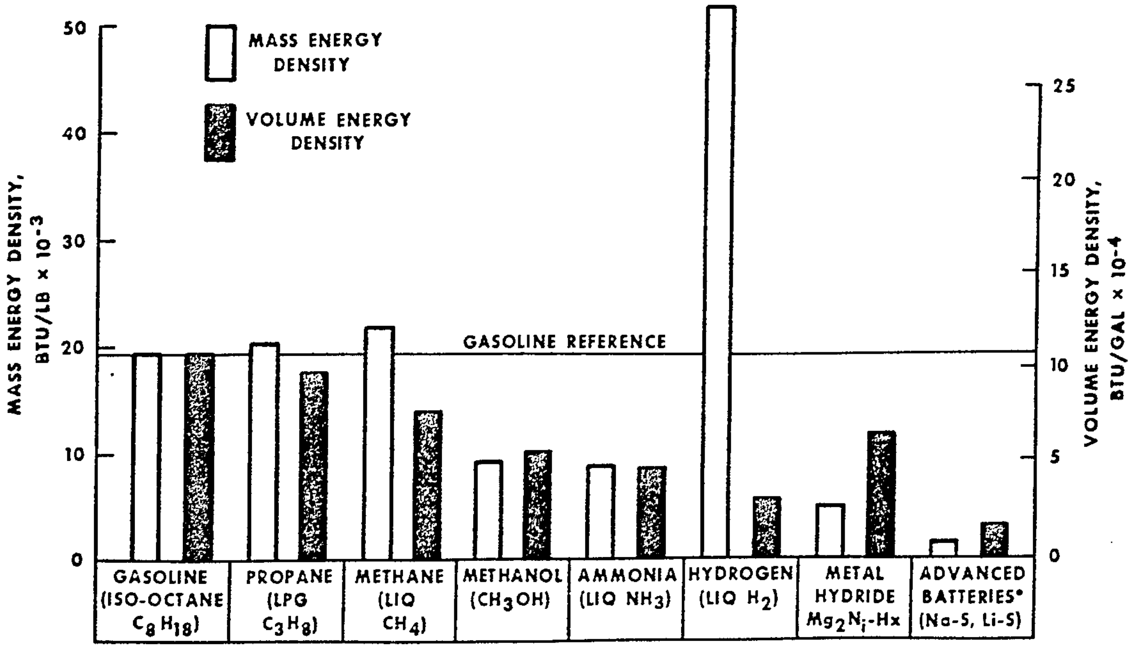
Must should have position on the effects of policy on the demand side for fuels. Will it make us technologically backward.

The relative economics of production, storage and distribution of these fuels, hydrogen included, will determine the future pattern of energy consumption. In addition to the straightforward economics, more complex issues such as oil pricing policies, environmental concerns and R&D policies will play an important role.

Many studies have addressed the subject of hydrogen technology in both an energy and non-energy context and within different time frames. Arguments have been presented both for and against the use of hydrogen as a fuel for automobiles and aircraft, as well as space heating, process heating and as an energy carrier in partnership with electricity. In most cases, technical presentations have focused on the physical characteristics of hydrogen as the major barrier to its acceptance. As shown in Figure 1, liquid hydrogen has about three times the energy content of gasoline on a mass basis and one-third the energy content on a volumetric basis. This characteristic in combination with its very low boiling point of $-253^{\circ}C$, has created technical difficulties with hydrogen production, storage and handling.

It is the purpose of this report to evaluate the potential for hydrogen technologies in Canada and to comment on the appropriateness of Canadian research and development activities.

FIGURE I ENERGY DENSITY CHARACTERISTICS OF FUELS



*INCLUDES ADJUSTMENT FOR DIFFERENT ENERGY CONVERSION EFFICIENCY

Fig. 1. Energy Density Characteristics of Fuels

SOURCE: Hydrogen As An Energy Carrier by R.G. Murray Proceedings of the Hydrogen Economy, Miami Energy (THEME) Conference, March, 1974

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CONVERSION FACTORS

1 calorie	=	4.19002 joules
1 Btu	=	1,055.87 joules
1 Kwh	=	3.6×10^6 joules
1 cu. ft. of H_2 (gas)	=	343.3×10^3 joules
1 m^3 of H_2 (gas)	=	1.21×10^7 joules

1 cu. ft.	=	0.0283168 m^3 (cubic meter)
1 gallon	=	0.004546 m^3
1 barrel	=	0.159 m^3

1 lb.	=	0.453592 kg
1 ton	=	0.907105 t (tonne)

scf	=	1 standard cubic foot		
MW	=	mega watts	=	10^6 watts
GW	=	giga watts	=	10^9 watts
TW	=	tera watts	=	10^{12} watts
GJ	=	giga joule	=	10^9 joules
PJ	=	pica joule	=	10^{15} joules

EXECUTIVE SUMMARY

Based on the analysis, the following general conclusions can be made about the potential for hydrogen technologies and the current level or research and development:

A) Potential

1) The potential for developing hydrogen technologies in these applications as a chemical feedstock, as an additive in synfuel production and as a reducing agent in metallurgy is quite high. As the price of natural gas increases more rapidly than the price of electricity, the economics will become more favorable for the use of electrolytic hydrogen. The timing of this transition is difficult to predict because of its dependence on the future price of natural gas and the effect of technological advances in electrolytic technology. Estimates of the initial penetration have ranged from year 1990 to 2025.

2) As a fuel for transportation, hydrogen has the greatest potential for use in aircraft and in intercity rail and truck travel. This potential is more difficult to quantify due to the uncertainties associated with existing fuel prices, the unresolved technical problems and the potential of other alternative fuels and sources of motive power.

3) The potential for hydrogen as an automotive fuel is less determinant but remains positive, mainly due to the wide range of other fuel substitutes under consideration and the potential developments in advanced battery research. A reduction in the costs of hydrogen production, storage and use in automobiles would greatly favour its use over alternatives because of its environmental advantages and unlimited supply possibilities. However, many technical difficulties associated with this technology remain to be resolved.

4) The use of hydrogen as an energy vector for space heating or for electrical energy storage in utility applications, seems very limited largely due to the economics. The development of improved load management techniques and pumped storage in direct electrical power generation will likely be less expensive alternatives than hydrogen in the future.

5) On the supply side, the potential for producing hydrogen in Canada is excellent. Electrolysis, the most attractive method, can be economically competitive with other

Find most likely use.

technologies and is highly compatible with our indigenous nuclear technology. The abundant reserves of hydraulic power in many provinces is perhaps the strongest incentive to develop electrolysis technologies. The development of a Canadian industrial capability in this field could ensure that optimum production costs are achieved.

Should the demand for electrolytic hydrogen as an energy vector develop, initial production would probably take place using off-peak electrical power, followed by the use of dedicated plants (nuclear or remote hydro) to produce sufficient quantities of hydrogen to satisfy demand.

B) Research and Development

1) There are currently no strategic guidelines for the development and implementation of advanced hydrogen technologies within the federal or provincial governments. As a result, fragmented studies and R&D programs have emerged which deal with hydrogen, both in general and specific terms and without clear-cut objectives in place.

Dev. guidelines for dev. of tech.

Rank potential uses according to specific criteria.

New Hydrogen Sub-Committee as part of Energy R&D panel.

This situation may change in the near term with the formation of the new Hydrogen Sub-Committee as part of the Interdepartmental Energy R&D Panel, however, what remains to be done is an in depth analysis of our technological base and the future role that hydrogen could play as part of Canada's energy base.

Or top down.

2) There appears to be a bottom-up system of R&D in place whereby the stimuli for activity are originating from key industrial players and pure research institutions such as N.R.C. and a few major universities. Electrolyser Incorporated and Noranda Mines Ltd., have been instrumental in raising the "consciousness" of government officials.

3) Current R&D is oriented around the functional areas of production, storage, safety and distribution, without an overall systems approach to address potential applications. There is a need for more applied and engineering research. Gaps in the government's analysis exist in the areas of automotive applications, aircraft applications and space heating. This reflects a lack of Canadian expertise and the non-committal attitude of public utility companies. One exception to this situation is the development of advanced electrolysis technologies for potential applications in chemical production.

Many

None

Not sure why this is considered an exception. - re - refer to public utilities, not automotive, aircraft or space.

Electrolyser Inc., and Noranda have worked closely with ITC and Hydro Quebec and are about to embark on the construction of a 100 MW demonstration project.

4) International levels of R&D in hydrogen do not reflect a firm commitment to the rapid development of a hydrogen economy. However, expenditures in many countries, since the mid-seventies, have been several orders of magnitude higher than Canada in all areas of hydrogen technologies. In particular, there is a threat imposed in the area of the electrolytic production of hydrogen. Although at the present time, Electrolyser Incorporated is not suffering from increased international competition, existing R&D disparities could result in a drastic weakening of its position in the future. The ultimate consequences for Canada could be reduced exports of this technology and the need for importing more cost-efficient systems should the demand for electrolytic hydrogen escalate in the future.

INTRODUCTION

An analysis of the potential demand for hydrogen in its role as a chemical feedstock in Canada is generally a straightforward marketing research task, which involves a projection of the existing markets for Canadian produced ammonia and methanol, and an analysis of international competition. The future performance of canadian producers in these markets will hinge on the production economics, relative to foreign firms and the existance of free trade barriers.

Hydrogen's entry into the energy scene, however, brings into consideration a number of complex economic and non-economic issues which are difficult if not impossible to predict accurately. For example, the econonic viability of hydrogen's application as a fuel would depend heavily on the future price of oil and natural gas. The task of predicting these prices has been greatly complicated by OPEC pricing strategies and the lack of a federal/provincial pricing agreement within Canada. Added to this is the difficulty of predicting the ultimate cost of hydrogen fuel to the consumer, which includes separate production, storage, handling and application costs. The sensitivity of these costs to future technological developments must also be determined. On the qualitative side, political objectives which deal with employment, social welfare, international trade and national security must also be taken into consideration.

As well, legal environmental and consumer satisfaction issues enter the analysis. Obviously there are many uncertainties associated with these factors which render "time frame" predictions of a hydrogen economy highly speculative.

Despite the difficulties of forecasting the evolution of new fuel substitutes, its potential can be assessed, relative to other alternatives, with an understanding that at some time in the future one or more of these alternatives will be implemented. This is possible because of the sufficient body of knowledge on alternate fuels which now exists and the well accepted fact that existing supplies of conventional fuels will ultimately be exhausted.

This paper first presents a brief description of existing and emerging hydrogen production, storage and transmission technologies in both an international and Canadian context as a background to the analysis. Next, existing and proposed applications of hydrogen technologies are assessed to determine their market potential in Canada and to identify technological requirements which would facilitate growth within each sector. In sections III and IV, research and development activities in Canada and other countries are examined in terms of their appropriateness of direction, scope and institutional arrangements. Lastly, policy implications are presented for further consideration.

I. HYDROGEN SYSTEMS

Hydrogen, like any other gaseous product, can be considered as part of a total system which consists of unique production, transmission, storage and application technologies. The characteristics of these components and their level of development depends greatly on consumption patterns, the physical properties of hydrogen and the economics of the processes. Today, hydrogen is stripped from common hydrocarbon compounds near the point of end use and on a demand basis, as an integral part of the production of ammonia and methanol. The central technology for this process, steam reforming or catalytic reforming of natural gas, is technically mature and widely used internationally. The production economics is such that the process has a high feedstock cost component (roughly 50 percent) which, in combination with the high costs of storage and handling, minimizes the benefit of production economies of scale. Storage and transmission technologies, therefore, have received little notice.

However, with attention now being focussed on hydrogen as a replacement for fossil fuels, the emphasis on production, storage, transmission and application technologies is taking on new proportions. What follows is a brief description of current and emerging technologies which are associated with these components of hydrogen systems.

A. Production

Hydrogen gas is not available in nature as a usable chemical and, therefore, must be produced from existing hydrogen/carbon or hydrogen/oxygen compounds. Today, this can be accomplished using one of three available chemical process technologies: Steam Reforming, Coal Gasification and Electrolysis. Two other methods, Thermochemical Water Splitting and Biophotolysis, show potential but as yet have not been proven. Table I, on page 10 presents a qualitative summary of these technologies.

As a component of a hydrogen system, the production phase is the most important economic variable and has received a corresponding amount of research attention which has focused on improving process efficiencies, reducing capital costs, and utilizing alternate renewable hydrogen sources. This latter area of concentration gives recognition to the fact that most hydrogen production methods are sensitive to the cost of hydrogen feedstocks, and because these feedstocks are normally in the form of fossil fuels, they are subject to unstable price increases and long-term supply limitations.

A realistic estimate of production costs is difficult to determine, because hydrogen production has taken place under captive conditions, as part of a total chemical production or oil refining process.

Table I HYDROGEN PRODUCTION ALTERNATIVES

Process	Thermal Efficiency	Hydrogen Feedstock	Advantages	Disadvantages	State-of-the-art	Estimated Production Cost ($Can. 1980)
Steam Reforming	70%	Natural Gas	Most inexpensive method	Natural gas is long-term supply limited	Well known Technology	$\$6.30/10^6$Btu
Coal Gasification	60-65%	Subbituminous Coal	Abundant coal reserves	- pollution - large plant size - capital intensive	Mature Technology	$\$12.20/10^6$Btu
Electrolysis	32%	Water	- Small plant size - Renewable and non-fossil sources	- high cost - low efficiency	Proven technology	$\$12.50/10^6$Btu
Thermochemical Water Splitting	55% est.	Water	- No need for electricity - Renewable sources	- large capital intensive plant	Research stages	$\$12\text{-}18/10^6$Btu
Biophotolysis	2-3% est.	Water	Use of renewable energy sources and biological catalyst	- low overall efficiency	Research stages	N/A

SOURCE: REFERENCE 1,15, 17

Under these circumstances,each industrial user may allocate capital and operating costs differently and therefore reported production costs can vary a great deal from their actual value. It is believed however, that the costs presented in this paper indicate economic relationships which are appropriate for comparison in a Canadian context. Estimates of "dedicated" plant costs using natural gas or coal as a feedstock have been made by the Noranda Research Centre and are shown in Table II. (page 12). It should be understood that dedicated costs are not important to present users of hydrogen gas, as their primary concern is how the cost of hydrogen-rich feedstocks affects the total cost of producing the final product, whether it be a chemical fertilizer or petroleum derivative.

1. Steam Reforming

Nearly all hydrogen gas which is used in Canada as a chemical feedstock is currently produced by catalytic steam reforming of natural gas (methane). As shown below, the process involves the chemical breakdown of natural gas or other light hydrocarbon feedstock by the introduction of steam and a catalyst at high temperature, to produce carbon dioxide and hydrogen gas.

Table II: DEDICATED COSTS FOR THE PRODUCTION OF H_2 (ALBERTA LOCATION)

	Natural Gas (Steam Reforming)		Coal (Coal Gasification)	
Plant Size	9.3×10^8 M^3 H_2/yr		9.3×10^8 M^3 H_2/yr	
	$ million (Can.)	%	$ million (Can.)	%
Fixed Capital Cost	90.1	-	258.5	-
Working Capital	9.1	-	10.2	-
Operating Cost	8.3	17	29.0	38
Feedstock	30.3	62	7.5	10
Interest	15.4	32	42.5	54
By-Product Credit	(5.6)	(11)	(0.6)	(2)
Total Costs	48.6	100	78.4	100
20% R.F.I.	18.0	-	51.7	-
Total Cost + Return	66.6	-	130.1	-
Total Cost ($/GJ)	$4.28	-	$ 6.90	-

[1] Debt/equity= 65/35 with Debt bearing 10% interest

S[redacted]ce:[redacted]lbe[redacted] R[redacted]arc[redacted]ou[redacted]

SOURCE: ALBERTA RESEARCH COUNCIL

Light Hydrocarbon Feedstock	+	Steam	+	Catalyst	=	Hydrogen Gas, H_2 Carbon dioxide, CO_2

1500°F and 250 psig

With a thermal efficiency of 70 percent, catalytic steam reforming is the most inexpensive method of producing hydrogen for use in the chemical industry. Based on an annual "dedicated" production of 9.3×10^8 M^3 of H_2/yr and a feedstock cost of $1.89/GJ, Noranda Research has estimated the cost of hydrogen gas at the plant to be $4.28/GJ. As part of the methanol production process, estimates of non-dedicated production costs are in the order of $6.82/GJ based on a world scale production of 1814 tonnes of methanol per day.[15]

As mentioned earlier, the cost of steam reforming of natural gas is sensitive to the cost of energy and feedstock inputs.

This has resulted in the use of light hydrocarbon feedstocks, such as methane which have a high hydrogen content in order to maximize hydrogen gas output per unit of energy required to beak up the hydrocarbon. With the future supply of light hydrocarbon being in doubt and given the certainty of further price increases, a greater effort is being expended on the development of improved catalysts and the search for alternate hydrogen feedstocks.

Besides the cost advantage, one additional factor favours the use of steam reforming to produce hydrogen. Natural gas is widely used as a source of building and process heat as well as a feedstock. This versatility allows chemical plants to utilize the existing pipelines infrastructure at their convenience for either purpose.

2. Coal Gasification

Hydrogen gas can be extracted from finely ground coal through a series of chemical reactions which take place in the presence of steam at high temperature. This process is similar to steam reforming but is more difficult largely because coal, a solid, requires more energy to react and must be treated before use.

Two slightly different gasification processes are commercially available; the Koppers-Totzek and the Lurgi process, with respective thermal efficiencies of 61 and 66 percent.[1]

Finely Ground Coal + Steam + Oxygen = Hydrogen, H_2 + Carbon dioxide, CO_2

Although coal is less expensive than natural gas on an energy basis ($1.00/GJ vs. $1.89/GJ), coal gasification has a much greater fixed cost component which makes the overall economics inferior to steam reforming. Dedicated costs of hydrogen production based on a plant capacity of 9.3×10^8 M^3 H_2/yr and a feedstock cost of $9.33/tonne are estimated to be about $6.90/GJ. For the production of methanol, coal gasification for a world scale plant has an estimated non-dedicated cost of $7.51/GJ.[15]

Coal gasification is a preferred method only where the cost of natural gas is high and there is easy access to inexpensive coal resources.

East Germany, Finland and South Africa have used this technology for years to produce fertilizers. In Canada, western chemical plants are located adjacent to large Alberta and British Columbia coal reserves, therefore, making coal gasification an attractive long-term alternative. Although the technology is readily available, a major barrier to its implementation are the undesirable environmental consequences such as acid rain caused by sulfur and carbon monoxide emissions.

In the U.S., coal gasification is viewed as a serious alternative for the production of hydrogen gas as well as the manufacture of synfuels for transportation, where less concern over environmental problems is being displayed.

3. Electrolysis

The process of passing a direct current through an electrolyte to produce hydrogen and oxygen gases is referred to as Water Electrolysis. The technology is by comparison very mature and has been used to produce hydrogen in small quantities for use in metallurgy and the production of vegetable oils, fats and soaps where high purity is required.

Industrial plants range in production capacity from 500 scf/day to about 40 X 10^6 scf/day consuming electrical power of 3 kwh and 240,000 kwh per day respectively. Most plants are in the 10,000 to 500,000 scf/day size range. Cominco Ltd. of British Columbia has one of the world's largest operating electrolyser plants with a capacity of 36 tons of H_2/day and a power consumption of 90 M watts. The output from this plant is used in ammonia synthesis. Other very large installations are located in Norway and Egypt.

As an energy conversion process, electrolysis is not very efficient on an overall basis because electricity itself is generated at about 35 to 40 percent efficiency using either nuclear, hydro, or steam generating plants. This, combined with an electrolytic efficiency of 70 percent based on current technology leads to an overall efficiency of only 25 percent.

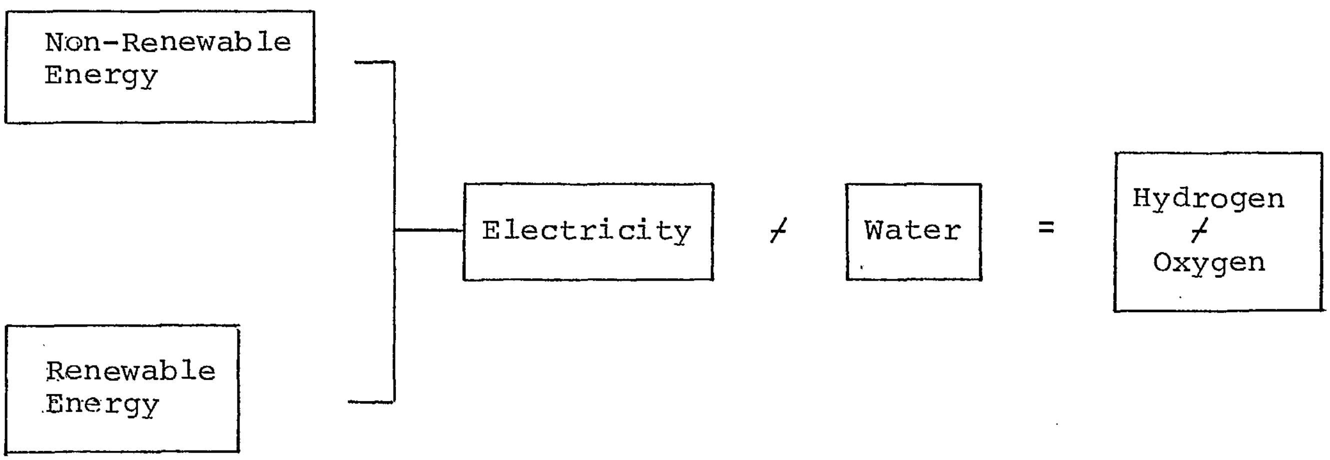
Advanced electrolytic technologies show considerable promise for improved efficiency. In the U.S., for example, General Electric is developing an advanced monopolar cell using a solid Polymer Electrolyte (SPE) which is expected to increase cell efficiency to about 90 percent.

Electrolyser Corp. of Canada is also developing an advanced unipolar cell which is expected to operate at 85 to 90 percent efficiency levels. It should be noted that it is theoretically possible for cells to reach 120 percent efficiency by absorbing heat energy which is converted into hydrogen gas.

The cost of large scale electrolytic production of hydrogen gas has not been determined on an operating basis. Current production in small quantities yields costs in the area of $11.50/GJ, for a cost of electricity of 30 mills. For advanced unipolar technology (1983) production costs are expected to be reduced to approximately $6.50/GJ[17].

Research and development in water electrolysis has mainly concentrated on improving process efficiencies through the use of advanced electrolytes and improved separators and electrodes. Emphasis on operating improvements rather than capital improvements reflect the fact that the process is highly sensitive to the costs fo energy inputs. This may restrict electrolytic hydrogen production to locations which have access to inexpensive electrical power.

Electrolysis of water is a very attractive production alternative for Canada because of its fit with our existing resources and indigenous technologies. Electricity can be generated from a number of primary energy sources such as tidal, wind, solar, hydraulic geothermal and biomass, and is currently generated from nuclear and thermal generating sources. Using Canadian technology, electricity can be produced at a cost which is one of the lowest in the world. Existing undeveloped reserves for the generation of electricity appears very high in Manitoba, Ontario British Columbia, Québec and New Brunswick.



4. Thermochemical Water Splitting

The thermodynamic inefficiency of Electrolytic Hydrogen (EH) production has led to the study of a production method which uses heat energy in combination with chemical reactants to break up water molecules. This process, called Thermochemical Water Splitting, takes place as a single or multiple chemical reaction at very high temperature (2000°C). Two heat sources which may be used include: high temperature gas cooled nuclear reactors (GTGR) and focused solar radiation.

Water	+	Reactant	+	Heat Energy	=	Hydrogen, H_2

Although this technology has not been proven as yet, thermal efficiencies are expected to be superior to EH (in the order of 55 percent).

5. Biological Systems

The biochemical production of hydrogen gas using algae, photosynthetic or non-photosynthetic bacteria is a relatively new approach which has potential because of its use of cheap renewable carbohydrate materials, and non-polluting operations.

The major drawback of this production method is the very low energy efficiency of only 2 to 3 percent which creates a problem with space requirements. For example, a 2 bedroom house located in Florida normally would need about 11 scm of H_2 per day which requires about 60 cubic meters of blue green algae. At a maximum depth of .5 meters for photosynthetic reaction, the system would cover an area of 120 square meters, about 1/3 the average size of a residential lot. The practical limitations of implementing biological systems production of hydrogen on a large scale remain a major obstacle.

B. Storage

There are two main factors which have curtailed the development of bulk storage technologies for liquid or gaseous hydrogen. First, current production economics cannot be improved by the combined use of bulk production and storage because of the high feedstock cost component. Secondly, the unique physical properties of hydrogen such as its low boiling point and low energy density on a volumetric basis has required that complex storage technologies be developed in comparison with conventional fuels. Table III summarizes the storage properties of various fuels.

The new-found potential for hydrogen as an energy vector has resulted in a higher level of interest in storage technologies, which is viewed by many scientists as the key to commercial acceptance. In Canada, this has special significance because of our extreme climatic conditions and large distances between supply and demand centers.

As part of a hydrogen system, it is important that storage technologies be compatible with production and application technologies as well as consumption patterns. In transportation applications, for example, on-board storage of hydrogen must be economical, convenient, safe and capable of supplying a sufficient amount of energy between fueling stops.

Table III

COMPARISON OF STORAGE PROPERTIES OF VARIOUS FUELS

	SI (metric) Units						Conventional Units					
	Density	Energy Density		Amount Equivalent to 20 gal. gas			Density	Energy Density		Amount Equivalent to 20 gal. Gas		
	KG KG/cu.m.	J/kg X 10^3	J/cu X 10^3	litres	Kg (fuel)	Kg (tank+fuel)†	lb./cu.ft. (60°f)	Btu/lb	Btu/ Cu. ft.	gal.	lb. (fuel)	lb. (tank/fuel)+
Typical Gasoline	702	44,300	311,700	75.7	53.1	68	43.8	19,080	835,700	20.0	117	150
Methane Gas	114	50,000	56,850	415	47.2	500	7.09	21,500	152,400	110	104	1100
Liquid Propane	510	44,400	236,000	100	51.1	85	31.8	19,900	632,800	26.4	112	180
Methanol	797	20,100	160,200	147	117.0	141	49.7	9,640	429,400	38.9	258	310
Ethanol	795	26,860	213,700	110	86.0	107	49.6	11,550	572,900	29.2	194	235
Liquid Hydrogen	71	120,900	85,900	275	19.5	136	4.43	51,000	230,300	72.6	43.0	300
Hydrogen Gas	1.07	120,900	12,920	1820	19.5	2090	0.667	51,980	34,650	482.0	43.0	4600
Metal Hydride	1760	10,100	179,000	132	233.0	284	110.0	4,350	479,900	34.8	513	625
Liquid Ammonia	771	18,600	143,500	164	127.0	152	48.1	8,000	384,000	43.3	279	335

Source: "What are the Possibilities for Synthetic Fuels," Automotive Engineering, Vol. 81 No. 7 P. 54 July, 1973

The storage of hydrogen gas or liquid hydrogen in small quantities has developed to a fair degree because of the Space Program in the U.S. and the use of "commodity hydrogen" in the production of fatty alcohols, soaps and vegetable oils. The emphasis in these developments has been on achieving practical operating levels rather than minimizing storage costs. The latter would be a primary objective for future development of bulk storage technologies. The following is a brief description of current and emerging storage methods which have demonstrated potential.

1. Pressurized Gas

Hydrogen gas can be stored in compressed form in medium or high pressure cylinders at 500 to 2450 psi in the same way as compressed natural gas (CNG). Although this technology is technically feasible for large volume storage, the system is highly capital intensive, with capital costs ranging from $.8 to $1.75 million for a facility with a capacity of one million cubic feet (340×10^9 Joules) at standard conditions.[1] In addition to the high costs, safety is also an important consideration because of the possibility of explosions caused by rapid depressurization in above ground storage vessels.

2. Cryogenic Liquid

Cryogenic or "cold temperature" storage of hydrogen is technically possible because of the advancement of space technology, but is also very expensive. Using available technology, hydrogen can be liquified at temperatures below $^{-}253^{o}C$ and stored in insulated, doubled-walled vessels. Because of the very low temperatures, the process of liquefaction is energy intensive and estimated costs are in the order of \$4.75/GJ.[1] Added to this is the capital cost component of the complex storage vessel amounting to about \$5 million for a liquid capacity of 150,000 cu. ft. (364 X 10^{11}Joules).[1]

3. Underground Reservoirs

Many proponents insist that underground bulk storage of hydrogen gas either under pressure or at standard conditions is the most economic and safe alternative. Practical experience has been gained with underground storage of natural gas in depleted wells, salt mines and aquifers, and it is generally felt that similar methods can be adopted for hydrogen.

Costs from an existing natural gas facility in Kansas have been used to estimate equivalent costs for hydrogen storage. This facility, with a capacity of 10^9 cubic meters, has an associated capital cost of $27 million (U.S.). Based on an annual throughput of 30×10^7 cubic meters and an operating cost derived from a 1975 estimate of 70¢/GJ (U.S.) for natural gas, storage costs for hydrogen gas would be in the order of $1.90/GJ (U.S.) or $2.20/G.J. (Can.)[1]. This represents roughly 1/3 of estimated minimum production costs using electrolysis.

One of the major drawbacks of underground storage is its dependence on location. Areas remote from demand centers or ideal production sites lead to high transmission costs which may significantly affect the economics of the entire system.

4. Metal Hydrides

Storage of hydrogen in chemical combination with metal alloys has been studied as a potential method for on-board storage in automotive applications and bulk storage in modular systems. High temperatures are required to add and disjoint the hydrogen with the metal in a fashion which resembles a sponge absorbing water.

The major attraction of this method over compressed storage is improved safety and higher energy densities at lower operating pressures. The disadvantages of metal hydride systems include large bulk, high temperature requirements and inconvenience of recharging. Although on a volumetric basis energy densities are higher than for compressed gas storage, on a weight basis, the system has only a 2 percent hydrogen content. Therefore a very bulky unit is required in order to deliver an amount of energy which is equivalent to conventional gasoline. The high operating temperature has reduced the overall efficiency of the system considerably and has increased the total cost. Estimates of mass production costs of metal hydride tanks for automobiles are in the order of $600-$1000 per unit.[3] Actual costs would depend on design pressures, temperature and choice of metal alloys.

5. Microencapsulation in Glass

Although very little is known about the operating feasibility of using special glass compositions to absorb hydrogen, supporters feel that this method could be technically and economically superior to metal hydrides in automotive applications. Hydrogen density on a weight basis is expected to approach 10 percent, double the maximum possible with hydrides based on known technologies.[18]

C. Transmission

For many of its proposed applications, hydrogen systems will likely require pipelines to transmit gas or liquid from production sources to demand centers. Prior to the 1950's, countries in Europe used a mixture of hydrogen and carbon monoxide gases, called "town gas", to heat urban buildings. This mixture, which contained up to 50 percent hydrogen by volume, was transmitted by a network of pipelines. Although very little hydrogen is now transported by pipeline, the possibility exists that the existing natural gas system could be used to transmit hydrogen in much the same way as in Europe, thereby utilizing the sunk cost of the pipeline to gain a cost advantage.

There are certain drawbacks to the above approach which deserve mention. First, the existing natural gas pipeline network has been designed specifically to deliver energy economically to consumers. Pipe sizes and operating pressures are balanced to satisfy this requirement. By using hydrogen gas, this balance will be disturbed because of the differences in energy and mass densities. Secondly, the locations of existing pipelines may not be compatible with production and demand centres. This would lead to additional costs for feed and distribution pipe systems. Third, existing pipelines are known to be "leaky" with losses of up to 10 percent being reported in urban areas. Because hydrogen is less dense than methane, losses would be much greater resulting in higher costs to the consumer. Finally, technical problems with metal embrittlement and cracking have been observed for hydrogen pipelines operating at high pressures. The full extent of these problems has not yet been explored.

The cost estimation of a new hydrogen pipeline is difficult because of the variation in pipe sizes and construction environments. Capital costs ranging from $135,000 to $415,000 per mile and transmission costs in the order of 4-6/GJ/100 miles have been quoted.[1]

Although this is more expensive than for a natural gas system, it compares favorably with electrical transmission costs of \$1-\$2/GJ/100 miles and associated higher capital costs.

For short-haul delivery of hydrogen gas and liquid hydrogen in small quantities, the use of truck and rail transportation methods are favored over pipeline transmission. Currently, cryogenic fluid hydrogen is shipped in insulated tank cars or trucks and compressed gas is shipped in tube trailers. Conventional trailer transport of gaseous hydrogen is expensive and not suitable for large quantities.

II. APPLICATIONS OF HYDROGEN TECHNOLOGIES

There are three distinct market segments in which the applications of hydrogen technology can be discussed. The first segment is refered to here as the "traditional" market and includes the use of hydrogen in chemical manufacture, petroleum refining and metallurgy. Application technologies in this segment are reasonably mature. The second market area which can be called the "indirect energy" segment, involves the use of hydrogen for synfuel production (upgrading petroleum products), and as an energy storage medium. This segment is now in its early stages of growth.

The final segment is called the "direct energy " market or fuel market where hydrogen technology can be applied as part of a fuel system for use in transportation or space heating. Growth of this segment is not expected to occur before the year 2000. Table IV summarizes the market areas and the probable time frame for the development of each segment.

The technological implications for hydrogen are different for each of the three segments mentioned, but not unrelated. Within the traditional market, the demand for hydrogen gas is not expected to increase a great deal; however, a change in the choice of a hydrogen feedstock from natural gas to coal, coke or water will likely occur. This decision will be made almost entirely on the basis of economics by the chemical industry participants. For the energy related market segments, especially the fuel market, many other non-economic factors will come into consideration which will support or impede the use of hydrogen technologies.

A. Traditional Applications

There is little doubt that the existing markets for hydrogen gas as a chemical feedstock will increase, but only at a modest rate of 1 to 2 percent annually to 2025.

Table IV DEVELOPMENT OF HYDROGEN DEMAND

	1978			1985			2005			2025		
Market Sectors	GM^3	PJ	%	GM^3	PJ	%	GM^3	PJ	%	GM^3	PJ	%
Traditional												
Petroleum Refining	4.1	50.0	33	5.2	63.0	31	7.1	86.0	25	7.5	91.0	17
Chemical	6.5	78.6	52	8.2	100.0	49	10.5	126.6	37	12.5	151.2	29
Metallurgy	0.4	4.8	3	0.6	7.3	4	1.0	13.3	4	2.0	24.0	5
Indirect Energy												
Synfuels	1.5	18.1	12	2.6	32.0	16	9.4	114.0	33	20.0	242.0	47
Electricity	-	-	-	-	-	-	-	0.5	0	0.3	4.0	1
Direct Energy												
Auto ≠ Rail	-	-	-	0	0.5	0	0.1	1.5	0	0.2	2.5	0
Air	-	-	-	-	-	-	0.1	1.5	0	0.2	2.5	0
Space Heating	-	-	-	-	-	-	0.0	0.5	0	0.2	2.0	0

PJ = PETAJOULES = $J \times 10^{15}$, GM^3 = GIGA M^3 = $M^3 \times 10^9$

1 BTU = 1,055 Joules

Source: Assessment of Potential Future Markets for the Production of Hydrogen from Water in Canada by: Noranda Research Centre Pointe Claire, Quebec July, 1980

A recent study entitled Assessment of Potential Future Markets for the Production of Hydrogen from Water for Canada, prepared by the Noranda Research Centre,[15] concluded:

- "Indications are that the total hydrogen demand in petroleum refining will expand at an average annual rate of less than 1 percent per year over the period 1985 to 2025."

- "It is estimated that the demand for hydrogen in the ammonia sector could reach 11GM^3 by 2025, based upon a growth rate of 1.2 percent per annum."

- "... hydrogen demand in the methanol sector could show a nominal increase through the forecast period of 0.3 percent per annum."

- "Hydrogen in Canada's Steel Industry is expected to experience a strong growth rate throughout the forecast period, based upon its usage as a reductant in the production of sponge iron pellets. Based upon a forecast of 3.0 percent per annum growth rate, demand in this sector could reach 2GM^3 of hydrogen by the year 2025."

Table V presents a breakdown of the traditional markets.

Table V TRADITIONAL MARKETS FOR HYDROGEN, 1978

SECTOR	GM^3	PJ	% of Total Demand
Petroleum	4.1	50.0	33
Ammonia	5.7	65.0	43
Methanol	0.8	13.6	9
Metallurgy	0.4	4.8	3

1 PJ = 10^{15} JOULES = $.95 \times 10^{12}$ Btu

Source: Assessment of Potential Future Markets for the Production of Hydrogen from Water in Canada
By: Noranda Research Centre, Pointe Claire, Québec July, 1980

Nearly all hydrogen consumed in these markets is derived from natural gas feedstocks using imported steam reforming technology. The fact that natural gas is supply limited and may be restricted to energy related consumption in the future has prompted a search for alternate hydrogen feedstocks. The possibilities under study are coal, coke and water.

The use of coke or coal feedstocks has considerable potential especially where demand centers are located close to large coal reserves. Gasification technology from the U.S. can be used to produce hydrogen gas from coal or coke at a cost which is second only to steam reforming of natural gas. There are, however, several factors which discourage the use of coal as a feedstock. First, coal gasification results in undesirable sulphur and carbon monoxide emissions. Environmental issues are expected to play a vital role in future chemical process decisions. Second, the use of coal may only be economic for plants located close to existing reserves. Although this would apply to chemical plants located in Alberta, existing plants in Ontario would not benefit from their location.

Third, coal is regarded by many as a future source of energy for Canada for use in heating applications and synfuel production. Under these circumstances, the use of coal as a chemical feedstock would compete with more important national energy requirements. In the U.S., the future use of coal as a feedstock is viewed as the best alternative, largely because of huge coal deposits and the lack of abundant, inexpensive electricity for use in electrolysis.

Possible the most promising replacement feedstock for Canadian applications is water and the use of electrolytic technology. The major factors which support electrolysis are as follows:

1. Canada has its own indigenous electrolytic technology developed by a North American leader, Electrolyser Incorporated. This firm has competed successfully in the international market, exporting 95 percent of its output to over 80 countires. Electrolytic cells sold by Electrolyser Inc. are used mainly to produce hydrogen for the manufacture of soaps, fatty alcohols and vegetable oils, where a high level of purity is required.[17]

ii. Canada has a considerable reserve of hydraulic power, especially in Quebec, British Columbia, Ontario, Manitoba and the Maritimes, as shown in Table VI. A total potential of 100 million kwh (100 GW) operating at 60% capacity can generate about 1.8 X 10^{15}Btu of hydro electric power. At a conversion efficiency of 80 percent about 140 X 10^{13}Btu of hydrogen gas can be produced from this power by electrolysis. This quantity is roughly 10 times the total hydrogen gas consumption in Canada in 1978.[15]

iii. There is potential to use off-peak hydro electric or nuclear generating capacity to produce hydrogen inexpensively.

iv. The existing electrical transmission system can be used effectively in combination with on-site electrolytic units to produce hydrogen.

v. Electrolysis technology can be used to convert other renewable primary energy sources, such as solar, tidal and wind into hydrogen. This versatility facilitates production in many locations and in limitless quantities.

Table VI CANADIAN HYDROELECTRIC RESOURCES

LOCATION	EXISTING[1] (GW)	POTENTIAL[2] (GW)
Quebec	25.8	21.3
British Columbia	12.1	25.8
Ontario	7.1	6.2
Manitoba	4.8	3.1
Maritimes	7.8	7.0
TOTAL	59.1	93.8

[1] Includes plants in operation and under construction, 1979

[2] Remaining sites technically capable of being developed

NOTE: 1 GW = giga watt = 1 million KWH

Source: Canadian Electricity Supply in a Period of Uncertainty
University of Manitoba, Winnipeg, June 1979

vi. Electrolysis is a relatively pollution-free method of producing hydrogen and is superior to gasification of coal and steam reforming of natural gas in that regard.

vii. Electrolytic production of hydrogen is economical at almost any production scale because it is not capital intensive. This makes it an attractive alternative to be used with low-head hydro projects, and is therefore of interest to hydro authorities in some provinces.

Although there appears to be many factors which support the use of electrolytic hydrogen (EH), in the near-term, hydrogen from the steam reforming of natural gas at a cost of $5.00/GJ will remain economically superior to EH which can be produced for about $11.50/GJ. The importance of choosing the most economic production alternative is brought to light when one considers Canada's position in the competitive international ammonia and methanol markets.

Nearly 50 percent of ammonia and ammonia-based fertilizer products manufactured in Canada is exported to the U.S. duty-free (1980 value-$650 million).

As competition is strong from Trinidad, Venezuela, Mexico and the Middle East, low prices are vital to maintaining competitiveness. Methanol exports account for about 64 percent of Canadian production, and competition from the Middle East and an existing tariff on methanol to the U.S. is expected to cause a slow decay of this export market.[15]

B. Indirect Energy Applications

Because hydrogen is a major chemical component of today's conventional fuels, it can be artificially added to low grade carbon compounds to produce a synthetic fuel suitable for many residential, industrial and transportation applications. Also, because hydrogen is by itself an excellent energy carrier (also referred to as "currency") it can be used to store electrical energy and conceivably be used for bulk energy transfers in utility applications. In the indirect energy markets, hydrogen gas technology takes on a different meaning where many issues within the energy forum play a more important part.

1. Synthetic Fuel Production

The addition of hydrogen to a low grade fossil fuel can occur using a number of slightly different processes.

Fixed Bed Hydrodesulphurization for one, converts process material at 1050°F by catalytic reaction at high hydrogen partial pressures of 2500 psi. This technology is licensed by Exxon Research and Gulf Research and Development Corp. Another process, called Hydro conversion/Vis-Breaking, which involves the simultaneous hydrogenation and cracking of bitumen, is expected to reach sustained commercial operation by 1985. This technology is suitable for oil sands deposits and will likely achieve a high crude oil yield of 84 percent. A third technology, hydrocracking, is used to convert intermediate boiling range materials (650-1050°F) to distillate fuels and naptha.[15]

The upgrading process might also involve the rejection of carbon which requires hydrogen for distillation and cracking. Available technologies include fluid coking, flexicoking and delayed coking. The potential demand for hydrogen using any of the above technologies is quite large because of the extent of Canada's oil sands and heavy oil deposits in Athabasca, Cold Lake and Lloydminster. According to the Noranda Research Centre, hydrogen used for upgrading could amount to 47 percent of total demand or 20 GM^3 by 2025.[15]

At the present time, only natural gas and coke are being used as a source for hydrogen in synthetic fuel production. As the cost of methane feedstock increases, however, more unconventional sources will be used. The possibility of combining a Candu reactor with a tar sands plant has been studied. In this case, nuclear power could be used for process steam, electrical power and electrolysis of water to produce hydrogen.

2. Energy Storage

Because electricity cannot be easily stored, it must be supplied on a demand basis which usually varies substantially on a daily, weekly and seasonal basis. For planning purposes, electrical utilities divide this demand into seperate base and peak load components where the actual level of demand at any point in time is never less than the base load and the peak load corresponds the maximum level of consumption which usually occurs at dinner time on hot summer weekdays. Because installed capacity must be able to satisfy maximum peak loads, there is always a certain amount of idle capacity during off-peak times. The high fixed costs associated with peak power generating facilities creates an incentive to utilize this off-peak capacity to reduce the average cost of electricity.

The use of hydrogen gas as an energy storage medium has been proposed in order to reduce total generating capacity requirements.

The concept of a hydrogen storage system envisions the production of hydrogen by electrolysis using off-peak electricity, storage in the form of compressed gas, cryogenic liquid or metal hydride, and eventual reconversion to electricity during peak demand periods by the use of fuel cells or high temperature turbines. Fuel cells essentially operate in reverse to electrolysis by combusting a combination of hydrogen and oxygen to form steam which drives a generator to produce electricity.

In Canada, the use of hydrogen peaking devices has been considered by many provincial utilities and AECL since the early 1970's. The majority of interest has centered around the use of fuel cells or hydrogen/oxygen combusters to fuel combustion turbines to produce peak power. Manitoba Hydro, Ontario Hydro and Quebec Hydro have expressed a significant amount of interest in this technology.

In the Maritimes, specifically Nova Scotia and New Brunswick, the use of hydrogen storage in combination with tidal power is being considered.

The primary consideration in implementing such a system is economics. The cost of using a hydrogen storage device or any other storage method must be compared to the cost of installing idle capacity. Important factors in this comparison are: the load duration characteristics, the existing mix of generating equipment and the potential for alternative uses of off-peak power.

The potential for hydrogen storage methods for use in Canadian utility electrical systems is not promising. Two main factors lead to this conclusion. First, the quantity of idle capacity as a percentage of total capacity in most provincial systems is small by U.S. standards and could be reduced further in the future. More effective load management techniques have led to smoother demand curves and capacity utilization rates of 80 percent. The use of nuclear power in Ontario, for example, to supply base load needs and less capital intensive hydro power for peak demand, has improved capacity utilization considerably.

Exports of electrical power during off-peak periods by British Columbia, Manitoba, Ontario, New Brunswick and Nova Scotia have also significantly improved capacity utilization. Secondly, the use of pumped storage in most applications is more economic than any other storage method. Off-peak electricity can be used to pump water to a higher reservoir, thereby storing electrical power in the form of potential energy. During peak demand periods this water can be used to drive turbines for the generation of electricity. The only situation where other peaking devices might be preferred is where there are space limitations. In most Canadian applications this would not be a restrictive factor.

C. Direct Energy Applications

Hydrogen can be used directly as a fuel for motive applications and conversion into heat energy. This characteristic, in the light of increased prices and supply limitations of fossil fuels, has been the main driving force behind the current hydrogen movement. It's true potential, however can only be determined after close examination of other liquid fuel substitutes in terms of convenience of use, availability and above all, economics.

In the transportation and industrial sectors, conventional fuels which are currently used include oil, kerosene and gasoline. All of these fuels are derived from petroleum and are therefore subject to long-term supply limitations. Liquid fuel substitutes under consideration can be grouped into three main categories: fuels derived from fossil sources which have different properties than regular fuels; fuels which have similar properties to conventional fuels; and fuels which are derived from renewable energy sources. In space heating applications, other heat sources must be considered as a potential substitute, such as solar, geothermal and biomass energies. As well, a major alternative to the use of liquid fuels is electrification of both heating and transportation systems.

A prime factor in the economics of alternative fuels is the extent to which modifications of the existing production, distribution and application infrastructures must be made. The complex systems which have evolved on both the supply and the demand side in the transportation, residential and industrial sectors are not easily adjusted to fit radically different fuel substitutes. Hydrogen is considered to be such a fuel which requires extensive technological changes to traditional methods of production, storage, distribution and applications.

For this reason, specific uses for hydrogen which minimize these modifications will have greater potential in the nearer term. The following sections of this report present a brief description of the applications of hydrogen as a fuel for aircraft, automotive vehicles and railway systems. As well, hydrogen is discussed as a fuel for space heating.

1. Transportation

In 1979, automotive, rail and air travel in Canada accounted for 26 percent of total secondary energy consumption, far ahead of all other industrialized countries with the exception of the United States.[16] Based upon this level, a complete changeover to hydrogen fuel would create a 15 fold increase in the existing demand to 2.6×10^{18} joules per year. Table VII provides a further level of detail of potential demand within these sectors.

Barriers to the widespread use of hydrogen as a fuel for transportation are largely economic; however, many uncertainties with the technology and the potential of competitive alternatives also exist.

Table VII SECONDARY ENERGY CONSUMPTION IN CANADA - 1979

Sector	%	10^{17} Joules
Transportation		
- Rail	1.6	1.58
- Auto	22.0	21.12
- Air	2.6	2.43
TOTAL	26.2	25.13
Energy Supply Industries	7.5	7.08
Domestic and Farm	18.1	17.53
Commercial	12.9	12.25
Industrial	35.3	33.05
TOTAL	100.0	95.04

Source: NEB Energy Update, 1979

From an economic standpoint, an accurate cost of hydrogen fuel delivered to the consumer is impossible to ascertain because no practical working systems have been put into operation. Theoretically, on the supply side, the delivered cost would include capital, operating and profit components for production, processing, transportation and distribution. On the demand side, the costs and/or savings of storing and burning the fuel will also enter into the equation. For cost comparison purposes then, only rough estimates for technically feasible components can be combined to form an overall estimate for the delivered cost of hydrogen fuel.

Most of the literature to date have failed to approach the issue of hydrogen as a transportation fuel on a systems basis. Instead, reports have focussed on the technical and economic aspects of component technologies such as production, storage, transmission and applications. In part, this is a result of the specialized nature in which most researchers apply themselves, but the lack of technical maturity of a feasible large scale fueling system has also prevented an accurate assessment of the economic picture.

The analysis of hydrogen or any other alternative fuel for auto, rail or aircraft applications must include an examination of the specific fuel requirements, consumption patterns and compatibility with the existing infrastructure, in addition to the direct costs. In this regard, the physical properties and availability of the fuel are important factors to consider. For hydrogen, because of its unique properties relative to other fuels, its potential is different for each application.

a. Aircraft

The consumption of energy in commercial aviation is expected to increase substantially relative to other modes of transportation. In Canada and the U.S. there is a great deal of competitive pressure to keep the costs of freight, business and personal air travel at a minimum. The price of these services to the consumer is greatly affected by variable operating costs of which fuel represents a very important component. For these reasons, serious consideration has been given to alternative fuels as a substitute for the currently used jet propulsion (JP) fuel, more commonly known as kerosene.

Liquid hydrogen (LH) has emerged as a promising candidate among these alternatives.

The existing international network of air transportation is a very complex system of aircraft hardware and supporting infrastructure. The fuel system is at the heart of this network and in its present form, is highly compatible with the airframe and engine design of the aircraft, as well as the supporting infrastructure. During the developmental stages of the aircraft industry, the focus was on aircraft design which yielded improved performance per unit of capital invested, and other elements of the system were developed to suit those improvements. Within the last decade, fuel economy has been a prime objective in engine design and operating procedures. A continuation of this trend will lead to future aircraft and engine designs which are centered around suitable alternative fuel systems.

Liquid hydrogen has a great deal of potential as an aircraft fuel, due to its wide availability, above average combustability and high energy to weight ratio.

This latter characteristic leads to a 25 percent lower overall take-off weight and an increased range of between 30 and 35 percent.[13] Other advantages include: quieter take-offs, lower speed landings and less harmful emissions. Despite these advantages, however, there are significant technological and economic barriers to its immediate introduction as a fuel. Because hydrogen has a low boiling temperature, it can only exist as a liquid in cryogenic form at $^{-}253^{o}C$. This property creates additional costs for liquefaction and technical problems with storage and handling. Although present technology is available as a result of the Space Program in the U.S., the costs remain very high.

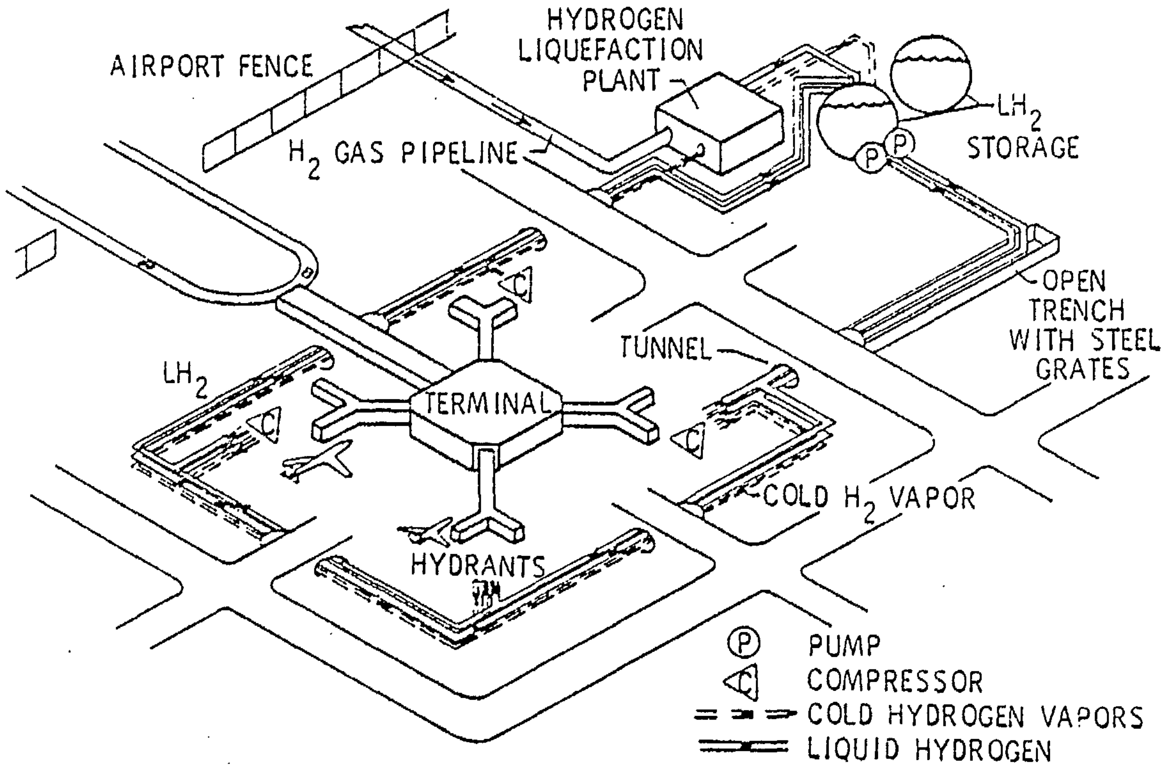
In addition to the costs of supplying LH_2, there would be additional capital costs associated with the technical changes in airframe and engine design. These costs would be reduced by the savings in energy consumption per tonne or passenger mile because of the higher energy content of hydrogen on a weight basis. Not including the above factors, the cost of LH_2 at \$16.78/GJ does not compare favorably with the present cost of JP fuel in Canada at about \$6.75/GJ. Clearly, on an economic basis, LH_2 has a long way to go.[3]

An estimate of the cost breakdown is as follows:

	$ Can./GJ
Production of H_2 gas near point of consumption using present electrolysis technology[1]	11.80
Liquefaction near point of a consumption using Union Carbide Linde module based on a daily production of 250 tons. of LH_2[3]	4.73
Storage at point of consumption using doublet-walled evacuated tanks. Capacity of 150,000 C.F.[3] Annual throughput - 7.5 X 10^6 C.F. Return on invested capital - 15% (D/E = .5)	.25
Approximate cost of LH_2 fuel supply	$16.78/GJ

Figure 2 shows a schematic of a hydrogen fueling system for aircraft.

FIGURE II SCHEMATIC OF A HYDROGEN FUELING SYSTEM



Source: Reference [15]

There are strongly competitive fuels in existence which may pre-empt the introduction of hydrogen as an aircraft fuel. These alternatives include synjet (synthetic jet fuel) and liquid methane (LCH4).

Synjet fuel can be produced using known technology from either shale or coal at estimated costs of $7.00/GJ and $9.00/GJ in Canadian 1980 dollars, respectively.[40]

Although these costs are based on U.S. conditions, production costs in using Canadian coal or shale reserves would not differ greatly. Besides the obvious cost advantage over LH_2, the use of synjet will not require drastic changes to the existing infrastructure because its properties will be almost identical to existing JP fuels.

Liquid methane derived from coal is also a more attractive alternative than LH_2 because of its lower cost of production (estimated to be $9.50/GJ Can., 1980)[40] and easier fit with the existing infrastructure. There is also the long-term potential of extracting methane from natural hydrate resources.

Although both LCH_4 and Synjet show more promise than LH_2 there are two significant factors which support continued study of the use of hydrogen. First, LCH_4 and Synjet rely on non-replenishable fossil reserves for their production which may at some point in time be required for higher priority uses such as automotive and industrial applications. Second, and most important, the mining and processing of coal has been associated with serious health problems and environmental pollution.

Participants included representatives from industry and governments from the U.S, Japan, Canada, England, France, West Germany and the Commission of the European communities. The concensus of the symposium specified that:

> "the use of liquid hydrogen as a commercial air transport fuel has sufficient long-term promise to justify a substantial research and development program".

A multinational Ad Hoc Executive Group, through a working committee, has developed the first phase of an R&D program with the objective of: "demonstrating the utility and advantages of LH_2 as an aircraft fuel so that it could be a credible candidate when nations address their individual energy futures and the air transport industry selects a fuel for the future". The estimated cost of developing the engine, aircraft and support facilities is $75 million.[40] At the present time, the project has not received sponsorship and no action has been taken.

Future R&D activity will likely be intensified in the U.S. and other countries which have a domestic manufacturing capability in aircraft frame or engine components.

Canada's potential contribution on the application side could be in the areas of materials science, and testing of airframe prototypes. On the supply side, a significant contribution can be made in the areas of hydrogen production, liquefaction and distribution. As well, the presence of two international scale airports at Montréal and Toronto gives Canada an opportunity to participate in early demonstration projects. In any event, the leading role in industrial activity will be taken by U.S. manufacturers because of the wealth of technical know-how and the huge share of the international aircraft market that they possess.

b. Automotive

In 1820, Rev. W. Cecil published a paper entitled "The Application of Hydrogen Gas to Produce a Moving Power in Machinery". Since that time, and more noticeably during the last decade, many scientists and entrepreneurs have advocated the use of hydrogen as the ultimate fuel in private and public automotive applications.

The major arguments in support of this advocacy are as follows:

1) Emissions from automobiles, trucks and public vehicles is the major source of urban pollution. The combustion of hydrogen is virtually non-polluting.

2) Present fuels and most alternative fuels under consideration are derived from fossil based resources and therefore are subject to eventual depletion. Hydrogen can be obtained from water using electricity generated from renewable resources and sufficient quantities can be made available to support future demand.

3) Technically, it is possible to retrofit present automotive technology to fit a hydrogen fuel system. This has been demonstrated by the Billings Energy Research Corporation, of Utah, U.S.A.

Despite these attractive advantages, the future of hydrogen as an automotive fuel is uncertain because of the remaining technical problems and the large number of other alternative fuels which are also under consideration.

The complexity of the existing fuel production, transportation, distribution and application technologies provides a strong economic incentive to introduce new fuel which most closely match the properties of gasoline or diesel fuels. Hydrogen is the least attractive substitute based on this criterion. More likely alternatives include: methane in compressed or liquid form derived from fossil deposits or biomass; Liquid Petroleum Gas (LPG); Alcohols from wood or biomass; and; propane from natural gas. Most of these fuels fit well with the existing system and are capable of delivering a sufficient quantity of energy to the consumer.

However, as long as the questions of supply and impacts of pollution remain unanswered, hydrogen should seriously be considered as a long-run alternative. During the next two decades, it seems plausible that the use of fuels and other means of producing motive power will become more specialized to suit the individual needs of the consumer. Fox example, low cost fuels such as alcohol could be available for short range applications on a local basis and can also be produced economically on a small scale.

Retrofitting and maintenance can also be performed locally. For longer range, more flexible mobility, the use of methane or propane could become popular. The cost of these fuels will be higher, offsetting the benefit of greater availability. The search for a fuel which can be "all things to all people" will continue as long as there is demand for the liberal use of the private automobile. On the manufacturing side, the economics gained in mass production of automobiles and development of an infrastructure of parts supply, maintenance and fuel distribution also encourage this search. Three alternatives appear to have the greatest long-term potential; electrification, methane from naturally occuring hydrates and hydrogen. Of these three possibilities, electrification and hydrogen technologies have been developed to the greatest extent but many technological problems are unresolved. There is presently no technology available for the extraction of methane from hydrates. However, reported reserves are immense in relation to existing consumption levels.

The major technical problem with electrification is the low energy content per unit of weight. Present lead batteries are 150 times heavier than the equivalent amount of gasoline or diesel oil.[25]

This results in significantly lower performance and shorter period of operation between charges. The development of liquid air batteries has improved the weight problem considerably but further development is required before satisfactory performance levels can be reached.

Although technically, hydrogen gas and LH_2 have already been proven in automotive applications, major technological problems remain to be solved. With regard to combustion, the low ignition energy of hydrogen causes problems with backfiring in the intake manifold. Under these circumstances, there is a high probability of explosions occuring. A more difficult problem is with the on-board storage of hydrogen. Pressure storage in tanks is not feasible because of the size and weight restrictions. Storage in liquid form, although technically feasible, is very energy inefficient and difficult because of the low temperatures that are required. As well, the safety implications of LH_2 spills have not been fully explored. A third method of hydrogen storage, using metal hydrides, seems to have a great deal of potential because of the higher energy efficiency and better safety record.

Energy densities in the order of 15 times lower than gasoline on a weight basis and 6 to 8 times lower on a volume basis leads to reduced vehicle operating ranges. A forth storage method, which uses glass spheres to encapsulate hydrogen, also shows potential as a way of overcoming the energy density problem. Practical operation of this system has not been demonstrated.

In an effort to solve the apparent shortfalls of independent electric or hydrogen powered systems, some research has been performed on hybrid technologies which use a fuel cell containing hydrogen and oxygen in combination with an electric motor to propell automobiles. Unlike present fuel systems which convert stored energy to heat energy and finally to mechanical work, fuel cells can convert the fuel's energy directly into work. Further development to improve material costs and performance is necessary, especially on electrocatalyst/substrate compounds and electrodes.

With regard to a possible introduction of hydrogen as a direct fuel or in combination with a fuel cell, there are specialized applications where the use of hydrogen will take priority.

Commercial fleets of cars, trucks and buses, for example, will be converted before private vehicles. Additional space requirements especially favors its use in trucks and buses. Under these circumstances, production and distribution of hydrogen fuel can take place at a central location, thereby eliminating the need for a costly widespread infrastructure. This pattern of conversion is now taking place for propane fuels.

Ultimately, a uniquely designed hydrogen fuelled vehicle would have to be manufactured if the private automobile is to be converted. The large engine and auto manufacturing companies in the U.S. will play the lead role in this transition. At the same time, a radical change in the fuel supply system will be required on the supply side. The timing, co-ordination and extent of these changes will greatly affect the final cost of hydrogen fuel to the consumer.

Under normal circumstances, Canada would play a secondary role in the development of automotive technologies to fit a hydrogen fuel system; however the cost of producing storing and distributing hydrogen could reach lower levels in Canada, thereby, encouraging the need for a change in automotive technologies in advance of the U.S.

Particularly noteworthy is the different emphasis on production technologies, with the U.S. favoring coal gasification and Canada favoring electrolysis of water as a source of hydrogen. On the supply side, Canada can contribute to storage and fuel cell research through the application of materials science techniques. Spinoffs from this effort can be applied to many other uses of hydrogen such as the use of fuel cells for industrial power and the use of storage in utility applications.

Current R&D activity in automotive applications of hydrogen is limited but not insignificant. There is a general awareness that existing hardware can be retrofitted to suit hydrogen but no concentrated effort on new engine design has been made. Billings Energy Corporation of Provo Utah has been the most visible supporter of automotive conversion by successfully retrofitting camp stoves, big cars, small cars, buses, and a U.S. post office jeep. In Canada, the major supporter of H_2 in automobiles is Dr. David Scott of University of Toronto, who is currently studying fuel cell technology.[17]

The Ontario government has commissioned a $6 million dollar, 3 year program for the demonstration of hydrogen as an alternative fuel for public transport to be performed by the Urban Transit Development Corporation (UTDC). The large auto manufacturers have not undertaken major studies, choosing instead to concentrate on nearer term alternatives such as propane and compressed natural gas.

C. Rail

The increased space availability in railway locomotives improves the likelihood of their conversion to hydrogen fuels. Technically, it is feasible to convert rail systems to hydrogen and demonstration projects have already taken place or are in the proposal stage. The potential for hydrogen in this application is different for long-haul intercity systems relative to short-haul commuter rail or mass transit systems.

The UTDC has successfully developed a magnetic transit system which is suitable for high density, short distance applications within an urban environment. Many cities have also elected to electrify their mass transit systems to improve operating efficiency and reduce harmful emissions.

The potential for hydrogen in these applications is very low because of its disadvantages compared to electrical or magnetic systems. It seems unlikely that highly specialized, capital intensive rail transit systems will become uneconomical to operate relative to hydrogen as long as electricity is used as a source of power.

For long-haul intercity travel and some applications of commuter rail travel, hydrogen could prove an attractive substitute to diesel oil. The length and frequency of use of these systems, do not justify the great expense of electrification. As well, central production and fueling stations can be easily integrated into the system.

In Canada, the possibility of railway conversions to hydrogen is being examined by the UTDC as part of its $6 million program on transportation applications. In Quebec, a private organization, PICA Mirabel has proposed the construction of a hydrogen powered transit system between Montréal and Mirabel airport. Although this proposal has not received financial support, a great deal of interest has been aroused.

Within the industrial sector, the introduction of intercity railway systems powered by hydrogen would not pose many difficulties mainly due to the existence of two national railways, CN and CP. In the U.S., however, the railway industry is composed of many small operations which would lead to management control problems.

2. Space Heating

The use of hydrogen gas is being contemplated for residential, commercial or industrial space heating as a direct fuel or fuel extender. In these applications it will come into direct competition with natural gas and electricity. At least two conditions must exist before a hydrogen heating system can be implemented economically.

First, hydrogen must be available to the consumer at a price per unit of usable energy which is lower than gaseous hydrocarbons or their synthetic derivations. Current production and transmission costs are at least two to three orders of magnitude higher than natural gas or heating oil, and there is an additional cost of retrofitting existing heating systems to suit hydrogen.

Secondly, hydrogen must be available at a lower cost than electricity. Electrical heating systems are now in place in many locations where electricity is less expensive and more convenient to use than oil or natural gas. In the long-run, when fossil fuel supplies are depleted, hydrogen will be in direct competition with electricity as a heating source. Hydrogen will be favored only when the difference in delivered cost per unit of energy is offset by the increased transmission cost of electricity over large distances. In most circumstances, however, a gradual upgrading in the transmission capacity of electricity will occur and result in a slow increase in the average price of electricity. Development of low head hydro power in locations close to demand centres will also favor the future use of electricity.

Many individuals have advocated the use of hydrogen gas to supplement or extend existing natural gas supplies. Experiments have shown that up to 15 percent hydrogen by volume can be added without requiring modifications to burners.[14] Although this appears to be an excellent way of providing an initial market for hydrogen as a fuel, there are two strong arguments which do not support this application.

Consumers would not be willing to pay more for the hydrogen content on an energy basis than they would for an equivalent amount of natural gas. It would only be economical then, if hydrogen could be produced and delivered at a lower cost than natural gas. Secondly, such a system would only be useful if it was used as a demonstration to gain practical experience in anticipation of a future saturation of hydrogen into the space heating market. As mentioned above, it appears that electricity will be a more attractive source of heat in Canada.

III. RESEARCH & DEVELOPMENT IN CANADA

Studies, research and development related to hydrogen have been undertaken in Canada for the last eight years but it is only within the past year that activity has reached a level of public awareness with the formation of task forces, research bodies and interest groups within the federal and provincial governments and the private sector. A summary of these activites is included in Appendix I. The following briefly describes the most notable R&D efforts which have recently been initiated.

A. <u>Federal</u>

Several federal government departments, the National Research Council and Atomic Energy of Canada Ltd., have undertaken responsibilities which are related directly or indirectly to hydrogen technologies. Through the Conservation and Renewable Energy Branch of Energy, Mines and Resources, NRC has been appointed the lead agency for the management of the National Hydrogen R&D Program.

Federal R&D expenditures on hydrogen R&D are allocated through the Energy R&D Panel within Energy, Mines and Resources mainly to industrial and government research bodies, and through the Natural Sciences and Engineering Research Council to university participants. These expenditures amounted to $1 million for FY 79/80 and current budgets for FY 80/81 and FY 81/82 are $1 million and $1.3 million respectively.[45] Recently, the Panel has formed three separate working committees to deal with proposals on hydrogen, conservation and alternative fuels respectively.

The National Research Council has recently prepared its 5-year-long range plan, <u>The Urgent Investment,</u> in which it proposes to study hydrogen as an energy carrier along with electricity and alcohol.

An estimated expenditure of $15 million and 23 person-years are required for the proposed program over the planning period.[12] Specific initiatives for study, shown in Appendix II attached include sub-programs on safety, bulk storage, high capacity storage, generation from liquid carriers, transportation fuelling sub-systems, hydrogen production by advanced electrolysis, fuel cells and small hydrogen generators. The objectives of the program are:

1) To develop hydrogen energy technologies for the displacement or extension of hydrocarbon resources by renewable, indigenous or inexhaustible sources.

2) To ensure that the necessary level of engineering and technological competence in hydrogen energy systems is available in Canada.

3) To co-operate with, and encourage participation of, provincial authorities and industrial groups in field trials and demonstration programs.

The establishment of a national research centre for the development of hydrogen technologies has been under study by NRC.

In an independent consultant's report prepared by Philip A. Lapp Ltd, it was recommended that the government establish a Federal Electrochemical Technology Centre with a mandate to perform R&D in the areas of hydrogen technologies (specifically electrolysis) and batteries.[41] It was further recommended that the centre be managed by a senior executive group from NRC. No decision has been made on the consultant's recommendations.

AECL has been studying the use of electrolysis as a means of producing heavy water (D_2O) for use in the CANDU nuclear reactor. By using a combined Electrolysis Catalytic Exchange (CECE) process, it is possible to obtain by-product heavy water from electrolytic hydrogen, as long as a suitable water feed-stock is used.[17]

Transport Canada is currently involved in an international study on the use of hydrogen in aircraft as a member of an ad hoc executive group formed in 1979. The objective of the study is to develop an international R&D program for the implementation of a "Demonstration Airline". Although a report on the proposed program has been released, no sponsor has come forward to implement the plan.[40]

A year long study by the Parliamentary Special Committee on alternative Energy and Oil Substitution has recently been completed. The notion that Canada should become a "world leader" in hydrogen energy technologies was heavily supported and recommendations included a $1 Billion expenditure on "the development of a hydrogen based energy system" over the next 5 years. The Committee also recommended that a Commission to be known as Hydrogen Canada be established to act as the lead agency for RD&D and commercialization in Canada.[34]

B. Provincial

The Ontario government has been very active in conducting studies and promoting the development of hydrogen technologies. In 1975, hydrogen production, transmission and storage methods were assessed by Ontario Hydro and in 1978, the Ministry of Transportation and Communications examined its potential as a transporation fuel. These studies concluded that major government action was not warranted at that time.[42]

More recently, a Task Force on Hydrogen Energy was formed with an assignment "to provide a perspective on the ultimate and transitional roles of hydrogen, particularly from non-hydrocarbon sources", and "to propose components of an Ontario strategy to maximize the economic and/or environmental benefits from the use of hydrogen". The Task Force is due to report its findings in June or July, 1981. Preliminary findings communicated to the author by the Task Force Chairman, Dr. Arthur Johnson, has led to the following impressions of Ontario's position:

- The potential and probable timing of hydrogen as a fuel is difficult to predict but it deserves as much research attention as any other popular alternatives.

- There is a definite requirement for hydrogen in the production of synfuels within the petrochemical industry.

- Hydrogen production by electrolysis in combination with nuclear or hydraulic power is the most promising alternative for Ontario.

As part of Ontario's BILD Program, the Ontario government plans to establish a Canadian Hydrogen Technology Centre and is asking for the co-operation of the Federal Government, Ontario Hydro, AECL and other provincial utilities.

The federal response, expected from the Hydrogen R&D Program Committee and Marc Lalonde has not been finalized. There are indications that Ontario will be approached with a recommendation for an electrochemical centre, an option which is preferred by NRC as delineated in the LAPP report to the NRC Associate Committee on Energy Conversion, Storage and Hydrogen Systems.

The Ontario Crown Corporation, Urban Transportation Development Corporation (UTDC) has received $6 million for a demonstration of hydrogen as an alternative fuel for public transportation over a three years period. The program is in its final detailed planning stage and is expected to enter the hardware stage shortly culminating in the conversion of several diesel powered public vehicles for operation on Toronto streets. Additional studies could involve fuel cell power systems.

The Manitoba government, through its Research Council, has initiated a $100,000 study, jointly with TransCanada Pipeline Corp. and AECL.[43] The objective of the study is to examine the feasibility of utilizing existing hydraulic reserves for the production of hydrogen by electrolysis and co-production of heavy water for use in nuclear reactors. Pipeline transmission of hydrogen is also being examined.

The Government of Quebec is working with Noranda, Quebec Hydro, Ecole Polytechnique, S.N.C., CRIQ and PICA Mirabel on a "Development Strategy for Hydrogen Energy R&D in Quebec". PICA Mirabel is a private group which is proposing the development of an industrial park at Mirabel Airport, which would include a hydrogen production plant. They are also proposing that a hydrogen fuelled mass transit system be constructed between the airport and Montréal. Hydro Quebec is also involved with the planning of a $2 million pilot scale electrolysis plant to be built this year at its laboratories, with the co-operation of Electrolyser Inc. and Noranda.

C. Industrial

The bulk of industrial R&D in Canada related to hydrogen, has been performed on electrolysis technologies by Electrolyser Incorporated and Noranda. With the assistance of Industry, Trade and Commerce and a $2.5 million grant from the Enterprise Development Program (EDP), these firms are in the process of developing advanced unipolar cells with the objective of reducing hydrogen production costs for applications in ammonia and methanol manufacture.

This new technology is expected to be superior to the S.P.E. bipolar cells being developed by General Electric in the U.S., by virtue of the fact that proposed titanium electrodes for the S.P.E. cells will greatly contribute to the capital costs with no appreciable gain in operating efficiency. A $2 million pilot scale plant using the advanced technology is scheduled for assembly this year at the laboratories of Hydro Quebec at Varennes. Also, a 100 MW demonstration plant has been proposed but no decision has been made as to cost sharing, location and applications.

Aside from the R&D activities of Electrolyser and Noranda, it would be useful to describe these firms in further detail as their strengths are often a central issue of arguments which support increased effort in developing hydrogen technologies in Canada. Electrolyser Incorporated is regarded among the world leaders as a manufacturer of electrolytic cells which produce high grade gaseous hydrogen for use in the hydrogenation of vegetable oils, fatty alcohols and soaps. They have been operating in Canada under private ownership for many decades and export up to 95 percent of their production to over eighty different countries. Noranda Mines Ltd., is a large diversified Canadian natural resource company, and through its subsidiary, the Noranda Research Centre, carries on R&D to support its growth and maintain international competitiveness.

The Noranda Group of Companies operates mines, smelters, refineries, extensive forest product operations and manufacturing operations in Canada and abroad.

Other participants who have conducted research on a smaller scale include: Atlantic Industrial Research Institute, Gould Battery, Daychem Ltd., Raylo Ltd. Energy Research, Bell Northern, CANNET and C.E.R.C. Approximately $450,000 has been allocated to these organizations through the Energy R&D Panel during FY 80/81. A description of their projects is included in Appendix III.

D. University

As of March, 1981, approximately $600,000 has been allocated to Canadian Universities through NRC and $150,000 for 1980-1981 through the Energy R&D Panel. The majority of this research has dealt with Photon and Non-Photon Import Production of hydrogen and to a lesser extent some research has dealt with hydrogen storage, fuel cells and automotive applications. Dr. D.S. Scott, of the University of Toronto is well known for his efforts in this latter category. Appendix III, provides a breakdown of the current R&D activities in Canadian universities and industries.

IV) RESEARCH AND DEVELOPMENT AT THE INTERNATIONAL LEVEL

Many other countries have increased the level of R&D in hydrogen technologies within the past decade. The most active nations include France, Belgium, West Germany, Japan and the U.S. A summary of their activities (as of 1978) is shown in Table VIII, and Appendix IV presents further details on the programmes.

By comparison, Canada's R&D effort is markedly inferior to that of other countries in all areas of hydrogen reserch. France, Germany and the U.S., for example, have expended more funds on thermochemical and electrolysis production methods as well as storage and application technologies, than Canada. Also, Belgium and Japan are more active in electrolysis R&D than Canada.

France views the potential for hydrogen technologies in much the same way as Canada. As part of their 10 year research plan they conclude:

- "By 1990 electrolysis should develop to a substantial degree".

- "... a great deal of uncertainty remains as to the possible market for the product (hydrogen).

One can nevertheless expect that by around the end of the century, the bulk of the market will still be centered around the chemical industry".[39]

Nuclear off-peak as well as hydraulic power will likely supply the electricity required for electrolysis initially; however, the use of dedicated nuclear plants is being contemplated for the long-term in France.

Two industrial groups in France were formed in 1979 and given the objective of developing a high performance apparatus for the mass production of hydrogen under high pressure, high temperature conditions. The aim is to reduce production costs and to construct a pilot plant with a 1MW capacity and later a demonstration plant with a 100MW capacity by 1982.

Although little is known about the specifics of Japan's R&D effort, it is believed that current expenditures of around $4 million p.a. are being allocated for the development of production, storage and application technologies as part of their "Sunshine Project", a forum for studying energy supply alternatives.[44]

The U.S. has expended the most funds in hydrogen R&D, placing emphasis on developing production and storage technologies and little on energy-related applications.

Table VIII

Summary of funding of programmes on hydrogen (^{O})

Country (*)	Thermo-chemical		Electrolytic		Storage, uses, safety, etc.		Other methods	
	1977	1978	1977	1978	1977	1978	1977	1978
Belgium	-	-	0.285	0.56	-	-	-	-
Canada	-	0.044	0.088	0.154	0.317	0.23	0.068	0.088
European (c) Communities	(5.97) 5.45	(8.5) 6.94	(3.0) 1.55	(8.26) 4.19	(0.89) 0.46	(2.54) 1.25	-	-
France	2.0 (76-77)	5.07 (75-77)	1.46 (76-77)	-	0.326 (76-77)	-	0.15 (76-77)	-
F.R. of Germany	4.87	4.58	-	3.05 (75-78)	-	-	-	-
India	-	-	0.09 (77-78)	0.97 (78-83)	included in other studies		0.26 (77-83)	-
Japan	-	-	-	-	-	-	3.0 (b)	
Netherlands	-	-	0.173	-	0.098	0.0323	-	-
Sweden	-	-		-	-	-	5.0/year (a)	
Switzerland	-	-		-	0.027		-	-
U.S.A.	3.9 (20.0 up to 1981)	2.9	2.5	2.9	11.0	5.5	12.0 (83.0 up to 1984)	8.5

(^{O}) Approximatively converted into millions US $ (1978)

(*) In alphabetic order.

(a) Total expenditure on the whole hydrogen programme.

(b) Estimated total funding of the whole hydrogen programme on the basis of global data.

(c) Because of the cost sharing basis of the E.C. "indirect action", the total investment, including the part shared by national partners of the E.C. is given in parentheses.

Source: Hydrogen Energy System, Proceedings of the 2nd World Hydrogen Energy Conference, held in Zurich, Switzerland, 21-24 August, 1978.

As well, electrolysis production techniques have received a great deal of attention by General Electric Ltd. However, there seems to be greater strategic emphasis on the production of hydrogen from coal by gasification in the United States.

Most of the activity in the U.S. has originated within the academic institutions and industry. The University of Miami, for example, has generated a large amount of world wide attention by hosting several international symposia on hydrogen energy through their Institute of Clean Energy Research. The Institute of Gas Technology has organized two (2) conferences on Non-Petroleum Vehicular fuels which included hydrogen technologies.

Internationally, there are three organizations which are active in hydrogen technology; the International Association for Hydrogen Energy, the International Energy Agency and the Hydrogen in Air Transportation Ad Hoc Executive Group. The first organization, formed in 1974, meets every two years to discuss technical and non-technical issues. The 5th World Conference will be held during the week of July 15, 1984, in Toronto. The second group was also formed in 1974 and channels its activities through its Hydrogen Production Programme where participants have entered into a "hydrogen agreement". A description of the proposed program containing six Annexes and a list of participants is included in Appendix V. It should be noted that France is not a participant in this activity.

A major study by the International Institute of Applied Systems Analysis (IIASA) entitled, "Energy in a Finite World", has dealt with the subject of world energy supply and demand, now and in the future, in a very comprehensive manner. Their report briefly refers to a future transition to an "electrical energy reference system". They go on to say:

> "At some point, conventional oil must ultimately be replaced by other liquid fuels, elaborately processed (shale oil) or essentially synthesized from carbon. As this transition occurs, liquid fuel production and use would become more expensive and would, therefore, be limited to immediate applications such as transportation and storable energy supplies for sporadic use in dispersed locations... Eventually electricity will become the primary energy carrier and will be supported by hydrogen produced thermochemically using solar energy or by electrolysis." [2]

Aside from this brief mention, IIASA made no concrete predictions about the role of hydrogen in any of its future energy scenarios, and made little reference to what the energy scene beyond the year 2030 might look like.

To summarize, it appears that there is a significant amount of international interest in hydrogen technologies with most of the R&D effort being focussed on its use as a chemical commodity, and not as an energy vector.

This is reflected somewhat in the level of research expenditure which is probably insufficient for a rapid development to a hydrogen economy. It is clear, however, that hydrogen is now the subject of many in depth studies and international symposia sponsored by respected organizations. A likely outcome of these meetings could take the form of a firm commitment by one or more countries to develop its full potential as an energy carrier.

VI. POLICY IMPLICATIONS

There are several strategic options available to Canada which can be considered to guide future developments in hydrogen technologies. However, in the context of achieving national econmic goals, the formulation of policies must be secondary to broader industrial strategies which govern the development of our energy industry and also components of the chemical industry. For example, it seems difficult to justify large expenditures on hydrogen as a liquid fuel substitute if the National Energy Program has placed little emphasis on the development of alternatives fuels as a way of achieving the objective of energy self-sufficiency by 1990.

The rationale for proposing strategic options for hydrogen outside the above context is based on two assumptions;

First, the National Energy Program has been developed for a time frame which is different than the probable time frame for the introduction of hydrogen as an energy vector. In this sense, a strategy for hydrogen technologies can be considered futuristic and R&D oriented rather than operational, while at the same time retaining the original objective of achieving energy self-sufficiency.

Secondly, hydrogen technologies can be considered in an international context with strategic options related to Canada's import/export potential.

On the basis of the above qualifications, the following general strategic options can be applied to hydrogen technologies;

1) "Do nothing but wait and see".

   Relative to other countries, Canada's need for developing alternative energy vectors or substitutes for fossil fuels is low. This observation is made on the basis of existing primary reserves of fossil fuels in the form of natural gas, conventional crude, coal and non-conventional sources such as tar sands, heavy crude and oil shale. With the successful development of these resources, it seems unlikely that Canada will suddenly require energy alternatives such as hydrogen before most non-producing countries including the U.S.

The undesirable consequences of following this strategy are twofold. First, it does not capitalize on our technological strengths but rather exposes them to the possibility of obsolescence brought about by strong international competition. Secondly, unlike its energy situation, Canada does not enjoy a strong position in the international ammonia and methanol market. The use of new hydrogen feedstocks (notably electrolytic hydrogen) by international competitors could threaten our existing exports to the U.S. and result in higher domestic prices.

2) A second strategic option is to "maintain our position relative to other countries".

This alternative would necessarily mean that Canada increase its current level of R&D expenditures to match those of other countries and in this way protect its domestic industry from foreign technological developments. There is also a possibility that Canada can improve its position in some areas because of the existance of indigenous nuclear, hydro and electrolytic technologies which have already gained international respect.

3) A final general option is to: "develop world leadership in hydrogen technologies".

This strategy places a high degree of emphasis on increasing exports and will only be sucessful if Canadian expertise can be used to develop technologies which can be applied in many different situations at a minimum cost. It appears that in many areas, Canada is in an excellent position to follow this strategy although the risks associated with the energy uses of hydrogen remain very high. The greatest potential lies in the use of electrolysis in the non-energy applications.

As a subset to the above major strategies, Canada has the option of specializing on particular components of hydrogen technological systems such as production, storage and applications. For the most part, research institutions in Canada should concentrate on production, storage, transmission and application technologies in non-energy uses of hydrogen, but should play a supporting role to the U.S. in the development of applications in the energy field such as automotive and aircraft where the U.S. has a significant advantage in R&D and manufacturing capability.

The lack of sufficient information on hydrogen technologies in Canada has demonstrated the need for further detailed study. More concise information is required in the following areas:

1) The potential, social, political, environmental and economic impacts of introducing hydrogen systems into the Canadian economy.

2) An accurate description of Canada's existing technological base.

3) A description of the existing participants in hydrogen R&D both in Canada and abroad including their activities and program objectives.

4) An analysis of the potential of all alternative fuels which directly compete with hydrogen in a time frame extending beyond the year 2000.

5) A clear understanding of U.S. R&D objectives with respect to hydrogen, particularly in its application as a fuel for automobiles and aircraft.

With regard to the implementation of an organized hydrogen R&D program, there are many issues which must be addressed that relate to the existing institutional framework and the individual objectives of provincial governments relative to national goals. With respect to the former, it is expected that EMR and ITC will play major roles in the overall administration of the program with emphasis on directing industrial activities within the chemical and energy sectors. The National Research Council should continue to concentrate on mission oriented research programs in co-operation with industry and universities.

Clearly, the provinces will place varying emphasis on the development of hydrogen technologies because of the differences in resource wealth and energy objectives. The federal government must avoid playing favorites under these circumstances by contributing to the development of technologies (including other alternative energy forms) which suit the resource strengths of individual provinces. For example, Nova Scotia and New Brunswick have not indicated an interest in hydrogen technologies, prefering to concentrate on the development of nuclear and tidal power. In addition to supporting these projects, the federal government could perform research on the integration of a tidal generating system into a hydrogen economy. The versatility of hydrogen production and storage facilitates this approach.

APPENDIX I

CURRENT STATUS OF
HYDROGEN ENERGY ACTIVITIES IN CANADA
March, 1981

Current Status of Hydrogen Energy Activities in Canada

J.B. Taylor, National Research Council

March 1981

1. Major Planning Studies

1.1 Assessment of Potential Future Markets for the Production of Hydrogen from Water in Canada.
International Energy Agency.
Author: P.S. Bailey, Noranda Research Centre.
Status: Reported September 1980. Update will occur every two years.
Companion reports from Belgium, CEC, Germany, Japan, Netherlands, Sweden, Switzerland, U.S.A.

1.2 Development of a Strategy for Hydrogen Energy R&D in Quebec.
Coordination: Mr. Jacques Rostenne, PICA Mirabel.
Dr. Guy Bélanger, Hydro Quebec - IREQ.
Status: Will report in May 1981.
Participants include: Noranda, IREQ, Ecole Polytechnique S.N.C., CRIQ, PICA Mirabel.

Note: PICA Mirabel are a group concentrating on the development of an industrial parc at Mirabel airport. Hydrogen technologies loom large in their planning, including liquid hydrogen production and use in rail locomotives and in aircraft.

1.3 Ontario Hydrogen Task Force.
Chairman: Dr. Arthur Johnson.
Status: Report deadline May 31, 1981.

Note: Studies largely evolve around the capability to produce hydrogen in Ontario from low cost electrical energy. Current political climate in Province favours development of electrical supply as indigenous energy resource.

1.4 Parliamentary Special Committee on Alternative Energy and Oil Substitution
Chairman: Tom Lefebvre.
Status: Report expected March 31.

Field covered included hydrogen energy technologies.

1.5 Ad Hoc Executive Group on R&D for Liquid Hydrogen Fuelled Aircraft.
This group formed after a special symposium "Hydrogen in Air Transportation" at Stuttgart in September 1979. Canada is represented by N.Gore of the Department of Transport.
Status: Regular meetings and reports. Major feasibility study for demonstration activity has not yet been started. Plans still relate to a 1987 cargo service operation out of the U.S. West and possibly involving a Canadian terminal (Mirabel).

1.6 A study on the Establishment of an Electrochemical Technology Centre.
Author: Philip A. Lapp Ltd. for the NRC Associate Committee on Energy Conversion, Storage and Hydrogen Systems.
Status: Report submitted to N.R.C.

Note: Aspects of this report impinge upon requirements associated with hydrogen energy technologies. The Minister of Energy for Ontario made a proposal to the federal government for joint action in the establishment of a Hydrogen Centre in Ontario. The federal response has not yet been made public.

2. Technical Program

2.1 University grants supported by National Sciences and Engineering Research Council

Major new support in two areas:
1. Photochemical conversion, J.R. Bolton, which is only in part related to hydrogen.
2. Fuel cells, D.S. Scott. This group now receives most of its support from Bell Canada.

2.2 Panel on Energy Research & Development

In spite of funding constraints, six new contracts were started. Five were for the development of alkali resistant membranes and separators for elevated temperature electrolysis. One was for studies of pipeline steel and weld embrittlement.

2.3 Industry

A cost shared agreement between Industry Trade and Commerce and Noranda/Electrolyser has resulted in the development of a new generation of electrolyser based on indigenous Canadian technology. A $2M pilot scale plant will be built this year at the laboratories of Hydro Quebec at Varennes, and will be coupled to a liquefaction unit. Siting of a 100 MW demonstration plant will likely be in Quebec. This is a very large scale electrolysis plant and no choice has yet emerged from a range of applications including, ammonia manufacture, heavy oil upgrading and liquid hydrogen for transportation. Considerable industrial interest has been generated through the PICA Mirabel group and the activities of Hydro Quebec and Noranda.

2.4 Urban Transportation Development Corporation (UTDC)

The Government of Ontario is funding a $6M ⁄ program at UTDC, Kingston for the demonstration of hydrogen as an alternative fuel for public transportation. The 3 year program is in the final detailed planning stage and is expected to enter the hardware stage shortly which will culminate in several converted vehicles operating on Toronto streets. Further developments could address rail engine conversions with fuel cell power systems under active consideration.

The initial conversions will be on diesel engines instead of spark ignition gasoline engines upon which a substantial data base has accumulated through work in Europe, U.S. and Japan.

3. Fifth World Hydrogen Energy Conference

The conferences of the International Association for Hydrogen Energy are held every two years. The 1984 conference will be in Toronto - July 15-19. It will be sponsored by the National Research Council and the Ontario Ministry of Energy. The conference chairman will be A.K. Stuart of Electrolyser Corporation. The theme chosen is"Transitions to Hydrogen Energy". A large international response is anticipated which will focus a lot of attention in Canada on the prospects for hydrogen energy utilisation here.

4. New Initiatives

N.R.C. has a mandate "to promote, assist and undertake scientific and industrial research" for national development. It has also been the lead agency appointed by EMR to manage the National Hydrogen R&D program. In response to this situation and being mindful of the rapidly evolving national and international interest in hydrogen energy, a new five year program has been drafted. It is entitled "Hydrogen Energy in Canada: Proposed New Initiatives"

New funding requirements are identified in a very broad range of topics including major new programs in applications technologies, engineering and safety related areas. The document also includes a rationale for a Canadian program and a description of what could conceivably constitute a Canadian hydrogen energy matrix.

APPENDIX II

PROPOSED NEW INITIATIVES FOR THE
CANADIAN HYDROGEN ENERGY PROGRAM, PREPARED BY
THE NATIONAL RESEARCH COUNCIL, 1980

CANADIAN HYDROGEN ENERGY PROGRAM

(Program objectives and funding requirements remain as submitted in outline under NRC 5 year plan 4/11/80)

OBJECTIVE: To develop hydrogen energy technologies for the displacement or extension of hydrocarbon resources by renewable, indigenous or inexhaustible sources.

To ensure that the necessary level of engineering and technological competence in hydrogen energy systems is available in Canada.

To cooperate with and encourage participation of provincial authorities and industrial groups in field trials and demonstration programs.

SUB-PROGRAMS:

1. Safety - standards, codes, embrittlement.
2. Bulk storage - feasibility.
3. High capacity storage systems - technical feasibility.
4. Hydrogen generation from liquid carriers - development prototypes.
5. Transportation hydrogen fuelling subsystems - engineering evaluation.
6. Transportation fuelling sub-systems - component development.
7. Hydrogen production - advanced electrolyser technology.
8. Fuel cells - testing & evaluation facility.
9. Small hydrogen generators for dispersed applications - engineering development.

CANADIAN HYDROGEN ENERGY PROGRAM

1. SAFETY

OBJECTIVE: To acquire and analyse performance data on experimental cryogenic and high pressure systems for the purpose of establishing a design data base and formulating standards and codes relevant to the safe use of hydrogen in energy applications.

STRATEGY: Test loops will be built to comprise a national facility for hydrogen component evaluation. Material and component specifications will be established. Systems design, assembly and testing requirements will be defined and the necessary standards and codes prepared. The program will draw in part on available U.S. expertise at NASA and NBS and will provide a test bed for component hardware from other sub-programs.

Data on metal embrittlement will be acquired and analysed in an independent program which is a necessary adjunct to the above. These two sub-programs will provide major support data to all subsequent engineering activities.

DURATION: 5 years (major activity to start after completion of sub-program 5).

PERFORMER: Industrial contract.

COST:

Test facility and preparation of specifications, standards and codes	900 $K
Embrittlement	500
	1400

CANADIAN HYDROGEN ENERGY PROGRAM

2. BULK STORAGE

OBJECTIVE: To assess the economic and technical feasibility of bulk hydrogen storage in underground caverns and above ground vessels as a high pressure gas or as a liquid.

STRATEGY: The analysis will assume that extremely large amounts of hydrogen are available on an intermittent basis. Storage using underground caverns or above ground systems will be considered. The work will be a detailed engineering study drawing upon existing experience with methane, L.N.G. and, to some limited extent, with hydrogen. Appropriate geological sites will be identified together with the limits on energy efficiency, size, pressure and the requirements of compression,liquefaction and ancilliary equipment. Economic effects of the utilisation factor and charge/ discharge rates will be determined.

DURATION: 1 year.

PERFORMER: Consulting engineers (Acres Consulting Services). Joint participation of Saskatchewan Power Corp. and Ontario Hydro expected.

COST: $150K.

CANADIAN HYDROGEN ENERGY PROGRAM

3. HIGH CAPACITY STORAGE SYSTEMS

OBJECTIVE: To develop high pressure hydrogen storage for on-board vehicle use using microencapsulation in glass to achieve a design target of 10 weight percent hydrogen.

STRATEGY: Special glass compositions having the requisite strength and permeability/temperature characteristics will be developed. Suitable microcontainers will be fabricated. A hydrogen charging and discharging system will be developed for laboratory scale evaluation. The economic and technical feasibility of the concept will be assessed. Successful completion of this program will lead to the design and development of an engineering prototype system suitable for vehicle use. The storage density target is twice that currently available in metal hydrides. System costs are expected to be much lower than for hydrides.

DURATION: 2 years.

PERFORMER: Ontario Research Foundation.

COST: $300 K

CANADIAN HYDROGEN ENERGY PROGRAM

4. HYDROGEN GENERATION FROM LIQUID CARRIERS

OBJECTIVE: To develop and evaluate small fuel systems primarily for road vehicle applications requiring the generation of hydrogen from liquid carriers such as methanol and ammonia.

STRATEGY: It is technically feasible to generate hydrogen on-board a vehicle from a variety of liquid carriers which are attractive because of the simplicity of storage and distribution. Prototype hydrogen generators will be designed, built and tested to establish the practicality of such devices. Design parameters will be based initially on the use of the endothermic hydrogen generation reaction to "bottom" the engine and thereby raise its thermal efficiency. Performance and systems costs will be compared with available data on 'direct' hydrogen use (hydrides, compressed gas, liquid hydrogen) as well as with direct engine fuelling with the carrier if applicable. Although potentially useable for IC engine fuelling, the eventual target of this investigation is the development of hydrogen systems for fuel cell applications and the sub-program will give direction to future R&D for this purpose.

DURATION: 4 years.

PERFORMER: Contract.

COST: $750 K

CANADIAN HYDROGEN ENERGY PROGRAM

5. TRANSPORTATION HYDROGEN FUELLING SUBSYSTEMS - STATE-OF-THE-ART ASSESSMENT

OBJECTIVE: To conduct detailed testing for the purpose of assessing the current state-of-the-art in vehicle hydrogen fuel systems.

STRATEGY: The performance of commercially available liquid hydrogen and metal hydride storage systems will be assessed along with fuelling components such as injectors, compressors, valves, pumps etc. This will be undertaken as an adjunct to the UTDC railroad and bus diesel engine conversion program. Very little independent data are available on commercial components and this is a necessary prelude to the new equipment sub-program #6 which will be defined on the basis of the results of this work.

DURATION: 3 years

PERFORMER: Urban Transportation Development Corporation

COST: $1,200 K

CANADIAN HYDROGEN ENERGY PROGRAM

6. TRANSPORTATION HYDROGEN FUELLING SUB-SYSTEMS - COMPONENT DEVELOPMENT

OBJECTIVE: To modify, improve, design, develop and test components for vehicle hydrogen fuelling systems including pumps, injectors, heat exchangers, regulators, controls and cryogenic tanks.

STRATEGY: The sub-program will be defined subsequent to the state-of-the-art assessment sub-program #5.

DURATION: 3 years - to start in 1984.

PERFORMER: Contract

COST: Estimate only $2,000 K

CANADIAN HYDROGEN ENERGY PROGRAM

7. ADVANCED ELECTROLYSER TECHNOLOGY

OBJECTIVE: To develop new materials and components for upgrading the performance of water electrolysers and reducing the cost of electrolytic hydrogen.

STRATEGY: This work continues and expands on that already being done in support of an IEA agreement and is critical to the success of the whole program and to the future of the electrolyser industry in Canada. Contracts for the development of electrocatalyst will continue. New work will be done on solid polymer electrolytes and separator materials. Long term tests of new materials will be done in large cells under production conditions. Ceramic hydrogen ion conductors for high temperature electrolysers will be fabricated and evaluated in laboratory prototype systems. The sub-program will continue to advance the state-of-the-art in components and materials for electrolysers and will ensure that Canada remains in the forefront of international electrolyser R&D activity.

DURATION: 5 years

PERFORMERS: Raylo Chemicals; Noranda Research: Atlantic Industrial Research Institute; McMaster; Ontario Research Foundation; Almax Industries, etc.

COST:

TOTAL	$4,100 K
EXISTING FUNDS	1,600 K
NEW REQUEST	2,500 K

CANADIAN HYDROGEN ENERGY PROGRAM

8. FUEL CELLS

OBJECTIVE: To establish a national facility for testing and evaluating fuel cells and to obtain performance data on commercial and experimental cells.

STRATEGY: A facility will be established at which fuel cell stacks will be subjected to detailed performance testing to determine power and energy capability as well as lifetime, resistance to fuel and oxidant impurities, thermal and water management etc. Both commercial and experimental cells and components will be tested over the contract period. The output data will be assessed against target requirements to be established for stationary and mobile applications to determine directions for additional R&D and ultimately the timing and the form of fuel cell demonstration programs in Canada.

The facility will include diagnostic and failure mode analysis capability which will in this respect interact with parts of sub-program 7. The facility will function in a coordinating role between experimental groups, industry and users for the purpose of fostering the evolution of Canadian competence in fuel cell technology.

DURATION: 5 years

PERFORMER: Contract

COST: $1600 K

CANADIAN HYDROGEN ENERGY PROGRAM

9. SMALL HYDROGEN GENERATORS FOR DISPERSED APPLICATIONS

OBJECTIVE: To develop small hydrogen generators for dispersed applications which include renewable and/or intermittent energy sources such as wind, solar PV and low-head hydro.

STRATEGY: Target specifications will be established by detailed analysis of the application requirements and taking into account the storage systems data acquired in sub-programs 3, 5 and 6.

Small pressurised electrolysers will be designed and built using existing electrode and separator materials but ultimately able to accept components developed under sub-program 7.

Laboratory scale units will be evaluated for the target objective and designs established for full-scale electrolysers. One full-scale electrolyser will be built and operated in conjunction with a suitable storage device to accumulate overall system performance data.

DURATION: 5 years

PERFORMER: HSA Reactors, Noranda, Electrolyser Corp.

COST: $2,200 K

CANADIAN HYDROGEN ENERGY PROGRAM

WORK PLAN AND SCHEDULE OF EXPENDITURE ($K)

Sub-Program / Year Number	1	2	3	4	5	Sub-program Total
1. Safety	100	100	400	400	400	1,400
2. Bulk Storage	150					150
3. High Capacity Storage	130	170				300
4. Hydrogen From Liquid Carriers		80	250	250	170	750
5. Transportation Fuelling - S.O.A.	300	400	500			1,200
6. Transportation Fuelling - Development			400	800	800	2,000
7. Hydrogen Production	730	820	850	850	850	4,100
8. Fuel Cells	200	250	500	400	250	1,600
9. Small Hydrogen Generators	50	200	500	600	850	2,200
TOTAL	1,660	2,020	3,400	3,300	3,320	13,700
Current Funding	400	400	400	400	400	2,000
New Requests	1,260	1,620	3,000	2,900	2,920	11,700

APPENDIX III

CURRENT INDUSTRIAL AND UNIVERSITY R&D IN HYDROGEN

TABLE 1: STRATEGIC GRANTS IN HYDROGEN ENERGY NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL - MARCH 1981

TOPIC	TITLE	PERFORMER	STATUS YEAR	STATUS TOTAL YEARS	AMOUNT IN CURRENT YEAR $
PRODUCTION NON-PHOTON INPUT	Hydrogen production by coal depolarized water electrolysis.	K.E. Johnson B.D. Kybett (Regina)	1	3	35,000
	Direct thermolysis of water by Zirconia composites.	P.S. Nicholson (McMaster) M. Sayer (Queen's)	1	3	44,000
	Biochemical production of hydrogen.	B. Volesky (McGill)	2	3	16,360
PRODUCTION PHOTON INPUT	Uses of homogeneous catalysis for the formation of synthetic fuels.	M.C. Baird J.D. McCowan (Queen's)	2	3	32,940
	Photochemical conversion and storage of solar energy.	J.R. Bolton (Western)	1	3	* 90,000
	Solar energy conversion into chemical energy.	R.G. Goel (Guelph)	3	3	* 18,183
	Molecular models of photosynthesis.	J.E. Guillet G.A. Kenney-Wallace (Toronto)	3	3	* 20,456
	Solar energy for the large scale production of hydrogen - photoelectrolysis.	J.F. Kos (Regina)	3	3	16,706
	Photoelectrochemical fuel synthesis using chromophore films on transparent semiconducting electrodes.	C.W. Lanford (Concordia)	3	3	22,161
	Approaches to the utilisation of solar energy using inorganic complex molecules.	A.B.P. Lever (York)	3	3	31,820
	Solar-hydrogen energy conversion.	H.J.J. Seguin (Alberta)	3	3	22,729
	Photoelectrolytic hydrogen generation.	F.R. Smith (Memorial)	3	3	35,571
	Antenna polymers for harvesting solar energy.	W.A. Winnik (Toronto)	2	2	16,470

* Not all devoted to hydrogen.

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TOPIC	TITLE	PERFORMER	STATUS YEAR	STATUS TOTAL YEARS	AMOUNT IN CURRENT YEAR $
STORAGE	Storage of hydrogen and methane on active carbons at ambient temperature.	H.D. Gesser (Manitoba)	2	3	17,788
	Alloy development for energy and gas storage in the hydrogen economy-hydrides.	G.C. Weatherly F.D. Manchester C.B. Alcock (Toronto)	3	3	39,775
FUEL CELLS	The development of a fuel cell based on alkaline air oxidation of carbohydrates catalyzed by chemically modified electrodes.	E.G. Janzen (Guelph)	2	3	27,450
	Parameters for strategic design decisions for Canadian fuel cell development.	D.S. Scott D. McCammond A.W. Neumann R.D. Venter J.S. Wallace C.A. Ward (Toronto) A.B.P. Lever (York)	1	1	80,000
	Rate of gas absorption and efficient use of electrocatalysts in fuel cells.	C.A. Ward (Toronto)	3	3	36,366

TABLE II: PANEL ON ENERGY RESEARCH AND DEVELOPMENT PROGRAM IN HYDROGEN
MARCH 1981

TOPIC	TITLE	PERFORMER	79-80 $	80-81 $
PRODUCTION NON-PHOTON INPUT	Long-term tests on electro-catalysts and separators.	Noranda (R.L. LeRoy)	75,165	44,371
	Catalysts for oxygen evolution reaction.	Atlantic Ind. Research Institute. (G.P. Wilson)	40,034	54,023
Advanced Electrolysis IEA Hydrogen Agreement.	Ion implanted catalysts.	McMaster (D.A. Thompson)	25,000	24,925
	Catalysts for hydrogen evolution reaction.	Gould Battery (K.V.N. Rao)	12,786	33,213
	Ion conducting membrane development and tests.	U. of Calgary (H.L. Yeagesr)	10,230	13,170 33,300
		Carleton (J. Apsimon)	*12,000	12,271
		N.R.C. (O. Kutowy)		
		McGill (A. Eisenberg)		31,000
		Daychem Ltd. (F.W. Harris)		52,000
	New separator materials	Raylo Ltd. (R. Vukov)		65,500
	Ceramic hydrogen ion conductors for high temp electrolysis and fuel cells.	Queen's (M. Sayer) McMaster (P.S. Nicholson)	13,292	46,685
PRODUCTION THERMOCHEMICAL	Reporting, analysis and experimental.	Exergy Res. (E. Bilgen)	65,000	72,073
PRODUCTION PHOTON INPUT	Materials, film development, evaluation.	Bell Northern ( )		[137,800]
IEA Hydrogen Agreement		CANMET (S.M. Ahmed)	*10,000 (0.3)	*10,620 (0.5)
STORAGE	Metal alloy hydrides - structural and calorimetric studies to develop new compositions for improved performance.	N.R.C. (J.J. Murray)	*43,500(2) [90,000]	*35,580 (2.6)
EMBRITTLEMENT	Mechanistic studies on pipeline alloy steels and weld material.	C.E.R.C. (M.R. Piggott)		25,140
		CANMET (W.R. Tyson)		
		N.R.C. (M.J. Graham)		*9,000(1

* In-house activities report only capital (PY).

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TOPIC	TITLE	PERFORMER	79-80 $	80-81 $
FUEL CELLS	Transport applications of fuel cells.	U. of Toronto (D.S. Scott)	27,000	[20,000]
MARKET ANALYSIS IEA HYDROGEN AGREEMENT	Assessment of potential future markets for the production of hydrogen from water in Canada.	Noranda (P.S. Bailey)	[50,000]	[22,000]

APPENDIX IV

INTERNATIONAL R&D IN HYDROGEN

HYDROGEN ENERGY SYSTEM

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Edited by

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R & D PROGRAMMES IN THE FIELD OF HYDROGEN ECONOMY

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ABSTRACT

After a short survey of the perspectives of hydrogen in the future energy market, the research and development programmes in the field of hydrogen are reviewed. Approximately homogeneous groups of research subjects are shown, with the corresponding efforts of each country. A rough estimate of the overall present R & D effort in the field of hydrogen is suggested and the possible outcomes are sketched.

INTRODUCTION

The interest in hydrogen as a clean energy carrier for our future technology stirred up, after the energy crisis of 1973, a considerable amount of work on its production, transport and use, stimulating as well many assessment studies about its possible penetration into the energy market. Accurately reviewing such a vast field would have been an overwhelming task without the positive collaboration of qualified representatives of all countries concerned. The preparation of this survey therefore has been started with a general enquiry about the research programmes on hydrogen with the help of national partners, whose assistance has been invaluable. Although it lacks some details and precisions, it is hoped that this paper may give a sufficiently clear overall view of the actual status of programmes on hydrogen in the world and possibly contribute to the evaluation of their future development.

The Energy Demand and the Hydrogen Society

The common basis to all programmes dealing with alternative energies, as well of those dealing with hydrogen as an energy carrier, is the even increasing world energy demand, which forces the active search and exploitation for new energy sources to cope with the relatively limited natural reserves. While it is clear that better energy use and process improvement will eventually limit somewhat the growth rate in industrialized countries, the overall world energy demand is likely to keep increasing, because of the demand of developing countries and because of the overall demographic increment.

Without going into too many details, it is useful to point out some peculiarities of the evolution of the energy market which will probably influence its future development and cause an increasing importance of hydrogen as an energy vector. It has been reported that, up to now, switching from one type of fuel to the next one was not directly caused by reasons of price [1,2] or by availability, but by a much more complex blend of circumstances, including the directing effect of technical innovation. Furthermore it has been observed that no fuel ever regained its share of market once it started losing it. The actual overall trends show that the market share of coal is steadily declining since the takeover by oil. However, the market share of oil is already declining in favour of natural gas, whose market share is actively growing for now.

What comes next is a matter of controversy:

- a revival of coal (or products derived from coal) will require a total renewal of the corresponding technology to keep the pace and will be subjected to severe constraints [3] (process water availability, siting of overburden, pollution and long term pollution by CO_2);

- the nuclear option (in addition to all other forms of new energies being developed) is the other alternative, the total implementation of which will eventually cause the gradual introduction of hydrogen as a secondary energy vector, supplementing the role of natural gas in non-electrical uses.

On the basis of the above considerations this second alternative seems at present the most probable, which fact explains why studies on hydrogen production, transportation and use are of such concern. In fact, if due allowance is given to the time needed to transfer new technologies from the laboratory to industrial practice, continuation of the existing programmes at the present level of funding, and even their increment seems essential to complete in time the necessary developments.

It is obvious that actually the cost of non-fossil-derived (NFD) hydrogen is not competitive with hydrogen from methane reforming. In some countries, however, sizable amounts of low-priced, off-peak electrical power will be available in a decade. As a consequence, relatively cheap electrolytic hydrogen may become available in increasing quantities either to the chemical industry or to the energy market(*). It will not be the beginning of a "hydrogen society", because of the relatively limited size of this kind of production when compared to the whole energy market. Nevertheless, the necessary technologies need to be fully developed before then and the timing of the programmes on hydrogen should comply at least with this requirement.

It is difficult to forecast, even approximatively, the critical date at which hydrogen will be used as one of the major energy carriers, because of the interplay of many unknown or incontrollable factors. It is clear, however, that sooner or later hydrogen will play this important part and therefore R & D programmes should provide the essential know-how in time, taking into account possible interactions with the development of new energy sources.

(*)Hydrogen prices may be estimated as follows:

- actual electrolysis: 10 ¢/Nm^3 of H_2 (at 20 mills/kWh)
- advanced electrolysis: 6,5 ¢/Nm^3 of H_2 (at 20 mills/kWh)
- off peak electrolysis: 5,5 ¢/Nm^3 of H_2 (at 14 mills/kWh)
- methane reforming: 5 - 5,6 ¢/Nm^3 (methane at \$ 2/GJ)
- coal gasification: 6 - 6,4 ¢/Nm^3 (coal at \$ 1,5/GJ)

The R & D Programme in the Field of Hydrogen

The range of research subjects covered by programmes on hydrogen is relatively broad, so that appropriate grouping is needed to show adequately well their general trend. Partitioning has been done around the two major (and well known) key subjects:

- thermochemical hydrogen production
- electrolytic production

Further partitions have been provided for:

- other potential production methods (covering the more fundamental studies)
- the R & D programmes connected to specific uses of hydrogen

The production of hydrogen from methane, which is the current industrial route, and the production from coal (which can supplement in the future that from methane) were not included directly in this survey, as they are already well-known processes, possibly requiring only minor improvements.

Thermochemical Hydrogen Production

Production of hydrogen by means of a thermochemical cycle, in which a closed cycle of chemical reactions leads to water splitting, is one of the newest and more fascinating methods proposed for the purpose. The amount of theoretical and experimental work devoted to this topic is considerable, but the size of the problems to be solved is so large that progress has been seemingly modest. On the contrary the advance of experimental studies and the gathering (generally experimental) of the necessary data has been rather important, so that a few small scale, full cycle experiments are already operating or will operate shortly. The complete exploitation of these experiments will supply the technico-scientific basis for deciding on possible further steps. In fact, the novelty of this approach is such that even the basic experience has to be provided and feasibility has to be demonstrated in practice, starting nearly from zero. The probability of success or failure of this venture is therefore difficult to evaluate before the completion of the actual laboratory phase.

Table 1 reports the status of R & D programmes in the field of thermochemical water splitting. Where available, the funding is given for each country in the national currency. An additional brief account of the more extensive research programmes is given hereafter (*) to properly supplement the table.

The activity of the European Communities carried out either directly in the laboratories of the Joint Research Center (JRC) in Ispra (Italy) or indirectly by research contracts (Directorate General XII, Brussels), has been concentrated mostly on Mark 11 (H_2SO_4 hybrid), Mark 13 (H_2SO_4 - Br_2 hybrid) and Mark 16 (H_2SO_4 - I_2), all of the sulphur based "family". A bench scale, full cycle (50-100 Nl/h of H_2) experiment is already operating [4]. The total manpower allocated is about 70 man-y/y (direct and indirect activities).

(*)Countries are taken in alphabetic order

In France an important effort (23 MF in the three years 1975 - 1977) in the field of theoretical evaluation (automatic cycle generation, analysis, technico-economic assessment etc.) of thermochemical cycles has been done. The work in this field has now been deferred and it is not clear whether it will be continued in future.

In the Federal Republic of Germany theoretical and experimental studies and technico economic evaluations have been done of Fe/Cl cycles, on sulphuric acid-methanal cycle, on the sulfuric-acid hybrid cycle.

In Japan, within the Sunshine project [5] several cycles are studied: a few variations of the Fe/Cl "family", a few ammonia-based cycles and a $Ca-I_2$ cycle. Process evaluation codes have also been developed and applied.

In the USA within a wide general hydrogen programme [6] several cycles are being studied either in government-funded or in privately funded projects. The main cycles are the H_2SO_4 hybrid cycle and the $H_2SO_4-I_2$ cycle, for both of which a bench scale experiment is planned; other cycles like Fe/Cl, $Cu-H_2SO_4$. $H_2SO_4-Br_2$ hybrid etc. are currently being studied and evaluated.

Electrolytic Hydrogen Production

Production of hydrogen by water electrolysis is a well-known technique, for which the basic know-how and the necessary industrial practice are already available. Although old, this process was not much improved in the past, because of its marginal industrial importance and of the total lack of economic interest in its exploitation. Industrial electrolyzers were, therefore, conceived as sturdy equipment, whose energetic efficiency was really of secondary concern. Starting from this basis, a relatively important degree of development had to be provided to increase the total energetic efficiency and lower the unit cost of electrolyzers. This overall object is being attained through different research lines, one of which, the use of solid polymer electrolytes (either acidic or alkaline), marks a real difference with respect to the classical process, in which the electrolyte is constituted of aqueous solutions.

For alkaline electrolysis other lines of progress are lowering the overvoltage by improving the catalytic activity of electrodes and/or by increasing the temperature of the cell and the development of new diaphragms as well as optimization of the cell and of the auxiliary equipment.

A totally new concept, whose future seems very promising, is the high temperature (800-900°C) electrolysis of water vapour. The corresponding technology is, however, still in its early stage, so that even if successful, its application is expected only for the relatively far future.

The overall progress of electrolysis is quite satisfactory. In fact, a few prototypes are already planned. Implementation on an industrial basis of the technologies developed till now will probably depend more on the rate of expansion of the electrolytic hydrogen market than on other factors.

Table II reports the status of R & D programmes in the field of water electrolysis. Funding is given, when available, in the national currency. To complete and supplement Table II, a further short description of the more advanced programmes is given hereunder.

In Belgium, an electrolyzer module, based on an inorganic solid polymer electrolyte (SPE) membrane working in alkaline solution, has been developed (partially funded by the C.E.C.) (*). Testing on a small laboratory prototype is proceeding.

In Canada, the development of electrocatalysts ($ 100 k in 1978, $ 195 k in 1979) and of advanced, efficient alkaline cells (several M $ in 1976 - 1985) is actively pursued, a 5 MW prototype being planned for 1980. Parallel studies of alternative electrolyzer technologies are being conducted.

For the EEC, the Commission of the European Community funds through indirect action (i.e., by means of research contracts on a cost sharing basis) a broad-range of actions described in another paper [7]; the work extends over the full range of subjects. Laboratory prototypes are (or will be) planned.

In France, an overall concerted development plan for improving alkaline electrolysis is currently pursued. Cell optimization, catalyst development, material studies, diaphragm improvement, high temperature electrolysis are studied, (several studies are partially funded by the C.E.C.). A 10 MW prototype will probably be constructed in 1979.

In the Federal Republic of Germany, most of the work is concentrated on high temperature vapour electrolysis. Long time testing of experimental cells is progressing. Development of scaling up concepts is pursued.

In India, electrocatalysts have been developed and component and structures optimization is being attempted to improve alkaline electrolysis. A prototype of about 130 KW will be constructed.

In Japan, the research programmes have been oriented on studies of electrocatalysts, of new diaphragms and on optimization of the cells and gas separators for alkaline electrolysis. Fundamental studies on solid polymer electrolyte based cells and of related problems are also going on.

In the Netherlands, electrode and cell configurations are studied as well as bubble formation and evolution (partly funded by the C.E.C.). Fundamental studies on electrodes and on gas-electrode interactions are currently done.

In the U.S.A. two main lines of research are followed: The improvement of alkaline electrolysis and the development and improvement of solid polymer electrolyte based (using Nafion - Du Pont) electrolysis. A 5 MW prototype SPE based electrolyzer will be developed.

(*)The Commission of the European Communities (C.E.C.)

Other Production methods

In this subchapter several generally unrelated methods of hydrogen production have been collected. Their only common point is their very early stage of development (excluding production from coal or pitch, that are quite old methods), so that even in case of success, their massive introduction on the energy market will probably be delayed to the far future when the corresponding technology will be sufficiently developed.

Table III gives a summary of the corresponding programmes.

It should be pointed out that most of the total funding of the USA for this topic is devoted to coal gasification and to the steam-iron process of hydrogen production.

Hydrogen Use, Storage and Handling

Until its massive use as a rocket fuel, hydrogen was used mainly as feedstock for the chemical industry; it was relatively unknown and little used elsewhere. To fill this gap several programmes have been set forth in the very large field of hydrogen use, storage and handling.

Problems like storage in hydrides, use of hydrogen for car propulsion, study and optimization of steels to be used in hydrogen, choice and characterization of components, safety problems, etc., are being studied. The range of possible topics is really extraordinary; their grouping in a table has been obtained quite arbitrarily around subtitles which were felt important or typical for this kind of technology. Table IV shows a summary of national programmes in this field. Funding is given, when available, in national currency. To better define the summary shown in the table, some additional details are given hereunder.

In Canada a relatively important programme is going on in electrochemical storage. Other programmes are materials studies and study of hydrides.

The programme of the E.C. (indirect action) has been detailed in a separate paper [7] and covers most of the subjects given in the table.

In France, high pressure storage is studied as well as storage in hydrides. Material testing and improvement is also pursued (several studies are partially funded by the E.E.C.).

Storage in hydrides and use in internal combustion engines is studied in India.

In Japan, the research programmes deal mainly with storage, combustion, assessments, materials studies and safety.

The USA is implementing the biggest programme in this "utility" field. The programme deals with study, testing and development of materials; evaluation of storage; study and improvement of hydrides; evaluation of several uses including automotive and railways traction; general assessment studies on hydrogen; and finally, development of a supporting technology for a broad range of hydrogen utilizations.

CONCLUSIONS

This paper has briefly reviewed the wide range of research and development programmes presently in progress in the field of hydrogen production and utilization.

To give a final view on the whole field, a general summary has been prepared and reported in Table V. All the data on funding have been converted into approximate US $(1978) to obtain an overall image of the actual programmes; however, many figures are missing and, therefore, quantitative conclusions are not possible.

Qualitatively, it is clear that the overall effort in the field of hydrogen is considerable although probably insufficient for the rapid development of a big scale hydrogen technology. How fast such development should be pursued is a very controversial point, this decision being tightly connected with the evolution and the orientation of the future energy market as argued in section 1 of this paper. In any case it seems clear that hydrogen, however produced, will play an important part in our future, and consequently, maintaining a sufficient overall level of research and development is essential for the timely growth of the necessary technology.

Table V shows that the overall funding of programmes on thermochemical hydrogen is equivalent (and even higher) to the overall funding for electrolysis, while smaller funds are allocated to other subtasks. The overall funds distribution does not necessarily correspond to the distribution for single countries and may even change completely in future either because of changes of strategy or because of the evolution of knowledge. It is felt, however, that this overall partition of funds corresponds adequately well to the actual advance of the research and to the future development needs in the field of the hydrogen economy.

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Prof. T. Ohta	(JPN)
J. Pottier	(F)
Prof. Dr. M. Sastri	(India)
Dr. W. Seifritz	(CH)
Dr. J. H. Swisher	(USA - DOE)
R. Van der Wart	(NL)

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TABLE I

THERMOCHEMICAL HYDROGEN PRODUCTION

Summary of programmes

Country (*)	Fundamental Studies	Experimental Measurements	Technico-economic Evaluation	Overall funding (year) (1)
Canada	unprecised studies	-	-	50 k (78)
European Communities	yes, mostly on 3 cycles	complete bench scale loops	yes, by augmented code OPTIMO	4.29 MEUA(77) 5.46 MEUA(78) (+)
France	automatic cycle generation	-	cycle evaluation by computer codes	9.11 M (76-77) 23 M (75-77) (2)
F.R. of Germany	a few cycles	mostly on Fe/Cl + sulfur cycles	cost evaluat. by computer codes	9.74 M (77) 9.16 M (78) (2)
Japan	several cycles	several cycles	Fe/Cu-Cl cycles	-
Sweden	yes	-	-	-
Switzerland	on H_2SO_4 splitting	-	-	-
U.S.A.	several cycles	experimental work + bench scale loops	-	3.9 M (77) 2.9 M (78) 20 M (to 81) (3)

(*) In alphabetic order. No mention of countries implies only a lack of information.

(+) Funding given (in European Unit of Account) is the total of the direct action (of the JRC funded at 100 %) and of indirecte action (on contracts for these only EC contribution is given, the total funding of contracts on this task is around 4.7 MEUA (77), 6.7 MEUA (78).

(1) In national currency (standard multiples used: $k = 10^3$; $M = 10^6$)

(2) National funding only, the EC contribution is given elsewhere.

(3) Including funds for electrolysis.

Table II : Water Electrolysis - Summary of programmes

Country (*)	Electro-catalyst Development	Diaphragm Improvement	Alkaline Electrolysis and systems	SPE Electrolysis	High temperature vapour electrolysis	Overall funding (year) (1)
Belgium	-	-	low temperat. inorg. SPE(°)	inorganic SPE in KOH (°)	-	8,9 M (77) 17 M (78) (°)
Canada	yes	yes	5MW prototype design. Assessment	Assessment + development.	-	100 k (77) 175 k (78)
European Communities	low-medium temperat.	several alternat.	Laboratory units.	inorganic SPE for alkaline media.	Laboratory studies.	1,22 MEUA (77) 3,2 MEUA (78) (+)
France	low-medium temperat. (°)	teflon-based (°)	low-medium temperature (°)	-	Laboratory studies (°)	6,6 M (76-77) (2)
F.R. of Germany	-	-	-	-	Hot Elly project System developmt.	6,1 M (75-78)
India	yes	-	Laboratory meas. and 100 KW prototype low temp.	-	-	0,6 M (77-78) 6,4 M (78-83) (3)
Japan	-	teflon based	low-medium temperature	Laboratory testing	-	-
Netherlands	large surface over electrodes	-	Prototype design. Cell configuration. Bubble evolut.	-	-	370 k (77) (°) (2)
Sweden	yes	-	-	yes	yes	-
Switzerland	-	-	yes	-	-	-
U.S.A.	yes	yes	yes	yes	yes	2,5 M (77) 2,9 M (78) (4)

(°) With the E.E.C. - (+) Funding given in European Unit of Account. The total funding, with the national contribution amounts to 2.3 MEUA (77) and 6.5 MEUA (78).

(1) In national currency (standard multiples used: k = 10^3; M = 10^6).

(2) National funding only. Contribution by the EC reported under the corresponding headings.

(3) Funding inclusive of prototype development and studies on hydrides.

(4) With thermochemical production (see table I).

Table III

Other Production Methods

Summary of programms

Country(*)	Photoelectrolytical	Photochemical	Production from coal or pitch	Photobiological	Overall funding (year) (1)
Belgium	by semiconductors	-	-	-	-
Canada	-	-	yes	-	77k(77); 100k(78)
France	yes	-	-	-	0,7 M (76-77)
India	yes	-	-	yes	1,75 M (77-83)
Japan	yes	$FeSO_4/I_2$-cycle.	-	-	-
Netherlands	yes	-	-	basic studies	-
U.S.A.	several studies	several studies	several studies	basic work	12 M (77) 8,5 M (78) 83 M to 1984

(*) In alphabetic order. No mention of countries implies a lack of information.

(1) In national currency (standard multiples used: $k = 10^3$; $M = 10^6$).

(°) With the E.E.C. - (+) Funding given in European Unit of Account. The total funding, with the national contribution amounts to 2.3 MEUA (77) and 6.5 MEUA (78).
(1) In national currency (standard multiples used: $k = 10^3$; $M = 10^6$).
(2) National funding only. Contribution by the EC reported under the corresponding headings.
(3) Funding inclusive of prototype development and studies on hydrides.
(4) With thermochemical production (see table I).

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Table IV

Hydrogen use and storage, materials studies

Summary of programmes

Country(*)	Hydrides	Materials	Various uses	Fuel cells	Safety	Assessment studies	Overall funding (year) (1)
Belgium	-	-	-	-	-	evolution of H_2	-
Canada	yes	yes	yes	yes	-	-	0,36 M (77) 0,26 M (78)
European Communities	evaluation & improvement	testing & improvement	several studies	no	yes	yes	365 k EUA (77) (+) 988 k EUA (78) (3)
France	evaluation & improvement	testing & improvement	several studies	yes	-	-	1,48 M (76-77) (°)
India	Hydrides, storage on oxides and sulphides	-	study of Ic-engines	yes	-	-	(included in other studies)
Japan	evaluat. & improvement	testing	several studies	yes	yes	yes	-
Netherland	evaluat. fundament. studies	-	-	basic stud.	yes	-	210 k (77) (°) 70 k (78) (2)
Sweden	yes	-	-	-	-	-	-
Switzerland	-	-	-	-	-	yes	50 k
U.S.A.	several studies	testing development & improvement	several studies	yes	yes	yes	11 M (77) 5,5 M (78)

(°) With the E.E.C.
(+) Funding given in European Unit of Account.
(1) In national currency (standard multiples used: $k = 10^3$; $M = 10^6$).
(2) National funding only. Contribution by the EC reported under the corresponding headings.
(3) The total funding, with the national contribution amounts to 0.7 MEUA (77), 2.0 MEUA (78).

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APPENDIX V

OVERVIEW OF THE CHEMICAL/HYDROGEN ENERGY SYSTEMS (C/HES) PROGRAM OF THE INTERNATIONAL AGENCY (IEA)

DOE CONTRACTORS REVIEW MTG ~~SEPT~~ OCT 1980

OVERVIEW OF THE CHEMICAL/HYDROGEN ENERGY SYSTEMS (C/HES) PROGRAM

Fred Gornick

Program Manager
Thermal and Chemical Storage Branch
Office of Advanced Conservation Technologies

During the last year the activities within the Division of Energy Storage Systems (STOR) have been restructured under a new Office of Advanced Conservation Technologies (ACT). The goal of the ACT is to develop advanced technologies for increased efficiency and use of renewable energy resources in transportation, industry, and buildings applications. The office directs programs designed to improve the technology base underlying energy technologies and development of advanced concepts in energy storage, conversion, and utilization. The Thermal and Chemical Systems Branch in the Office of Advanced Conservation Technologies is responsible for the administration of research, development, and demonstration programs on thermal, chemical, and hydrogen storage systems. In this branch the Chemical/Hydrogen Energy Systems (C/HES) program encompasses the production, storage and transmission, and utilization of hydrogen. The current management structure and the programmatic emphasis of C/HES are summarized briefly below.

The decentralization policy initiated by DOE a year ago is progressing. Its goal is to shift an increasing amount of day-to-day management responsibility to the field, leaving headquarters with greater freedom to perform the "Washington duties", i.e., long-range planning, budget preparation, congressional responses, coordination and critical evaluations. There have been no major changes in the management structure of the C/HES program. However, for the third successive year, the program does have a different manager at headquarters. This is ameliorated by continuing access to the experience and expertise of the former program manager, Robert R. Reeves.

The C/HES program is now managed full-time at the DOE's Brookhaven Area Office (BHO) by Doug Miller. He replaces Robert Friess who previously performed the job on a part-time basis. Technical support for approximately a dozen projects under BHO's control are provided primarily by Brookhaven National Laboratory (BNL) and the Jet Propulsion Laboratory (JPL). BNL's program, which centers on hydrogen production by electrolysis and chemical heat pumps, has not undergone any major shift in direction since last year. It continues to benefit from the vigorous leadership of Al Mezzina. The JPL program, which is smaller in scope than that at BNL, continues to emphasize closed thermochemical cycles, related materials problems and economic analysis related to International Energy Agency (IEA) activities.

The heart of the C/HES program is the work in the field, which headquarters must support to the best of its ability. The largest single project in the C/HES program is the SPE Electrolyzer development. The electrolyzer is a truly modular system capable of use in conjunction with any one of a number of sources of electric current, i.e., hydroelectric, OTEC, photovoltaic, off-peak-electricity, etc. At the present time this device is being developed for use in conjunction with a small head hydro-electric project in Potsdam, NY. The longer term goals of the hydrogen project are also being pursued. These include coupling hydrogen production with solar energy sources as well as with waste heat. The emphasis on closed thermochemical cycles is of interest in these contexts.

The chemical heat pump (CHP) program, under Al Mezzina's direction, continues to focus on two systems which have several potential applications, including heating, cooling, and upgrading of low-grade thermal energy. These are the sulfuric acid and the metal hydride systems. Here again, one of the major virtues of the CHP is its modular nature, i.e., the source of waste heat can be any one of a number of sources. The use of industrial waste heat now appears to be the most likely candidate for early commercialization of these devices. The use of thermal energy from solar systems is also of considerable interest.

The prospects are good that the present level of funding for the C/HES program will remain substantially at its FY 80 level of \$6.7M, with about 2/3 of this sum for hydrogen and 1/3 for chemical heat pumps. The program is varied with respect to the size of its constituent projects. This results in a variety of viewpoints and a healthy diversity of approaches to the overall program, which itself is a component of the larger problem of energy conservation. Appreciation of the merits of conservation has increased in recent years along with the understanding of its potential for decreasing the use of non-renewable fuels without the imposition of unacceptable economic and environmental penalties. That is a goal which we in the hydrogen program can support without reservation.

STATUS REPORT ON THE INTERNATIONAL ENERGY AGENCY'S (IEA) HYDROGEN PRODUCTION PROGRAM

James H. Swisher
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Division of Thermal and Mechanical
Energy Storage Systems
Office of Advanced Conservation Technologies
U.S. Department of Energy
Washington, D.C.

The IEA Agreement for the Hydrogen Production Program was signed by ten member organizations in October, 1977. At the same time, two annexes to the Agreement were approved for implementation. The initial term of the Agreement was three years, which means that extension of the Agreement is now under consideration.

During the past three years, four additional annexes to the Agreement were signed, but work on one of the original annexes was discontinued. In the following sections, a status report on each of the annexes will be given. In the initial effort, the cooperation was to be restricted to information and personnel exchange. During the past year or so, more task sharing and dovetailing of programs between member organizations has evolved. Consideration has been given to combining financial contributions for joint projects, but there are differences of opinion on whether or not these projects should be undertaken.

The only serious problem encountered during the past three years was with so-called intellectual property rights under the Agreement. The Commission of the European Communities (CEC) is a member of the IEA, but some countries within the CEC, e.g., France, are not. There was concern, particularly on the part of U.S. Department of Energy (DOE) attorneys that France could use inventions arising from the IEA Program without contributing results of its domestic program. The problem was solved by agreeing that such countries could not use any results of the program in commercial ventures unless they contributed all background information from their domestic program. This solution was particularly important because it set a precedent for later agreements under the IEA.

The DOE effort under the Agreement involves participation by the solar, energy research, and energy storage program offices. I represent DOE on the Executive Committee and also serve as Vice Chairman. J.P. Contzen of CEC is Chairman.

Annex I Thermochemical Hydrogen Production

The benefits to the U.S. of cooperation on thermochemical hydrogen production have been greater than in the other project areas, mainly because of the large effort contributed by the Ispra Laboratory of the CEC. The U.S. followed their lead in completing bench-scale facilities for demonstration of integrated processes. We are also making use of their "OPTIMO" computer code for technical and economic evaluation of thermochemical cycles. Another result of the cooperation includes identification of solid sulfate decomposition as a possible improvement over sulfuric acid decompositon in sulfur-based cycles. Also significant progress has been made in the selection of corrosion resistant materials for H_2SO_4 and HI systems. One U.S. scientist spent six months at the Ispra Laboratory and several European scientists have worked at U.S. laboratories for shorter periods of time.

Plans are now being made for a task-shared hardware test. It is likely that the U.S. will send a component for H_2SO_4 decomposition to the Ispra Laboratory for evaluation in a new test facility under construction.

Three workshops have been held for information exchange. The Commission of European Communities is the Operating Agent.

Annex II Heat Source Interface Technology

Although this annex was approved at the same time as the overall Agreement, only the U.S. and Germany agreed to participate. Also the plans included heavy emphasis on interfaces with gas-cooled nuclear reactors, an area which has been de-emphasized in the DOE program. Because of these and other problems, a decision was made approximately a year ago to discontinue effort as a separate annex. A smaller effort is now included in Annex I, with a balanced effort between nuclear and high temperature solar energy sources.

Annex III Assessment of Potential Future Markets

Work was initiated on market potential assessments in December, 1977. A common methodology and set of assumptions was established, then each of the ten participating organizations conducted an analysis for its geographic region. The results have been combined into a final report which should be published in the Fall of 1980. One of the participants, Italy, withdrew before completion of the study. An overall result is that hydrogen markets are projected to increase from 1.6×10^{18} J in 1978 to a value between 23 and 33×10^{18} J in 2025, summed for the following countries: Belgium, Canada, Germany, Japan, Netherlands, Sweden, Switzerland, and the U.S. Corresponding values for the U.S. alone are 1.0×10^{18} J in 1978 and between 20 and 28×10^{18} J in 2025. Separate projections are available for non-fuel uses, direct fuel uses as hydrogen, and indirect fuel uses, e.g., hydrogen produced for coal gasification.

Follow-on studies that have just started include a comparison between hydrogen and methane as energy carriers, and methanol which is derived from hydrogen as an energy carrier.

The Commission of European Communities is the Operating Agent.

Annex IV Advanced Alkaline and Solid Polymer Water Electrolysis

Work on both advanced alkaline and solid polymer electrolysis are aimed at reaching significant improvements in efficiency and reductions in capital cost compared to commercially available alkaline electrolyzers. The emphasis in Europe and Canada is on alkaline systems, while the emphasis in the U.S. is on a solid polymer system. Thus a quid pro quo was established at the time the annex was signed. To avoid major difficulties with proprietary information, cooperative work on alkaline systems does not include equipment design. Instead, the effort focuses on development of high temperature separators and better electrocatalysts. For example, data are being generated on the following new separator materials: polyantimonic acid in polysulfone matrix (Belgium), metal gauze-oxide composites (CEC), polytetrafluorethylene impregnated with potassium titanate (Japan), and $NiCo_2S_4$ (U.K.).

The principal contribution of the U.S. is the engineering development of electrolyzer components with solid polymer electrolytes, but we also contribute results of applied research on alkaline systems.

The U.S. is Operating Agent for Annex IV.

Annex V Solid Oxide Water Vapor Electrolysis

The technology for water vapor electrolysis at high temperatures is an adaptation of technology for solid electrolyte fuel cells. Applied research is still required, principally in materials and fabrication techniques, before engineering development is appropriate. There is a clear advantage to using cells that operate below 1000°C. To do this, the solid electrolytes in all likelihood must be hydrogen rather than oxygen ion conductors. Canada and Italy are contributing in this area. Germany and the U.S. are concentrating their efforts on the preparation and properties of zirconia-yttria and other solid oxide electrolytes. A major portion of the U.S. work is contributed from fuel cell development projects.

Italy is the Operating Agent.

Annex VI Photocatalytic Water Electrolysis

Work on this project started in November, 1979, with six participants and a level of effort of 15 manyears/year. During the first two years, the effort will be restricted to basic and applied research. A decision will then be made on whether or not to start a development effort. A workshop was held in Belgium in March, 1980, as a forum for discussion of past work and future plans. The existing participants are trying to convince Germany and Japan to join the project because their domestic programs are judged to be large and high quality. A progress report describing specific accomplishments will not be available until the end of the year.

Belgium is the Operating Agent for this project.

General Comments:

The levels of effort for the Program are listed in Table I by Annex and in Table II by participating organizations. The total level of effort is equivalent to $20 million in financial support. The data show that the U.S. contribution is thirty percent of the total, which means that we should and are receiving more results from abroad than we contribute. Initiation of some of the work has been slower than desired because of administrative details and a rather slow communication process, but all parts of the present program are proceeding at a productive, steady pace. All activities contributed by the U.S. are included in our ongoing domestic program, so the only cost of participation in the IEA Program are modest administrative and travel expenses.

In the future increased emphasis will be placed on task sharing as opposed to simple exchange of results. I expect that we will continue to concentrate on success of the existing projects rather than extension of the Agreement to add more projects. We hope to do better on dissemination of results, which is the main reason I offered to give this status report to our contractor community.

Table I: Participation in IEA Hydrogen Production Program by Annex

(Data in Manyears/Year of Effort)

Annex	U.S.	Others	Total
I	32	51	83
II	----------	----Discontinued----	----------
III	1	10	11
IV	14	65	79
V	6	7	13
VI	6	9	15
Totals	59	142	201

Table II: Participation in IEA Hydrogen Production Program by Organization

Participant	Effort (Manyears/Year)
Belgium	9
Canada	8
CEC	60
Germany	22
Italy	19
Japan	13
Netherlands	4
Sweden	4
Switzerland	2
United Kingdom	1
United States	59
Total	201

PROJECT SUMMARY

Project Title: International Energy Agency Program on Hydrogen Production

Principal Investigator: James H. Swisher (for DOE)

Organization: Divison of Thermal and Mechanical Energy Storage Systems, U.S. Department of Energy, 600 E Street, N.W., Washington, D.C. 20585. (202) 376-4919

Project Goals: Accelerate technology development in the production of hydrogen from water through international cooperation.

Project Status: Information and personnel exchange is now in progress in five project areas: thermochemical production, low temperature electrolysis, high temperature electrolysis, photocatalytic processes, and market projections. A final report on hydrogen market projections will be published shortly. Experimental work on the various production processes is proceeding at a steady pace, although no significant new discoveries have been made. Bench-scale facilities for thermochemical hydrogen production have been built and operated both in the U.S. and in Europe. One U.S. scientist has worked at a Commission of European Communities laboratory for six months under the Agreement and several European scientists have worked at U.S. labs for shorter periods. At least one workshop has been held each year for each activity to accomplish exchange of results and ideas. Some task sharing of projects has evolved since the Agreement was signed.

Contract Number: None

Contract Period: October, 1977, to October, 1980. Continuation likely.

Funding Level: U.S. Dept. of Energy - $6 million; IEA total-$20 million in FY 1980.

CHEMICAL/HYDROGEN ENERGY STORAGE SYSTEMS

Douglas S. Miller
Field Program Manager

Al Mezzina
BNL Program Manager

Organizational Structure (1980 - 1981)

The hydrogen energy R&D projects sponsored by the Division of Energy Storage (STOR) in FY 1979 were transferred to the Brookhaven Area Office (BHO) in FY 1980 in response to the Department of Energy's (DOE) program decentralization objectives. Subsequently, the Office of Advanced Conservation Technologies (AC) was created from STOR. The hydrogen energy research and development (R&D) projects previously sponsored by STOR were re-organized into two basic R&D areas (with related technologies) as part of the decentralization plan. Those two areas are:

- Hydrogen production via thermochemical cycles with related material compatability R&D, and
- Hydrogen production via electrolysis-based systems with related hydrogen storage systems R&D.

The Brookhaven National Laboratory (BNL) serves as technical monitor on all projects included in the electrolysis-based R&D subprogram and performs the management tasks associated with these projects. The Jet Propulsion Laboratory (JPL) performs a similar function for all projects included in the thermochemical cycles subprogram. Both BNL and JPL report directly to BHO. This includes technical direction on all projects, financial reporting, milestone compliance, monthly reporting, and the annual operating plan. BHO ensures that Headquarters/AC receives copies of all correspondence submitted and keeps HQ/AC appraised of all important issues. All other contractors and national laboratories will report directly to BHO. The overall program management structure is illustrated in Figure 1, including the roles of AC, BHO, BNL, JPL and The Aerospace Corporation.

C/HES Program Overview (1980 - 1981)

Hydrogen Production Systems and Chemical Heat Pumps have maintained their lead budget and programmatic priority. Modest activities, deriving from technology spinoff, are planned to examine near-term resource recovery options. The C/HES major program elements are: (1) Electrochemical Production Systems; (2) Thermochemical Production Systems; (3) Chemical Heat Pumps. Minor elements are: (4) Chemical Storage Systems and Materials; (5) End-Use Applications and Systems Studies.

(1) Electrochemical Systems The engineering development of General Electric's Solid Polymer Electrolyte Water Electrolysis System has progressed to the fabrication, assembly and continuous test of a 200 kW unit. Findings have shown no inherent design or electrochemical limitations to meeting system cost and performance projections; thus scale-up of electrodes from 2.5 ft to 10 ft^2, consistent with proceeding to multi-megawatt designs, was approved. In FY 81 actual fabrication of scaled-up systems will await clear demonstration of electrolysis module cost reduction as well as improved performance efficiency of 2.5 ft^2 electrode systems. Fabrication improvements look to quality control as well as elimination of electric resistance problems.

Advanced alkaline water electrolysis system components and materials testing results have been equated to cost. Preliminary evaluations suggest that these advanced systems may produce hydrogen at costs similar to those projected for SPE systems. Also, efforts have been initiated looking to scaled-up vapor lift or static feed alkaline electrolyzers. Successful implementation of the static feed concept may offer capital cost reduction advantages as well as permit the direct electrolysis of impure water feeds.

(2) Thermochemical Systems Given a high temperature heat source, worldwide investigations have pointed toward indentification of closed cycle reactions which would provide for the dissociation of water into hydrogen and oxygen while preserving the intermediate reagents for recycling. While early U.S. efforts were directed toward ties with nuclear heat sources, the prospects of using solar energy high temperature sources and storage schemes will be emphasized in the future.

Process development actions have concentrated in two areas (1) sulfur/iodine thermochemical water splitting cycle at General Atomic Company; and (2) the hybrid sulfur cycle at Westinghouse. The processes each offer a common sulfuric acid decomposition step to interface with high temperature sources. Additional efforts into identification of other thermochemical cycles and related electrocatalysis are ongoing at LASL and the Institute of Gas Technology.

The thrust of activities in FY 81 will aim for selection of the optimum process with ties to high temperature solar heat and the upgrade of technology state-of-the-art which will permit such selection. Support systems engineering studies will be conducted for competing processes which will identify cost of hydrogen production for the several options under investigation.

(3) Chemical Heat Pumps Requirements analyses addressing technical, cost and marketing factors for sulfuric acid/water chemical heat pumps were completed. Findings have pointed to system designs which will find application as industrial chemical heat pumps capable of upgrading 200°F to heat to "marketable" 300°-350°F process steam. The subcontractor indicates return-on-investment potential of 1.5 to 2 years.

Engineering development tests of calcium chloride/methanol chemical heat pumps show that targeted performance goals are attainable. Capital/operating cost trends indicate that market penetration of this solid/vapor, low-pressure system will be seriously inhibited. The desirable materials properties of relatively innocuous calcium chloride and methanol compared to corrosive acid systems or toxic NH_3 are offset by cost penalties to override heat transfer and mass flow limitations, therefore, while market acceptance for residential/commercial applications may be more promising, cost/economics considerations will probably prevail.

A competitive procurement for development of metal hydrides chemical heat pumps was initiated. Target date for award of contract has been set for late FY 80. Industrial response to the competitive RFP was most encouraging in terms of the expressions of interest demonstrated on a national and international level.

Consistent with goals and objectives for Chemical Heat Pump development and commercialization, a contract has been let which will permit continuing technical, cost and marketing analyses of promising systems. Evaluations will consider market penetration potential in light of current and emerging competitive technologies. These evaluations will be applied to developing criteria and rationale for the current as well as future programmatic action regarding CES/CHP development.

(4) End-Use Applications and Systems Studies Merchant hydrogen production and marketing from small hydropower sites continues as the nearest-term renewable resource conversion opportunity. A contract has been executed with New York State Energy Research and Development Authority (NYSERDA). This is a cost-shared effort equally divided among DOE, NYSERDA, and the City of Potsdam. NYSERDA will complete analytical and design efforts associated with small hydropower application to hydrogen production. Cost analysis will define whether dedicated excess power can be used to produce and market merchant hydrogen to the local industrial community.

"Over the fence" hydrogen marketing from small hydroelectric sites was examined. It has been concluded that site availability in close proximity to a single user would seriously limit the replication potential of the concept. Further, cost impacts arising from conventional financing compounded by commercial return-on-investment requirements would drive costs out of the competitive range.

Consideration is being given to a reevaluation of the natural gas supplementation option, although no programmatic commitments have been made. Driving the systems reevaluation rationale is the conclusion that intermittent renewables such as solar and wind energy conversion systems virtually mandate storage. An alternative to costly bulk storage systems is to gain "energy credits" by direct injection of hydrogen into available distribution networks. Successful development of hydrogen separation schemes may be more cost effective than the bulk storage option.

(5) Storage Systems and Materials In the last quarter of FY 80, development efforts were initiated to examine the prospects of using metal hydrides in an industrial process off-gas resource recovery mode. Pretreated refinery gases passed through metal hydrides chemical separations systems offer up to 0.1 Q per year of recoverable hydrogen as a valuable commodity. Cost projects for the separation process indicate several-fold savings over the current price of hydrogen obtained from hydrocarbon steam reforming or partial oxidation processes.

Bench-scale metal hydrides chemical compressors have been fabricated and tested in FY 80. Design and performance data obtained from the development test units will be applied to development and fabrication of field test prototypes.

Bulk storage of hydrogen in glass microcavities was investigated through the conduct of characterization tests of commercially available microspheres normally used as plastic fillers. Cost and performance trends based upon evaluation of test results indicate a need for materials optimization in order for microcavity storage (MCS) to be a viable mobile or bulk storage option. Microsphere production appears to require an optimum sodium/silicate materials content so as to effect a compromise of hydrogen permeation, retention and delivery rates consistent with storage application scenarios.

FY 81 Programmatic Guidelines

Pressures are being imposed on the technological community to respond to near-term commercialization goals. Also, it is becoming increasingly apparent that conventional fuel prices as projected for this time frame are still less than current hydrogen production costs. These two factors provide the major criteria for program formulation in FY 81 and beyond.

While projects in chemical heat pumps development fall within the criteria for near-term technology transfer, hydrogen energy storage systems are relegated to a base technology development role seeking out targets-of-opportunity which may offer near-term impact. Budgetary constraints will force programs to compete for funding allocations which in turn will be made in accordance with guidelines for near-term impact. Yet, the ultimate benefits accruable from hydrogen as an environmentally benign energy form, as an energy carrier, and as a versatile commodity remain valid. These considerations alone justify modest research and development support to hydrogen energy storage systems. A premium must be paid to ensure against the uncertainties of our present-day vulnerability to international whim and future considerations of an environmental nature. In FY 81, DOE should give due consideration to beginning technology transfer via an evolutionary process. In most instances, engineering development can be viewed as individual or separable hardware projects; but when these projects are integrated into an overall concept carrying through from, say, renewable resource conversion to hydrogen production to storage and/or distribution and end-use, a series of technical, legal and institutional complexities can arise. These issues may be treated more comprehensively with input derived from industry hands-on testing and evaluation. Implementation of such system engineering studies will require "across-the-board" interaction among DOE divisions and branches as well as industry participants. Project activities for FY 81 are summarized as line item listings by program element. The listings are presented in order of programmatic priority which in turn will be reflected in budgetary allocations by priority ranking.

1981 Budgetary Overview

Each of the program elements indicate a planned growth over FY 1980 funding. The required BA for FY 1981 ($7400K) is approximately the same as FY 1980, and BO requirements for FY 1981 are 22% greater than the FY 1980 funded BO of $6306K. Each of these elements indicate a pattern of growth over the FY 80 funding. The following summary reflects an overview of the financial trend for fiscal years 1980-82:

Electrochemical Production Systems SPE Water Electrolysis Systems development will receive top technical oversight priority. Emphasis will be placed on demonstrating cost reductions at GE in electrocatalysts as well as on demonstrating improved electrochemical efficiency (85%).

Advanced Alkaline Water Electrolysis development activities will concentrate on completion of electrocatalyst, electrode, and materials testing. New efforts to validate the potential of static feed systems will be completed. DOE policy will determine possible future consideration of the design and fabrication of a several-hundred kilowatt advanced alkaline water electrolysis system incorporating all design and material advances in state-of-the-art.

Support activities to advanced water electrolysis will take the form of efforts into advanced electrocatalysis and materials. New starts will deal with high temperature electrolysis and anode depolarizer systems.

Thermochemical Production Systems The two thermochemical production systems currently under development will be continued at about equal funding levels. Emphasis will be shifted toward process modifications leading to coupling to solar high temperature sources. Investigations of competitive process economics will be performed to provide data for 1981 selection of the process for a solar demonstration pilot plant.

Modest support activities in the areas of alternate process chemistry and materials compatability will be funded. JPL in-house efforts will focus on understanding of the mechanical chemical and economic comparison between the two major processes in preparation for the decision on the solar pilot plant process selection.

Chemical Energy Storage (CES) and Chemical Heat Pump (CHP) budgets reflect a modest increase of 10% over FY 1980 BO funds. This is affected, in part, by the initiation of BNL in-house R&D to support CES activities and the intensification of CHP contract activities initiated in FY 1980. The

	1980		1981		1982	
	BA	BO	BA	BO	BA	BO
Electrochemical Production, H_2	2.1	2.0	2.3	2.4	2.4	2.3
Thermochemical Production, H_2	1.3	1.4	1.7	1.6	2.8	2.0
Chemical Heat Pump	2.7	1.1	1.3	1.6	1.4	2.0
Chemical Storage Systems	.8	.6	.8	1.0	1.0	.8
End Use Applications	.3	.2	1.3	1.1	.7	1.0
Total $\$10^6$	7.2	5.3	7.4	7.7	8.3	8.1

CHP activity was transferred to BNL during FY 1980 and funding projections through 1982 reflect the program focus and direction outlined in the BNL CHP Five-Year Plan (BNL 27955).

Rocket Research will proceed with fabrication and assembly of a 1,000,000 BTU/150,000 BTU/hr sulfuric acid/water CHP following DOE/BNL approval of system design. The unit will undergo performance verification testing and plans will be initiated for unit field testing.

Metal hydrides chemical heat pump development activity will begin at the awarded contractor facilities. Concept development will have been completed to set the stage for engineering development test unit design and fabrication.

Cooperative DOE/BNL/Exxon development of a $ZnBr_2$/$LiBr_2$/Methanol industrial CHP will begin and design/performance parameters identified based upon criteria as apply to the most promising industrial application. Based upon analytical/experimental component and materials evaluations, residential/commercial prospects for a $ZnBr_2$/$LiBr_2$/Freon CHP will re reviewed as a potential project task.

TRW will proceed with cost-value analyses for systems currently under development or in project formulation phases. These analyses will deal with the cost competitive and performance competitive comparisons with current and emerging technology.

Storage Systems and Materials Chemical separation/purification systems development will assume lead priority within this program element. Initial phase activity evaluation will set the stage for future process development. Support efforts complementing this activity will deal with hydrogen separation from natural gas mixtures.

Chemical compressor design and fabrication will proceed to field test prototype systems which will tie to make electrolysis systems hydrogen output considered as feed in a natural gas supplementation application.

Microcavity hydrogen storage efforts may be redirected from bulk characterization of commercially available materials to optimization of materials consistent with application design and use parameters.

BNL in-house technical support will be directed toward validation as well as extension of advanced MCS development and application. Investigations will be initiated for considering "hydrogen storage and transport" in NH_3 and CH_3OH. Cost, energy balance and environmental considerations will be weighed against conventional and advanced storage schemes.

End-Use Applications & Systems Studies End-use applications funding will more than double as the NYSERDA effort at Potsdam NY gets underway. A modest effort will be funded jointly with the State of Alaska to perform a preliminary evaluation of the production of hydrogen from renewable sources available within Alaska. This study will emphasize wind and water power energy sources coupled with Alaska's unique energy requirements.

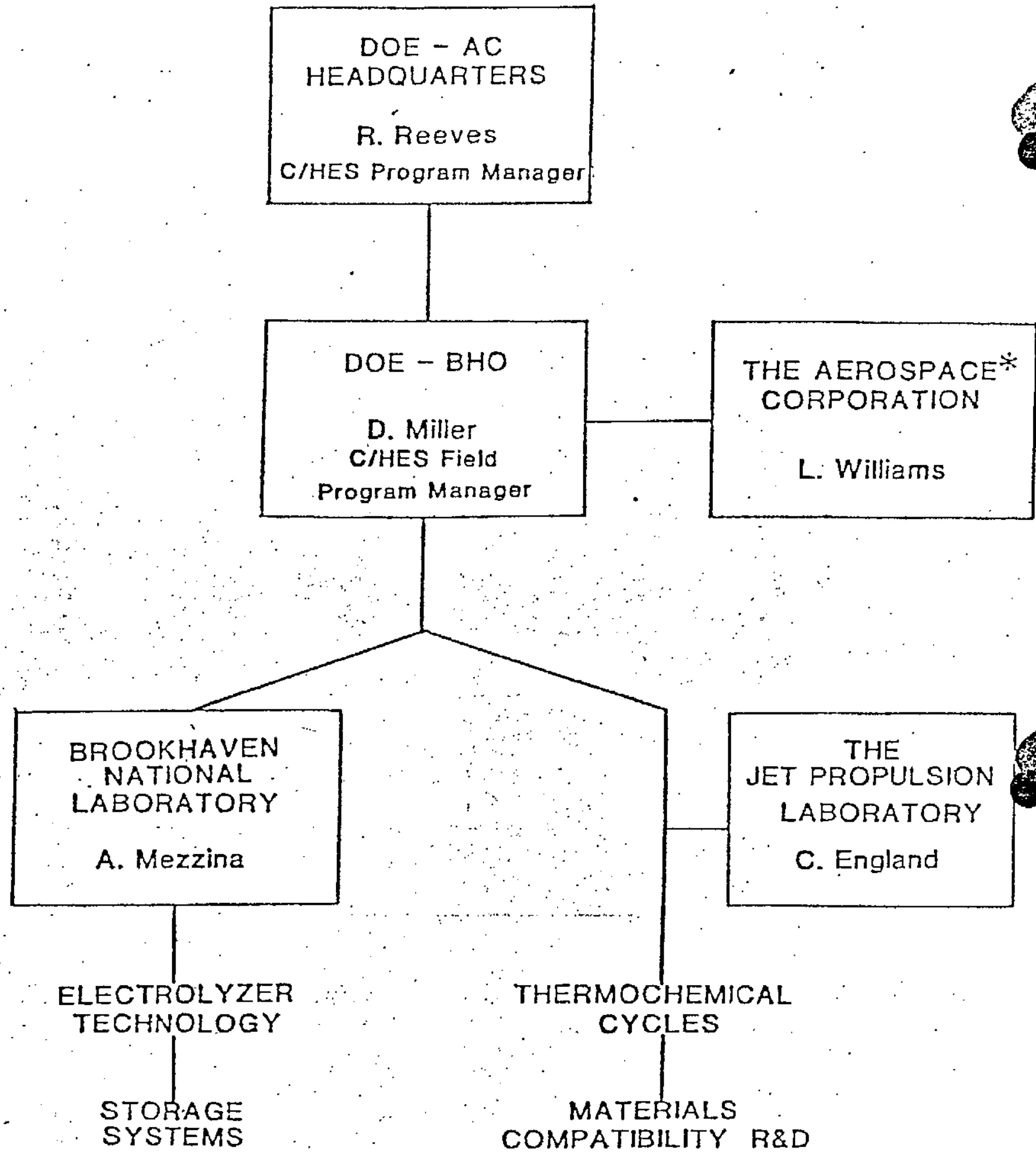

FIGURE 1. DOE C/HES PROGRAM ORGANIZATION CHART

*Technical Support Contractor

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