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HYDROGEN PRODUCTION PLANTS USING ELECTROLYTIC CELLS WITH LOW COST ELECTRODES BUILT INTO PRESSURE TANKS

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ABSTRACT

Electrolytic production method of generating hydrogen gas is briefly reviewed and critical components of electrolytic hydrogen production plants are listed. These components are then discussed and recommended approaches and arrangements cited. Recommended arrangement would be operated at moderate temperatures and gas pipe line pressures. A hypothetical 150 MW Hydrogen Plant is described, including estimates of cost and performance. Comments are made in regard to several possible generating systems which might be used to power hydrogen production plants. A comprehensive energy policy is appended.

SECTION ONE. ELECTROLYTIC PRODUCTION OF HYDROGEN REVIEWED

1. Electrolysis of Water

When electrical potential is applied to electrodes immersed in solutions containing an acid, a salt or a base current will flow and power is consumed. Such an electrical circuit is completed between immersed electrodes by migration of charged ions within the electrolyte. Among these are H_3O plus ions and OH negative ions. As power is imposed above a lower threshold voltage, current flow begins and increases if voltage is raised or resistance of electrolyte is lowered. Bubbles of hydrogen are always evolved at cathodes. Bubbles of oxygen may evolve at non-rusting anodes or will oxidize and destroy anodes such as iron which readily rusts in an oxygen-rich environment. Cathodes of iron do not rust in the presence of excess hydrogen gas. Such an arrangement of imposed power and electrodes immersed in electrolyte is called an electrolytic cell.

2. Electrolytic Cells and Fuel Cells

Fuel cells differ from electrolytic cells in that a directly opposite effect takes place. Again, electrodes are immersed in an electrolyte but with very small separation distances. Raw streams of oxygen and hydrogen are introduced continuously at electrodes and burn to water. In the process electrical charges are deposited on anodes and removed from cathodes creating a voltage difference. If an external electrical circuit is closed, current will flow through it. Electrolytic cells absorb electrical power, while fuel cells create low voltage dc power. Electrolytic cells must receive a continuous input of fresh water to replace evolved gas streams while fuel cells must either lose water or have additional acids, salts or bases added to retain electrolyte solution strength.

3. Electrolytic Cells and Battery Cells

Battery cells differ from electrolytic cells in that a directly opposite effect takes place. Again, electrodes are immersed in an electrolyte having sacrificial anodes or the equivalent. Chemical reactions which take place quickly die out in absence of a closed external electrical circuit. A voltage difference is maintained between dissimilar metal anodes and cathodes. When external electrical circuit is closed, electrical current will flow through it. Battery cells are used to create low voltage dc power and are rated in ampere-hours. Battery cells can furnish a high current for a short time or a low current for a longer time, but eventually become depleted. Many, such as car batteries, can be recharged many times, but batteries generally are self-destructing mechanisms. Electrolytic cells absorb electrical energy, can run continuously and can be designed to last indefinitely.

4. What Becomes of Electrical Energy Absorbed in Electrolytic Cells?

Each ampere-hour absorbed releases finite amounts of hydrogen gas and of oxygen gas. Hydrogen gas is a fuel and when burned releases energy. Electrical energy absorbed in electrolytic cells is converted into potential energy in hydrogen gas as a fuel. Hydrogen gas as evolved at cathodes is very pure. This process has inefficiencies. First, electrical power supplied to electrolytic cells must be generated with usual generator losses, distribution cable losses, electrode losses and electrolyte I^2R losses. The latter loss is partially offset in that as electrolyte temperature rises its internal resistance is lowered, thus reducing cell voltage required. Finally, water will not disassociate below a threshold voltage which increases electrical power required, but does not increase current flow or hydrogen gas release.

5. Electrolytic Cell Use in Past

Early in this century when cheap hydroelectric power was plentiful, electrolytic cells were commonly produced and used to produce very pure hydrogen gas for numerous chemical industry processes. In addition, electrolytic cells were used in numerous chemical processes where evolvement of hydrogen gas was merely a by-product. With the advent of cheap fuel oil, petrochemical processes became economical for the production of raw hydrogen gas. This made production of hydrogen gas by electrolysis of water method very expensive except in locations where very inexpensive hydroelectric power continued to be available. Use of electrolytic cells for producing hydrogen became increasingly difficult to justify unless cells are also used to produce chemical stock which can only be created using electrolytic cells

6. Electrolytic Cell Use at Present

Electrolytic cells are widely used in many chemical industry processes where by-product, hydrogen gas, is fed into satellite chemical processes located nearby. Such cells are also used in electroplating processes, but in this case cells are open tanks since solutions contain metal ions and there is no hydrogen evolvement at cathodes. As electrolytic cells are only rarely used today for sole purpose of generating pure hydrogen gas, interest has dwindled and specific information on such cells is rare and even decades old. Such information is not necessarily very useful because it was prepared before stainless steels and plastic materials were developed. Materials commonly used then were cast iron cathodes, nickel-plated cast iron anodes, asbestos diaphragms to keep hydrogen separate from oxygen, and glass bell jars for removing entrained liquid from evolved gases.

7. Future Use of Electrolytic Cells for Generating Hydrogen Gas

Any comprehensive energy program for converting from past use of inexpensive fossil fuel to whatever we end up doing later on is faced with a gap in the near future. This gap can be greatly eased and even eliminated if a national consensus agrees that hydrogen gas should be used on a large scale as an energy converson and storage medium and as a commonly used fuel gas. Short-term production of vast amounts of hydrogen gas will require large low cost production plants. In order to alleviate our energy crisis soon and be competitive, next generation of hydrogen plants would have to be the electrolytic cell-type powered from "free fuel" sources, such as energy derived from flowing water, wind or solar heat gain.

8. Basic Hydrogen Production Plant Constituents

These include:

(1) Electrolyte
(2) Electrodes
(3) Cell Arrangement
(4) Gas Removal Piping
(5) In-Cell Gas Separation Diaphragms
(6) Dielectric Separation
(7) Makeup Water System
(8) Thermal Insulation
(9) Compressors
(10) Refrigerators
(11) Electrical Power Supply Equipment
(12) Variable Voltage Power and Control

SECTION TWO. DISCUSSION OF COMPONENTS OF ELECTROLYTIC CELL BANKS

General

Next few paragraphs will discuss H^2 plant constituents, as listed in Section One. When that has been done, detailed cell arrangements can be considered.

1. Electrolyte

Electrolyte could be acid dissolved in water. Use of acid is rejected on basis of egregious corrosion problems that might have to be faced, ever present danger of injury to in-plant workers, no possibility of reducing electrolyte cost and no demonstrable performance advantage as an electrolyte.

Electrolyte could be salt (NACL) dissolved in water. A 2.5% salt solution is of obvious interest. Sea water could be used at no cost in many plants. Use of salt is rejected on basis of corrosion problems. Even stainless steel electrodes are attacked in a short time and electrolyte becomes noticeably contaminated.

Electrolyte can be a base dissolved in water. Use of basic solutions is most acceptable and even bare steel is not attacked. With corrosion problems eliminated, which base should we use. Chief contenders are sodium hydroxide (NaOH) and potassium hydroxide (KOH). Optimum strength of NaOH lies at about 15% and it costs up to 20¢/lb. Optimum strength of KOH lies above 25% and it costs up to 30¢/lb. Relative cost is 40% for NaOH and 100% for KOH. On the other hand, KOH has a consistely lower resistance in ohms/in./sq.in. than NaOH at all temperatures of interest. This is a critical factor in electrolytic cells for producing hydrogen gas in large quantities, as for an energy conversion and storage medium and also as a commonly used fuel gas. Nitric acid of 20% strength has a low resistance which is much lower than any base or salt at 500°R. However, this advantageous feature is lost in comparison to KOH when operating temperature is increased to 700°R. In principle, initial charge of KOH will last forever. Its higher initial cost can be amortized over decades.

2. Electrodes

Anodes must be impervious to rusting. Platinum, nickel and nickel-plated electrodes have been used successfully, but are expensive. Lengthy testing indicates Type 304L austenitic stainless steel can be used. While it is also expensive, this impact can be minimized by using very thin sheets as will be expanded on below.

Cathodes can be of steel, but there are disadvantages. If cells are misconnected even for a few hours considerable destructive attack can occur. If cell life was to be short, this would not be a problem, but an essential need in an economic hydrogen gas fuel based economy is production cells that will last for decades and longer. Even worse is problem of sealing iron sheets against dielectric insulators. Even epoxy used to glue lucite to iron that has been carefully cleaned and dried is unsuccessful. In each case electrolyte seemed to progressively percolate along steel surface destroying its bond to the epoxy. This does not happen when 304 austenitic stainless is used.

Although thin-sheet austenitic stainless steel costs three times as much as thin-sheet carbon steel, it offers advantages. It is easy to work with and is easily sealed to dielectric separators. Prior to assembly all electrodes are identical and any can be used as an anode, a cathode or both at same time. Electrical flow of current through assembled cell banks can be in either direction and no harm is done. Although 304L austenitic stainless steel costs close to $2 a pound in thin sheets, steel in thin sheets costs $0.65 a pound. In principle, stainless steel electrodes should last indefinitely and even if long-term superficial damage should occur to anodes, cell life can be doubled by merely reversing direction of current flow. Added cost of cathodes is easily amortized over decades. In addition use of all stainless steel electrodes allows serious consideration of tanks having cells arranged in series rather than in parallel. Electrical resistivity of stainless steel is 7.6 times greater than carbon steel, but with proper arrangement this disadvantage is easily overcome (sheets can be stainless clad steel).

3. Cell Arrangement

In the past, common electrolytic cell design was to support nickel-plated iron electrodes from a removable cell tank top lid. In tank, cells were in parallel to provide a single fresh-water makeup control and no division of electrolyte fluid. Top edge of each electrode was heavily strapped with copper. Such cells attained a low current density and thin stainless sheets used as electrodes in this manner would not be efficient nor would a tank of cells be inexpensive.

More recently, there is published interest in pressure tanks operated at high temperatures. Cited temperature is 800°R+. Cited pressure is 200 atma. Ampacity ranges from 2.8± to 5.5± per square inch and maximum thermal efficiency is close to 90%. Electrodes are described as being of milled solid nickel which must represent a double expense. In thin sheets, nickel is available in only 24-inch width at $4/lb. which is twice unit price of 36-inch wide 304 stainless sheets. Added thoughts are, 800°R precludes use of plastic as a dielectric within tanks and 200 atma pressure must require, for large capacity units, heavy metal shells carefully separated from anodes or cathodes or both.

For the immense number of hydrogen production cell tanks that may be needed in the near future, internal pressures of 200 atma could cost such tanks out of sight. Also, off-gas cannot be used in gas transmission lines without pressure reduction since these generally are designed for a working pressure of close to 47 atma.

A different approach is needed if we are to mass-produce hydrogen gas production cell banks at little cost per KW. Such an approach is presented in Section Three.

4. Gas Removal Piping

Despite large overall H_2 gas flow (a 150 MW plant will discharge 27000 SCF/M or 1,600,000 SCF/HR) under 50 atma pressure these figures become 540 CF/M and 32,000 CF/HR. If such a plant has 12,400 cells in five parallel runs, each of 2480 cells in series H_2 gas leaves a single cell at rate of only 0.044 CF/M or 2.6 CF/HR. Smallest microalescent filters are rated for 10 CF/M. These remove 99.999998 or so of particulates but do not impede vapor. Using one of these every 20 cells will rigorously trap all, leaving liquid froth and permit its return by gravity to cells with a factor of safety of 12, and, hopefully, preclude long-term unidirectional migration of KOH within a cell-bank. In-bank pressure would be accomplished using small, high-pressure body, back-pressure valves on each off-gas (oxygen and hydrogen) line from each cell-bank whether oxygen is ultimately collected or not. Most of these lines will be small and should be stainless tubing connected using high quality compression fittings. As collected off-gas flows get larger, Schedule 5 single pass, butt-welded stainless pipe should be used for economy and cleanliness ahead of station refrigerators.

5. In-Cell Gas Separation Diaphragms

In past years asbestos cloth was used with some problems which, in turn, require rigorous quality control to prevent in-cell deterioration. I would hope a suitable grade of glass or polyester cloth could be used to preclude such problems and improve life expectancy of these diaphragms, which are vitally needed to prevent in-cell readmixture of H_2 and O_2 molecules and still permit ready migrations of charged ions in solution to pass through in both directions. In-tank pressure will help suppress gas bubble size and permit bubbles to rise close to electrode surfaces and away from cloth diaphragms. It will also help preserve a stable electrolyte surface some four inches below underside of cell ceilings where very small bubbles can break through cleanly with a minimum of foaming.

6. Dielectric Separation

This was discussed previously. PVC is fairly ideal (especially when one-inch thick) in that it is not damaged by insolation. If higher operating temperature were needed, either glass or ceramic might be used. However, decreases in resistance of KOH become less and less as temperature is increased, and by holding to less than 685°R there should be no problem. Other advantages here for PVC are reasonable cost and fact it can be welded to itself using hot plates at 890°R.

7. Makeup Water System

For cell-banks to be operated successfully for decades at a time, accumulation of particulates, scale and metal ions is to be avoided. Hydrogen plants should have duplex demineralizing stations to provide totally clean makeup water year after year. Water should be introduced through surge tanks at top of these low conductivity systems which are blanketed by nitrogen gas under positive pressure. Deoxygenation is completely unnecessary, since all water entering cells never comes back. Before arriving at cells LCW water should be used to cool critical parts of Station Rectifiers, if these are used, as they will be in any large plant. Rectifier losses are about equal to average makeup water heating needed to maintain desired in-cell operating temperatures.

8. Thermal Insulation

One-inch PVC is probably adequate except in harshly cold climates, as noted under 7 above. In many locations in hot weather it may be necessary to pass LCW returning from Rectifier water jackets through a fan coil cooler (car-radiator-thing) prior to admission into cells.

9. Compressors

If in-cell pressures are maintained at 50 atma pressure, there should be no need for multistage compressors which are big and expensive at most hydrogen production plants.

10. Neon Refrigerators

These will be a must at most large hydrogen production facilities. While much more expensive than hydrogen compressor, payback is easily demonstrated. Hydrogen is very fluffy stuff. By weight it has four times heat value of best grade of coal and three times heat value of average petrofuel. By volume it has only one-third of heat value of natural gas, although average NG is 85% hydrogen by weight. To transport H_2 gas economically, its bulk volume must be reduced which requires cryogenic refrigeration. If H_2 is chilled to 60°R, it shrinks to one-ninth of its former volume; it is still more bouyant than air at 540^{o}R and is almost as dense as LH_2, but nowhere near as dangerous to handle. Of all cryogenic gases, ability of neon to refrigerate at 60^{o}R is enormous. Below 60^{o}R it has little capacity and freezes solid at 43^{o}R. Over the long term, lost product used to chill or compress hydrogen becomes name of game. Hydrogen can be chilled to 60^{o}R for 5% burn-off to drive neon refrigerator compressors. Hydrogen can be compressed from 1 atma to 50 atma by burning off close to 8% of throughput to fuel engines driving compressors. Combination of low cost cell-banks in tension to permit hydrogen evolvement at 50 atma, plus use of neon refrigeration to chill product to 60^{o}R, plus multiple feet thick dirt cover over existing gas transmission lines (and depleted N G field available for storing H_2), all indicate that booster gas compressor stations could become rather rare in the years ahead.

11. Electrical Power Supply Equipment

In principle, DC generators could be close coupled to H_2 production cell banks with no switchgear or transformer used. It was a lovely dream. In very small plants it may make sense. Our conversion to a hydrogen fuel-based economy requires very large plants. Accordingly, high speed low cost 13.8 KV AC generators will be used. Hard facts of life say combo of inexpensive AC alternators and AC/DC solid state rectifiers are all-out winners for powering most H_2 plants.

12. Variable Voltage Power and Control

Primary side vacuum switches should be used to allow automatic cut-in and cut-out of cell banks many times each hour. If AC alternator speed is not controlled, AC voltage and frequency will vary. Modern AC vacuum switches allow solid state rectifiers to gate power flow. When voltage is up, current flows and hydrogen evolves in all cell-banks. When voltage is down, cell-banks will go off air selectively as coupled rectifiers cut out. As units cut out, remaining units stay on as voltage builds up. Inherent ability of this capriciously variable voltage AC generator: AC/DC solid state gating rectifier: DC cell-bank combination to vary between one-fifth and five-fifths load and handle all overloads up to complete stall while operating in parallel with tenacity is not only a good thing (for remote, unattended totally automated H_2 plants) but is worth noting because it is so very different from control concepts of modern interlocked 60 cycle AC power systems.

SECTION THREE. DISCUSSION OF A SPECIFIC DESIGN FOR ELECTROLYTIC CELL BANKS

Let us list high-priority features of an attainable electrolytic cell-bank design which is solely intended to disassociate water into oxygen and hydrogen and separately collect reasonably pure hydrogen for use as a common fuel gas and perhaps collect reasonably pure oxygen for use in firing hydrogen in gas-turbine drives or any other use it might have. Tank ships can be used to bring home gelid H_2 but O_2 at any temperature is not worth enough to go after it. Such priority features are:

(1) In tank, pressure should be somewhat higher than 50 atma to allow off-gas H_2 to flow through refrigerators to reduce its bulk volume and into existing gas transmission pipe lines without use of expensive multistage gas compressor stations.

(2) In tank, temperature should be less than $685^{o}R$ in order that plastic having good heat resistant characteristics such as PVC can be used as dielectric separators or even as part of cell-tank walls where this makes sense.

(3) Cell-tank cross-sectional dimensions should be reasonable for shipping by truck such as 9'x9'x50' maximum dimensions except for piping manifolds.

(4) In tank cells should all be in series with no external electrical connections to eliminate tons of copper and allow use of very thin 304 stainless clad steel plate electrodes. Each electrode would act as an anode on one side (facing cathodic side of its opposite electrode in that direction) and as a cathode on other side (facing anodic side of its opposite electrode in this other direction). Now thinness of electrode sheets is presented to once-through flow of current and its 9'x9' bulk area is presented to allow high surface area to reduce current density except for a one-inch border all around for tank dielectric walls and a four-inch margin at top of tank over liquid to permit separation of gas from bubbling surface of contained electrolyte. Resistance through thousands of sheets of 304 stainless clad steel sheets should be very small.

(5) Electrolyte path should be in order of one inch which allows reasonable space for inclusion of a glass-cloth diaphragm to separate gas bubbles but allow free migration of ions in solution and for fresh-water makeup and off-gas tubing penetrations (fresh-water makeup would be accomplished using self-contained pressure sensitive adjustable toilet tank fill units except unit bodies would be adapted for 50 atma pressure). Each cell will need its own independent fill unit. Available units for use in toilet tanks sell for less than $5 each.

(6) Glass-cloth diaphragms should have a foolproof method of attachment to dielectric tank walls. A "U" frame of very thin 304 stainless steel is recommended for reasons discussed under (7) below.

(7) Side walls should be of plastic which is easily bonded using suitable adhesive both to 304 stainless electrode sheets and 304 stainless "U" frames holding glass-cloth diaphragms. PVC is recommended as being capable of withstanding in-tank operating temperatures of close to 630°R and readily adhering to stainless steel when proper adhesives are used. With an internal tank pressure of 50 atma, shear stress against adhesive is 375#/square inch and bending moment at "U" frame is only 31.25 inch pounds. Side walls must act as a dielectric separation which PVC will also do.

(8) Internal arrangement must positively resist all stresses imposed by 50 atma of pressure. The transverse stainless clad thin sheets spaced at one-inch centers along length of cell bank will easily prevent structural failure. At each end of each bank there must be a heavy (one inch thick) steel end plate to properly distribute and recover thousands of amperes current flowing through cell banks. These end plates must be lined with stainless steel to prevent contact with electrolyte. These end plates must have equal pressure on each side to prevent tank destruction. Pressure will be restrained at outsides of end plates using same approach as for sides, tops and bottoms of tanks. Vertical diaphragms will be strips of electrode sheeting at one-inch centers to form 105 8'-10" long pressure equalizing cavities. Similarly PVC stock will be epoxied to end plates and/or diaphragms for support and closure. Welded 304 LSS piping will connect each cavity to oxygen gas phase piping.

(9) In-cell pressures of up to 50 atma must be equalized from cell to cell. This is accomplished above electrolyte surface via off-gas piping.

(10) Rectifier bus-bars and cell-bank "U"-bend return bars should be attached to copper current equalizing bars attached to exposed top edges of copper end plates. Top run busing will shorten busways and permit maintenance people to easily pass between equipment at grade.

(11) Carry-over loss of water droplets containing KOH should be rigorously stopped near cells of origin. Any water vapor lost is easily condensed out in gas transmission piping and made up cell by cell by individual cell level controllers.

SECTION FOUR. DESCRIPTION OF A 150 MW HYDROGEN PLANT

1. Electrodes

Let electrodes be 0.052 inches thick steel clad with 304 stainless at one-inch centers with edges built into tank walls; electrode sheet will be 9'x9' to allow cell-bank tanks to be shipped by truck. Tensile stress per sheet is 1.414x750#/ 1 inch x 0.052 inches or 20,400#/sq. in. which is 67% of yield strength. Resistance per clad sheet is 0.00000376 OHM/inch/ in^2 x 0.04" plus 0.0000287 OHM/in/in^2 x 0.012 in. or 0.000000495 OHM across sheet. Assume 0.75 amps/sq.in. Inner wetted area = 102"x106" = 10,812 sq.in. Total current is 8109 amps. Resistance of 12,450 electrodes is 0.00616 OHM. Voltage drop per plate is

0.000000495 OHM/in^2 x 0.75 amps/in^2 or 0.000000371 Volts

Electrodes would be 18 ga. (0.0478" thick) cold-rolled steel clad on both sides with 38 ga. 304 stainless (0.006" thick).

2. Electrolyte

Assume 25% strength KOH is used. Specific resistance is

0.7284 OHM/in/in^2 at 524°R which will reduce to

0.1821 OHM/in/in^2 at 689°R. Operating resistance will be

0.1821 OHM in/in^2 x 1"/10,812 in^2 or 0.00001685 OHM

Voltage drop per cell will be

0.00001685 OHM x 8109 AMP - 0.137 volts

3. Voltage Drop per Cell

Ideally this should be 1.23 volts for an electrolytic cell. Hydrogen gas density is 0.00523#/CF at 528°R and 1 atma pressure. This 1 CF of hydrogen has gross fuel value of

0.00523# x 123,100 BTU/#- Mol/2.016#/mol or 319.352 BTU/#.

One thousand CF of hydrogen thus contains equivalent of 93.576 KW and this much gas will be liberated if 63000 AMP-HR pass through a cell. Ideal energy input would then be 1.23 volt x 63000 AMP-HR or 77.49 KW. Unfortunately, this is not equivalent and actual cell voltage drop is larger even without losses. Base voltage drop is 93576W/63000 AMP or 1.485 Volts. Operating voltage drop will be 1.485 Volts plus 0.000000371 Volts (electrode loss) plus 0.137 Volts (electrolyte loss) for a total of 1.622 Volts.

4. Other Voltage Drops

Assume one-inch thick steel end plates. Current-per-inch width is 8109 AMP/106" or 76.5 AMP. This current is assumed to exist for six inches downward from top plus 51 inches within portion facing electrolyte through stainless cladding. Resistance is

0.00000386 OHM/in/in^2 x 57" or 0.00022 OHM. Voltage

drop for four plates is 4 x 76.5 AMP x 0.00022 OHM or 0.067 Volts. Copper bars would be used to laterally distribute current at top of end plates. Assume 2"x4" copper bars, four places. Resistance is

4x0.000000679 x 27 in/8 in^2 or 0.00000917 OHM. Voltage drop is

8109 AM x 0.00000917 OHM or 0.074 volt

Copper U-bend would be used to transfer current from cells extended away from power source to a second cell bank leading back to power source. Assume one 2"x4" copper bar would be used. Resistance is

0.000000679 OHM/in/in^2 x 90 in/8 in^2 or 0.000000764 OHM.

Voltage drop is

0.000000764 OHM x 8,109 AMP or 0.06 volts

Rectifier buses would connect to end plates at end of each of two cell banks. Assume two 1"x8" copper bars 20 feet long would be used. Resistance is

0.000000679 OHM/in./in^2 x 240 in./8 in^2 or 0.0000204 OHM.

Voltage drop is 0.0000204 OHM x 8,109 AMP = 0.33 volts. It is concluded that voltage drops external to cell banks can be low enough as to be inconsequential.

5. Total Number of Cells

Value in KW of hydrogen gas to be produced is 150,000 by definition. Hydrogen gas output for a 150 MW plant will be

150,000 KW-HR x 3412.76 BTU/KW/319.352 BTU/CF or

1,602,500 CF/HR. Number of cells required is

1,602,500 CF/HR x 63,000 AMP-HR/1000 CF x 8109 AMP or

12,450 cells. Assume five parallel sub-units each having 2,490 cells. Each sub-unit will have an out cell-bank and return cell-bank containing 1245 cells. Use of five 30 MW rectifiers will permit load variation above 20% of design load. Rectifier DC voltage would be 1.622 volt/cell x 2490 cells or 4039 volts.

6. Cell-Bank Input Power and Thermal Efficiency

Cell-bank input power equals

(1.622 volts/cell) 8109 AMP x 12,450 cells or 163,753 KW.

Cell-bank thermal efficiency would be

150,000 KW x 100/163,753 KW or 91.6%. Makeup water flow is

1,602,500 CF/HR x 0.00523 #/CF x 18.016/2.016 or 75,000#/HR

This is 150 GPM. Makeup water heat load in cold weather would be 75,000 #HR x $175^{o}R$/3412.76 BTU/KW-HR or 3846 KW. Rectifier input is 163,753 KW/0.98 or 167,095 KW. Using makeup water to cool rectifiers will supply 3342 KW of makeup water cold weather heating load. This leaves 504 KW which would be needed only in coldest weather and could be supplied by five hydrogen gas-fired auxiliary heaters. Likewise in hot weather water heated from rectifier cooling jackets toward cell-bank makeup water manifold could be passed through five motor-driven fan-cooled radiators. Makeup water pumping power is

150 GPM x 800 PSI/1600 Factor at 70% off, or 75 KW.

Five 15 KW 30 GPM motor-driven pumps would be used.

7. Closing In

We have set output at 150,000 KW gross fuel value. This results in a constant off-gas hydrogen flow of 1,602,500 CF/HR. We have found that I^2R losses external to cell-banks are very small for a plant having several thousand cells in series and can be disregarded. Hydrogen evolved per cell would be

1,602,500 SCF-Atma/HR/12,450 cells x 50 Atma or

2,574 CF/HR/Cell which is 0.0429 CF/M or 0.000715 CF/S

With cell pitch set at one inch there will be 0.5" PVC on each side of glass-cloth diaphragms. Makeup water average flow/cell is 150 GPM/12,450 cells or 0.012 G/M/Cell which is 0.002 G/S/Cell. This is same as 0.0000267 CF/S. If 3/16" OD tubes are used to vent gas and introduce makeup water, these will have 1/8" ID and leave close to 5/32" of undisturbed PVC on both sides of each tube. Tubing flow area would be 0.0000852 SF. Hydrogen gas velocity would be

0.000715 CF/S/0.000852 SF or 8.4 FT/S

which is 503.4 FT/M. This is marginal with respect to entrained moisture droplets. Extended tees should be used inside cell to reduce entry velocity to 4.2 FT/S. Makeup water velocity would be

0.0000267 CF/S/0.0000852 SF or 0.313 FT/S

Water tubing within cell would be PVC and extend to within four inches of cell bottom to insure proper mixing. It seems a one-inch cell pitch is about minimum due to materials used, size of cell tanks and assembly labor operations that will be required. Cell pitch could be larger but this would increase electrolyte resistance and reduce production efficiency. Thus, setting cell pitch at one inch eliminates another variable. We can now look at performance of these cells at other current densities and determine total current, cell voltage drop, cell KW, number of cells required, cell I^2R heating, total KW input and indicated thermal efficiency in each case.

At 0.25 AMP/in.^{2}, total current is 2,703 AMP, voltage drop is 1.53 Volts/cell, cell KW is 4.139, number of cells required is 37,350, cell I^2R is 0.123 KW, KW input is 1,544,592 and thermal efficiency is 97.0%.

At 0.5 AMP/in^2, total current is 5,406 AMP, voltage drop is 1.5 Volts/cell, cell KW is 8.542, number of cells required is 18,675, cell 1^2R is 0.25 KW, KW input is 159,522 and thermal efficiency is 94.0%.

At 1.0 AMP/in^2, total current is 10,812 AMP, voltage drop is 1.67 Volts/cell, cell KW is 18.056, number of cells required is 9,338, cell 1^2R is 2 KW, KW input is 168,608 and thermal efficiency is 89.0%

At 2.0 AMP/in^2, total current is 21,624 AMP, voltage drop is 1.85 Volts/cell, cell KW is 40.004, number of cells required is 4,669, cell 1^2R is 8 KW, KW input is 186,781 and thermal efficiency is 80.3%.

At 3.0 AMP/in^2, total current is 32,436 Amp, voltage drop is 2.03 Volts/cell, cell KW = 65,845, number of cells required is 3,113, cell 1^2R = 18 KW, KW input is 204,976 and thermal efficiency is 73.2%.

8. Heat Balance of a 150 MW H_2 Plant

Assume optimized plant with 12,450 cells

Output KW in H_2 gas by definition	=	150,000
Electrolyte 1^2R = 8109A^{2}x0.00001821 OHMx12.45	=	14,908
Electrode 1^2R = 8109A^{2}x0.000000495 OHMx12.45	=	405
End Plate 1^2R = 76.5A^{2}x0.00022 OHMx20	=	26
Copper Bars 1^2R = 8109^2 x 0.00000229 OHMx20	=	3
Copper U-bend 1^2R = 8109A^2 x 0.00000306 OHM x 5	=	1
Rectifier Bus 1^2R = 8109A^2 x 0.00000153 OHMx40x5	=	20
Subtotal, input power		165,363 KW
Makeup Water Pump KW		75 KW
Instruments & Control, Fan, Lights		14
Total Input Power from Power System		165,442 KW

True Thermal Efficiency = 150,000 KWx100/165,442 KW = 90.7%

Rectifier input = 168,800 KW
AC Generator Drive Output = 179,575 KW
Rectifier heat to makeup water = 0.9(168,800 KW-165,424 KW) = 3376 KW

$$\text{Makeup Water Heating Load} = \frac{75000\#/\text{HR}\times 175^{\circ}\text{R}}{3413\ \text{BTU/KW}} = 3846\ \text{KW}$$

Need small heater for winter. Need small radiator for summer.

9. Cost Estimate of 150 MW Hydrogen Production Plant

0.052" SS Clad Steel Plates 12,490 x 9 x 9 x 1.25	$1,264,600
0.006" SS Diaph.Borders 12,450 x 36 x 1/6 x 0.50	37,400
Pressure Lids 106 x 0.33 x 9 x 3.20	1,000
1" Clad Steel End Plates 20 x 9 x 9 x 15.00	24,300
Single Pass Heliarc Weld 12,490 x 19 x 0.75	178,000
Drill Press Equalizing Holes + SS Lining 20 x 120.00	2,400
Dielectric Frames (1/2"x1" PVC) 12,450 x 2 x 36 x $\frac{1.00}{24}$	37,400
Adhesive - 12,450 x 3 x 36 x 1/12 x 0.15	16,800
Glass Cloth Diaph. 12,450 x 81 x 0.10	100,900
Copper Bars (2"x4") 4 x 5 x 9 x 1/3 x 60.00	3,600
Copper U-bends (2"x4") 5 x 11 x 1/3 x 60.00	1,100
Copper Rectifier Buses (2"x4") 10 x 20 x 1/3 x 60.00	4,000
Makeup Water Controllers 12,450 x 40.00	498,000
Makeup Water Piping 5 x 2 x 104 x 5/4 x 4.00	5,200
Gas Manifolds 5 x 2 x 110 x 10.00	11,000
10 CFM Gas Filters 620 x 100.00	62,000
Back Pressure Valves 20 x 500.00	10,000
Shut-off Valves 40 x 200.00	8,000
Check Valves 10 x 300.00	3,000
LCW Pumps (30 GPM) 10 x 900	9,000
Duplex Demineralizer (10 GPM) 5 x 1200	6,000
Electrical Panels 5 x 1000	5,000
Gas Flow Recorders, Instruments	7,500
LCW Surge Tanks 5 x 2000	10,000
	$2,306,200

Material	$2,306,200
Sales Tax	115,300
Assembly Labor	1,537,500
Inspection	51,000
Trucking Costs	20,000
Site Preparation	3,500
Paving	33,000
Rigging	3,000
Installation Labor	53,000
Potassium Hydroxide	324,000
Supervision	6,000
Insurance	14,000
Maintenance Shed	10,000
Fork Lift Rental	2,000
Construction Power. Tel.	2,000
	$4,480,500
Overhead	224,000
	$4,704,500
Profit	470,500
	$5,175,000
Contingency	125,000
	$5,300,000

10. Cost Picture, Continued

Hydrogen Cells 5 Banks @ 30 MW U.C. = $35/KW (12450 Cells)	$ 5,300,000
Rectifiers 5 Units @33.8 MW U.C. - $35/KW	5,900,000
Generators & Waterwheel Drives (Axial Flow) = 180 MW @ $300	54,000,000
Neon Compressors & Transmission Line, also access road, landing strip or dock	2,000,000
	$67,200,000

Unit Cost = $448/KW H_2 Output Capacity

Reason for using rectifiers is to save money allowing use of standard AC 13.8 KV generators. These would be driven at variable speed depending on driving water currents. AC Voltage and frequency would fluctuate as water current velocities change.

H_2 Capacity = 150 MW normally = 187.5 with waterwheels extended to 125% of normal and 255 MW at 492°R.

11. Cost Picture, Continued

Since bulk of cost is for waterwheel drives and generators, can we afford more efficient H_2 plant?

Cost of 94% Eff. Cell Banks (deduct 1% for auxiliaries =

5,300,000 x 18,675/12,450 =	$7,950,000
Rectifiers 150 MW/0.93 x 0.98 @35	5,800,000
Generators 150 MW/.93 x .98 x .94 @300	52,500,000
Answer is No	2,000,000
	$68,250,000

Can we save by reducing H_2 plant efficiency?

Cost of 89% Eff.Cell Bank (deduct 1% for auxiliaries) =

5,300,000 x 9,338/12,450 =	$ 3,975,000
Rectifiers 150 MW/.88 x .98	6,100,000
Generators 150 MW/.88 x .98 x .94	55,500,000
Answer is No	2,000,000
	$67,575,000

Cost of 80% Eff.Cell Bank (deduct 1% for auxiliaries) =

5,300,000 x 4669/12,450	$ 1,988,000
Rectifiers 150 MW/.79 x .98	6,800,000
Generators 150 MW/.79 x 98 x .94	61,800,000
Answer is No	2,000,000
	$72,588,000

12. Assume a 150 MW H_2 Plant is Base Loaded

Deducting for maintenance shutdowns and cooling of produced gas to 60°R to reduce bulk volume by a factor of 9 net output should be 1,485,000 SCF H_2/HR. This is 7767 #/HR or 93.2 tons per day or 34,000 tons per year. Produced gas would contain

139,650 KW x 8766 HR or

1,224,000,000 KWHR @ 2¢± for a value close to $24,000,000

12% of $67,200,000 = $8,064,000

At $1200/KW a nuclear fission plant is worth $180,000,000 and requires expensive fuel and a large crew.

13. Electrical Power Generators

All large capacity generators are high RPM AC-type to reduce cost, size and eliminate carbon brushes. Use of 13,800V reduces feeder current, saves copper.

Waterwheels are slow and speed, voltage and frequency will vary. AC rotors must be redesigned or speed increasers used. Armatures should have high reactance. Self-contained shaft-driven exciters should be used. At maximum design water current velocity AC generator should rotate at close to 2400 RPM. Design should be rugged so overspeed of 25% (3000 RPM) can be tolerated intermittently. Alternators should be 4-pole.

Such AC generators will operate in parallel.

14. Gas Production Control

Need for free fuel to be economically competitive forces H_2 plants to depend on varying and even part-time sources (wind currents, water currents, solar heat gain, etc.). For this example, assume a tidal basin with water velocity varying from 0% to 100% to 0% four times in each 24-hr period. AC generators will furnish power while turning. Voltage and frequency would be uncontrolled and vary from 40 to 80 cycles/S. Power would also vary from 0% to 100% to 0% four times in each day. Rectifiers must maintain rated volts minimum to cell banks or production stops, as AC load falls off. Cells could have one-half inch thick copper plates encased in stainless steel every 1240 cells to allow 1/5, 2/5, 3/5, 4/5, 5/5 and 6.25/5 load operation by short circuiting switches which would close out 2480 cells at a time (of 12,400). Switches would be expensive and subject to extreme wear at knife blades. Use of five Rectifier-Cell Bank units per 150 MW Plant allows easy cut-in-cut-out operation of cell banks on primary AC side using inexpensive vacuum breakers. As noted previously for a 150 MW plant, five parallel units might be used. This allows operation between one-fifth load and full load or higher. Upper limit of AC generator use and rectifier use depends on ambient temperature and operational judgment in setting and locking safety cutout devices. In icy water and frigid air, AC generators and AC/DC Rectifiers can operate at well over rated loads. Such equipment can operate continuously when ambient is $564^{o}R$. Likewise, this is so when ambient is $492^{o}R$ (freezing point of water). Increased performance can be ($176^{\circ}R/104^{\circ}R$)100 or 69.2% higher.

15. Should Cell Banks be Made Bigger?

If Transverse Area is doubled, then 6,200 cells = 150 MW and 10 lines of 620 cells would suffice. Current could double but Rectifier voltage would be lower (still 5 @ 30 MW), Bars would be same.. U-bends might double. Rectifier Buses would double for practical reasons. Cell costs would not change much and might increase. Cell banks would become WIDE LOAD and shipping would be difficult. Answer would seem to be no, as in not necessary.

SECTION FIVE. NOTES ON POWER GENERATING SYSTEMS FOR HYDROGEN PRODUCTION

1. Power Generation Cost Remarks

An estimated cost per H_2 plant power supply of $335 KW is used. Of this, $35/KW is for Rectifiers which leaves $300 for installing AC generator drive systems, AC generators, AC distribution feeders and vacuum switches between generators and rectifiers. There is nothing else needed. Obviously, this lets out nuclear fission as a possible source of non-fossil fuel heat for driving H_2 plant generators. Likewise, this mitigates heavily against new conventional high head hydroelectric plants requiring expensive dams. Ocean thermal gradient plants and fusion power plants are presumed to be possible sources of power since these would be very large and $/KW costs hopefully would be low. Economically it would appear that ocean thermal gradient plants or diffuse RF receiving stations for power generated from solar heat in plants that are artificial satellites of earth or are located on the moon could be used for little else than generating hydrogen. There is no demand for electrical power stations but at sea and diffuse RF receiving stations start with DC power. Such DC power converted into H_2 gas should cost less than large new overland power lines and DC/AC converters. Should RF generating plants be economical and get placed in space, two thoughts occur. From then on more heat would reach earth and our ecology would change whether for better or worse. Diffuse RF power beams possibly could be greatly intensified at a turn of a knob and easily aimed anywhere at visible surface of earth or its moon including large cities. One must ask which committee of angels amongst us will sit at the control consoles?

2. Back to $300/KW Power Generation

AC distribution between H_2 plant generators and Cell Bank Rectifiers should generally be short and not much of a cost factor. Modern high-speed AC generators in turn are a low cost part of overall power plant costs. In typical fossil-fuel-fired thermal plants, costs of furnaces, boilers, superheaters, high pressure turbines, reheaters, low pressure turbines, condensers, condensate pumps and condensate extraction heaters, boiler feed pumps, feedwater treatment, combustion air preheaters, stack effluent cleanup equipment, step-up transformers and high tension switchgear en masse greatly outweigh in cost the generators per se. If $50/KW are allocated to generators this leaves $250/KW for generator drives. For reasonably large generators this leaves waterwheel drives using water current velocity impulse power and airwheel drives of same type in running. High temperature concentrating solar panels used to heat liquid metal which in turn could heat gas used in closed gas-turbine loops are a possibility. Even better outside air could be heated to drive gas-turbine-generator units with exhaust, then passed through furnaceless conventional high performance steam-electric equipment using very compact, low cost platefin-type heat exchangers in lieu of expensive boilers, superheat coils and reheat coils. Such a topped cycle should have the highest thermal efficiency achievable to our present technology. For waterwheel generator drives there likely would be an artificial and/or natural concentrating fore-conic to increase water current velocity, fore and aft waterwheels, main shaft, speed increasing gear, flow cylinder, straightening vanes, watercooled journal block support tubes, weight supporting platform, possibly a swivel mount and steering rudder(s) if unit rests on a swivel mounting, concrete substructure placed on channel bottom, and a brief flared outlet ring (with highly tensioned guy wires used to stabilize position of fore-cone if it is free to move). To me this sounds like $250/KW or less. There is no R&D requirement. Such units could be designed, assembled and deployed within 18 months by many manufacturers if they receive valid purchase orders.

This is also true of windwheel drive systems. I personally think that clusters of nacelles (either three rows of three or 9+4 or 9+12, with fore and aft axially staggered impellers of 40-foot diameter) make a lot more sense than single impellers of tremendous diameter which must be mounted on very high and expensive towers. If vertical shafts are attempted to obviate cost of mounting towers, these fail inherently because whether water or air currents are used, transversely-placed impellers simply out-produce paddle wheels. Airwheels suffer in power capacity due to 867 to 1 difference in density between water and air. Again, $250/KW would still appear adequate to purchase such windwheel clusters using heavy duty bicycle chain drives to turn a single AC or DC generator of low KW capacity. Any of numerous manufacturers would quickly design, assemble and install such low power units if requisitioned to do so. On the whole, windwheel power is limited to low power requirements as in small towns and waterwheel power using swift water currents, or augmented by concentrating cones where current velocity is lower, can do much to provide us with future low cost energy through use of waterwheel impellered AC generators coupled to AC/DC rectifiers coupled to high performance, low cost hydrogen gas producing electrolytic cell banks.

Solar heat collection for useful purposes is like chasing a shadow. The energy is there. There are four temperature levels of interest. Capture at 600°R± requires low cost single paned window boxes protected by average insulation against back losses. Collector metal plates should be black, but need not have selective surfaces. Plates can be used to heat domestic water for toilets, swimming pool water and recirculating water or air used to heat houses. Such systems can reduce use of fossil fuels as at present or hydrogen gas as in future for such purposes, and will reduce operational outlay while increasing capital costs. In new construction, if window boxes are used as roof deck members, payback picture improves. Any such stationary window box can have its solar collection capability doubled by adding wing mirrors at doubled cost.

Capture at 700°R± is more enticing. At this temperature, water for large automatic dishwashers and restaurant food heating counters can be heated, buildings can be heated in winter and cooled in summer using absorption-type water chillers. Window boxes need to be double-paned and backed by double mats of spun-glass insulation. Evacuation of boxes is difficult to justify but blackened collector plates should have selective surfaces which reduce re-emittent losses due to radiant heat losses to ambient by a factor of 9 or more. Again, boxes are best left stationary with payback picture improved by use of boxes as part of new construction roof decking or through doubled collection effectiveness by adding concentrating wing mirrors at less than doubled cost.

None of above solar collectors are of any use in power systems as required to generate hydrogen gas for use as fuel.

Next temperature level of interest is 2400°R±. Here a higher order of collection paraphernalia is needed. Heat collected at this temperature would be carried using liquid metal such as NAK coolant to platefin type, compact, inexpensive heat exchangers used to boil, superheat, reheat, and rewarm condensate and boiler feed water. Steep differential end temperature gradients must be used if critical feedwater heater temperature difference is to stay above 5°R. Such a system can drive any preferred standard conventional steam electric cycle.

Collector boxes or tubes should be single-glass-paned and evacuated. Selective surface is not important if entire blackened metal area is wetted on back side by NAK Coolant which allows very thinnest sheets of exotic metals to be used at least cost. At 2400°R, certain grades of stainless steel or super alloys can be used. Collector boxes or tubes must be flanked by extensive mirror systems to greatly increase collector scope of solar heat capture while using low cost materials. Collector box systems or tubes must continuously track sun in at least horizontal/simple from east to west diurnal clock motor motion reversed at sundown to swing boxes back to face east without snarling flexible NAK coolant connections.

Rather than attempt to analyze cost picture now, let us advance to highest level of temperature for solar heat capture of use to power generation equipment not yet designed. Temperature of interest would be 4000°R+. Again, a higher order of collection paraphernalia is needed. Heat collected at this temperature would be carried using liquid metal (NAK has been called out in sense of close-to-eutectic-mix which melts at 472°R and thus cannot freeze in mini-passages of very compact platefin heat exchangers) coolant to heat compressed high heat capacity gas as hydrogen or helium to power a closed loop gas-turbine-generator cycle, then heat all phases of a conventional high efficiency conventional steam-electric system. Such a binary cycle would be most efficient which is worthwhile considering heat source on clear days is high enough in sky to see into collectors much less than half of each day.

Sun rises in a curve toward zenith and descends in a like curve as it sets in west. Peak insolation occurs at noon. Shape of solar heat gain curve is rougly parabolic with focus located beneath 12 noon and halfway between 10 AM and 2 PM. This is to say heat collection before 9 AM or after 3 PM becomes very marginal while heat gain between 11 AM and 1 AM is steadily good unless a single little cloud or a very light haze obscures the sun.

Solar furnaces have been built using heliostat reflectors to achieve close to 7800°R. To achieve 4000°R+ our collectors would have to continuously track sun both from east to west and up and down and have highly concentrating parabolic or spherical mirrors. Either mirrors or heat sink can move. A popular version has an enormous water boiler, superheater, reheater assembly mounted on a tower in middle of a field of gyrating parabolic mirrors, each requiring its own special tilt.

Personally I prefer following arrangement. Each mirror would be fairly large and spherical with its center axis trained at and following sun in all its motions. Through back of spherical mirrors would be extended a heat pipe which would collect heat at all times from all directions at varying heights above base of spherical mirror-dishes. Coolant could be water or any liquid or liquid metal which would climb by osmosis through outer shell of packing until evaporated along stem due to heated outer wall. Evaporated coolant would then fill inner open core of heat pipe and expand outward through bottom carrying very high temperature heat to compact inexpensive platefin type heat exchangers, for use in furnishing heat to conventional closed loop gas-turbine and/or steam electric equipment as described previously.

An advantage of such heat pipe collectors is that these can be aimed in any direction without spilling. Dual motion tracking mounts would be relatively inexpensive if spherical half mirror has no weight despite mirror diameter selected. If a balloon, which has one hemisphere of water clear PVF film and other hemisphere of aluminized PVF film, is inflated using a mix of natural gas and helium, as stored in depleted natural gas fields near Amarillo, Texas, it can be made to weigh nothing. Solar collector tracking mount would have to be designed only to resist wind-imposed stresses. Collection area transverse to solar rays would be 314.16 SF with a 20-ft diameter, 31,416 SF with a 200-ft diameter and 3,141,600 SF with a 2,000-ft diameter. Heat pipe length must equal balloon radius (10 ft, 100 ft and 1000 ft for above collection areas). Collection efficiency would be high and might approach 275 BTU/HR-SF or 0.08 KW/HR-SF on clear days. Collected energy for the three diameters cited would be 25 KW, 2,500 KW and 250 MW. Balloon surface areas would be 1257 SF, 125,700 SF and 12,570,000 SF, respectively. PVF 20 mil thick film would cost about $0.25/SF in place so our three balloons should cost $314, $31,400 and $3,140,000 at a constant unit cost of $12.60 per KW of collection capacity.

A complete, large, modern gas-fired (natural gas or hydrogen) thermal electric plant costs about $250/KW at this time. Deducting $30/KW for deleted furnace, $20/KW for deleted switchgear and step-up transformer, and $50/KW for reduced cost of boiler, superheater and reheater heat transfer area when very compact liquid metal to waterside heat exchangers are used instead of vast arrays of convection and waterwall tubing, results in an estimated cost of $150/KW for the steam-electric generator portion. Large, modern gas-turbine generator units, as used in peak shaving, cost about $150/KW at this time. A binary cycle for a solar-fired plant might thus cost $300/KW and have an overall thermal efficiency of 60%. Thus one 2,000-ft diameter balloon collector with combined gas-turbine-steam-electric could be used to drive one 150 MW hydrogen production plant as described earlier.

There is no way, however, to get around fact that average clear sunshine per day at best will, using 56% cloud factor, be 100 x 11 x 9/24 x 16 or 25% of the time. With solar energy availability in mind, net output of a 150 MW hydrogen production plant would be only 37.5 MW worth $6,000,000 annually at 2¢ per KW-HR.

SECTION SIX. A PROPOSED COMPREHENSIVE ENERGY PROGRAM FOR AMERICA

For mankind to convert everywhere to a hydrogen economy, generating, storing and using gaseous hydrogen as its commonly used fuel requires considerable rethinking and rather universal consensus if it is to happen soon and with a non-rock-the-boat economic transition from a former economy based on low cost fossil fuel which no longer exists.

Since America is largest user of energy obtained mainly by combustion of fuels, it makes sense that the conversion to a gaseous hydrogen fuel-based economy start here. If it is to be done well it is important that we in America face up to the task and adopt a comprehensive energy program toward that end. As of now America does not have such a policy.

In interest of helping obtain a national consensus on what we should do to assure ourselves and our successors complete success in meeting future energy requirements I have assembled a brief statement of policy plus several short attachments during past year. Appropos of First World Hydrogen Energy Conference interest, following items are attached:

1. A Proposed Comprehensive Energy Program for America (3 pages)
2. Table of Contents of its Attachment Two
3. Page 3 of Attachment Two which lists some of major cost factors which favor conversion to a gaseous hydrogen fuel-based economy
4. Table of Contents of its Attachment Three
5. Page 20 of Attachment Three referencing possible use of neon refrigeration
6. Table of Contents of its Attachment Four
7. Page 8 of Attachment Four describing the four Attachments

This paper is equivalent to an Attachment Five. Attachment Six would deal with roles of government, utility systems, fuel suppliers and industry during period of transition to use of hydrogen gas as our basic fuel. Government can help by forming a publicly-owned Hydrogen Energy Corporation funded to $100,000,000. Its sole mission would be to advertise positive aspects of use of hydrogen gas as a fuel and work with industry in development of basic equipment. Government can also help by refraining from passage of punitive laws as might inhibit such a transition. By using existing utility systems and fuel suppliers to pace such a transition, it can be done painlessly as opposed to unprofitable lobbying and open warfare between new ways and old ways. Industry can help by designing, fabricating and selling billions of dollars worth of equipment instead of waiting for multi-million dollar orders from USG for studies of better ways to burn fossil fuel.

I wish to thank Donn B. Robbins, a mechanical engineer and Mario Machicao, an electrical engineer of my staff for their spare time assistance in developing some of the information presented.

Appendix A.

A PROPOSED COMPREHENSIVE ENERGY PROGRAM FOR AMERICA

1. **Preamble**: America, like many other nations, is faced with an energy crisis as of 1975 A.D. Yesterday we generated growing amounts of electrical power using cheap, abundant, fossil fuels. Today we generate immense amounts of power using expensive fossil fuels and fissionable reactor fuels which are source limited. If we buy contemporary fuels we will go broke. If we do not, American culture will have seen its day, unless we turn to a non-fossil-non-fissionable fuel. Fortunately such a fuel exists in abundance and is readily obtainable. Better yet is can be used, with minor changes, in existing equipment. Conservation of energy makes good sense above and beyond contemporary value of dollars. Most heat sources in common use today are source limited. These include natural gas, oil, coal, and fissionable nuclear fuels. Other potential fuels such as shale oil, burnable trash, wood, methane from garbage and wood alcohol are also source limited. Fission reactors including regenerative fueled breeder reactors may never be economical and will always be dangerous. Fusion reactors might solve our problems but when this will occur is unknown in terms of decades to centuries or never. Maximum use should be made of free power available from even remote waterfalls, known channels of strong winds, known channels of high oceanic tides or currents and optimum areas of strong insolation. Such programs would (1) stretch out world reserves of fossil fuels; (2) make fissionable fuels unnecessary; (3) solve our immediate energy problems for millenia, and; (4) permit diversion of technical talent toward solution, if this is possible to man, of how to obtain controlled and beneficial power from fusing atoms. Any programs to arbitrarily curtail use of energy by individuals or families should be undertaken only as a last resort and lifted at earliest opportunity. In best interest of people everywhere low cost energy should be readily available in ever increasing amounts.

2. **Fusion Reactors**: Fusion reactors as opposed to fission reactors have marvelous potential for man in his quest for ever greater amounts of power. Nuclear ashes from such plants are short-lived and nowhere near as nasty as those from fission reactor plants. In-plant accidents would be equivalent, damagewise, to explosions of boiler drums or structural failures of small dams. Unlimited power would be available through fusion reactor plants and fuel is totally plentiful. We should intensify our R and D efforts to solve this extremely vexing technical problem. If we succeed, we will have no energy source shortage and even can realistically envision practical space travel not only to other solar planets but to other stars. That we may not succeed should not deter our efforts. At least we would have tried. Inability to predict when we will succeed, if ever, to develop fusion reactor plants makes it vital that we develop alternate power systems that will allow us to exist here on earth as we want to.

3. **Kelp Technology**: About 3/4 of earth surface is ocean. Remaining 1/4 consists of 6 continents, 1 subcontinent, two dozen large islands and innumerable smaller islands, cays and reefs. Extent of littoral in sufficiently warm areas is enormous. If buoy-supported lattices are placed in shallow coastal waters, seeded kelp will grow and cling to these horizontal frames. Where there is kelp there can be fish, seals and birds. If man, everywhere, places such frames in shallow oceanic waters, even at great distances from shores, then a plethora of balanced (plant and animal) ecological subsystems will be result. Kelp can be converted into edible food in part as is true of all genera of animal life. Artificially initiated kelp beds can vanquish hunger, an ancient enemy of mankind. Kelp is buoyed toward surface by rounded pockets which contain methane. Methane can be used to fuel most internal combustion engines and fossil-fuel fired heaters. Vigorous prosecution of Kelp technology might ultimately solve our gastronomic and energy needs. In the meantime we need a readily obtainable, non-fossil-non-fissionable fuel which, with minor adjustments to carburetors or burners, can be used in existing equipment. It must, for economy, be obtained using free fuel, exist in abundance, be readily transportable and be about as safe to use as natural gas, methane or gasoline. Obtaining such a fuel should require very little in way of research and development so that it can be brought to market within 2 or 3 years. Fortunately, such a fuel exists. It is hydrogen.

4. Hydrogen Gas as an Answer: Hydrogen gas burns to water in air. It is as clean as any fuel can be. Its energy content per pound is 3 times that of petrofuels and 4 times greater than best grades of coal. While very light, it can be stored under high pressure. Except for rockets, where liquefaction of hydrogen and oxygen is justified, hydrogen as a fuel should be delivered to users as a gas. Hydrogen can be burned in any commercially available furnace, gas-fired heater, gas-fired stove, or internal-combusion engine with a minimum of alteration to carburetors. Hydrogen is extremely plentiful. There are two atoms of hydrogen in almost all molecules of water on this planet. To obtain pure hydrogen, one can liquefy air at great expense and decant 0.5 parts per million of liquid hydrogen. To obtain pure hydrogen at normal temperatures, one can disassociate acidic water using electrolytic cells and this takes exactly as much energy as will be regained when evolved hydrogen is burned later. It follows that hydrogen gas fuel plants must use free fuel to generate power needed for production of gas on an economical basis. Fortunately, free energy sources exist, upon reasonable investment, for energy conversion equipment. These include energy available from falling water, rapidly flowing water, geothermal heat, blowing winds, ocean currents and insolation. Most of these are not available on a full-time basis. River flows vary widely between wet and dry seasons. Winds can blow from any direction with widely varying force. Sunshine is at best a less than 50% proposition. Another even more vague possibility is use of remote area agricultural chaff or wood alcohol as fuel for generating power to produce hydrogen gas. Beauty of these answers is that any part-time, free fuel process for hydrogen gas production produces a clean fuel which can be used any time later, anywhere, and for any existent fuel burning purpose except riddance of burnable trash. It is more efficient and less expensive to transmit power as gaseous fuel through underground pipes than as electricity using overhead transmission lines. Widespread use of hydrogen-gas-producing plants eliminates any need for storing large blocs of electrical power which would be very expensive and may be impractical. In many cases it might be economical to fire hydrogen gas in existing steam electric plant furnaces, particularly for shaving peak loads of public power utilities and large manufacturing plants. Hydrogen plant dc generators can be unitized and have no electrical switchgear to lower investment. An unusual feature of such plants is that dc generator rotors can rotate at any speed with wide ranges of output voltage and dc current. As long as there is current, hydrogen gas will evolve at cathodes. This is decidedly not true of conventional plants which generate electrical power and must operate at synchronous speeds or not at all. Hydrogen compressors should be gas-fired engine-driven to be fully operable at all times. Hydrogen plants should be fully automated with routine annual visits for maintenance. Hydrogen would reach market by pipelines or in barges.

5. Where can Government Help? Most of costs of conversion to a hydrogen gas fuel-based economy can and should be borne by utility companies and private oil companies. Costs of new hydrogen plants will be easily offset by not building fission plants and not importing foreign petrofuels. Car manufacturers can amortize costs of design changes over five years and existing vehicles can continue to be used by changing carburetors. Certain contemporary uses of fossil fuels, under present circumstances, are now against good public policy. These include heating swimming pools using natural gas-fired heaters, heating buildings and cooking food using natural gas, coal or electricity, air conditioning of buildings and vehicles using motor-driven refrigerant compressors, electric battery-driven cars and use of oil mixed into gasoline in 2-cycle internal combustion engines to drive motorcycles, power mowers and outboard motorboats. Public laws should be initiated to ban or discourage such use and to encourage their replacement with solar heating systems, hydrogen gas-fired or engine exhaust waste-heat-recovery-fired ammonia-solution absorption-type air conditioning units and hydrogen gas-fired, 4-cycle internal combustion drives for small mobile power plants. Suggested replacements are all more efficient, quieter and free of noxious emissions. A five-year transition period is suggested as coequal with average life expectancy of such equipment.

6. Fission Reactors: America has spent enormous sums on various atomic programs relating to obtaining fissionable material and its use for peace as well as war. We have produced reliable A bombs and can use them to trigger H bombs. We have produced reliable power systems for U-boats armed with H-bomb-laden rockets which preserve such international peace as exists on this planet. Through MIRV we can potentially deliver more H bombs than there are rockets to carry them. We canceled a program to power planes using reactor plants as unnecessary, very expensive, and downright dangerous. We have built numerous fission reactor plants for producing electric power but have not developed plans for safe disposal of nuclear ashes developed by such plants. These plants cannot be justified because they are very expensive, nuclear fuel is rarer than coal, oil or gas, they operate about 75% of time as opposed to 98% on-line record of conventional power plants and their spent fuel elements are a terrible threat should these escape containment. Breeder reactors make more sense but not enough sense. While nuclear fuel could be regenerated again and again, cost per plant is much greater, on-line time will be no better and chances of accidental escape of nuclear wastes are increased. Fission reactors should be shut down systematically at earliest possible date as other, safer and more practical methods of power generation come into use.

7. Implications: Best bet for man, in absence of fusion reactor power plants, to progress with ever increasing amounts of power is to make immediate, full use of all part-time, remote, free fuels to produce hydrogen gas which can be used anywhere, any time for any productive, clean, fuel burning purpose. Readers of deep understanding will recognize that the Hydrogen Age is under way. The conversion of America to a hydrogen-fuel-based economy will be complete when many large fossil-fuel-fired electrical generating plants have been put on standby status and all fissionable fueled non-military reactors have been mothballed. Ultimately people or groups requiring power will obtain hydrogen (or methane produced from kelp) through underground piping or from storage tanks and will own their own low capacity, mass-produced, low cost, low voltage ac or dc generators driven by gas-fired engines. Whatever applies in America will also apply in any other nation on earth, including OPEC countries. Until kelp technology is fully developed, fossil fuels will be used for production of plastics which all of us find to be of utmost convenience in so many ways. Humanity will find its Hydrogen Age to be a very exciting time.

Above was completed by Frederick F. Hall (031-12-3148) on June 3, 1975 working from notes prepared in April and May. Mr. Hall lives at 2452 Villanueva Way, Mountain View, California 94040. His home telephone number is (415) 961-4064, and his business telephone number is (415) 854-3300 extension 2524. He is Manager of Plant Engineering at the Stanford Linear Accelerator Center (SLAC), which has given its permission for him to publish independently. Mr. Hall is grateful to Dr. R. B. Neal, Associate Director of SLAC Technical Division for his encouragement. Mr. Hall is solely responsible for content and a copy of his updated resume is attached. Mr. Hall has prepared more detailed rationales for a number of points made, and these comprise Attachment Two dated 061575. Mr. Hall is also preparing calculations, estimates, performance specifications for equipment and a bibliography, and will forward same to addressees shortly as Attachment Three.

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9. Can hydrogen plants compete?

Answer is decidedly yes and rationale is as follows:

(a) Hydrogen plant location need not be close to load centers as is true of electrical power plants.

(b) Hydrogen plants can be located to take advantage of even remote, part-time available, free fuels such as falling water, running rivers, blowing winds, oceanic tides, ocean currents, geothermal heat and solar heat.

(c) Hydrogen plant dc generators can turn at any speed with widely variable output voltages and currents, which is decidedly not true of conventional electrical power plants where generators must turn at close to synchronous speeds or not at all.

(d) Hydrogen plants do not require expensive high voltage switchgear, and step-up transformers as is true of conventional electrical power stations.

(e) It is more efficient and less expensive to transmit power as gaseous fuel through underground pipes than as electricity using high tension overhead transmission lines.

(f) Existing natural gas pipe transmission lines can also be used for transmitting hydrogen and this is also true of local gas utility piped distribution systems.

(g) Hydrogen gas with minimum changes to carburetors and burner tips can be fired in any existing furnace, heater, gas turbine or internal combustion engine.

(h) Hydrogen plants can be completely automated and run unattended which is not true of fission reactor electric or other conventional electric power plants.

(i) Hydrogen plants can be easily financed by private or public utility companies and private oil companies out of immense saving that will accrue by not building fission reactor electric plants and not importing foreign oil for fuel-burning purposes.

(j) Paragraph 9.0 is by no means intended to exhaust all factors wherein a <u>hydrogen gas fuel-based economy</u> makes much more sense than present system which depended on low cost crude oil for its stability.

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(15) Cryogenic Systems by Randall Barron
(16) Stanford Linear Accelerator Center (SLAC) Technical Note 73-14 Cryogenic Refrigeration Using Neon as Refrigerator by Fred Hall
(17) Uniform Building Code, 1973 Edition
(18) Marks' Mechanical Engineers' Handbook, 6th Edition
(19) Thermal Environmental Engineering by J. L. Trelkeld
(20) Calculations by the author
(21) Marks' Mechanical Engineers' Handbook, 4th Edition

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12. Subsequent Attachments

America needs a comprehensive energy policy. Such a policy is described hereinbefore. This spelled-out, proposed, energy policy for America has much to recommend it. By itself, in light of our hectic, crisis-to-crisis, daily existence it occurred that more information would be needed to convince a majority of Americans that this is the way to go, at this time in order to easily, quickly and inexpensively cross the gap between what-we-did-which-made-economical-sense-yesterday and what will become our next stage, if any, beyond our Hydrogen Age. Accordingly the basic proposed policy had two attachments. First attachment was the author's resume merely to indicate that material presented had been subjected to engineering review. Second attachment presented supporting arguments and promised a third attachment. Third attachment offered sample calculations specifications and a bibliography, but did not refer to an Attachment Four. Attachment Four covers some new ground and expands on some material presented in Attachments Two and Three. A fifth attachment is in preparation and will deal largely with hydrogen gas production using the electrolysis of water method. A sixth attachment, just started will expand on division of tasks foreseen for government, utility systems, fuel suppliers and industry during period of transition to use of hydrogen gas as our basic fuel.

13. Hydrogen Gas Additives

Illuminating gas when widely used in homes for heating, cooking and lighting had a distinct odor which helped detect leaks. When it was supplanted by natural gas utility systems had to add an odor for this purpose because natural gas is normally odorless. Pure hydrogen gas is odorless and so an odor additive will be needed. Hydrogen gas flames in the air have very low emissivity and can be hard to see. A second additive to make flames clearly visible will be desirable in many services particularly as used in homes.