

HYDROGEN-ELECTRIC POWER DRIVES

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ABSTRACT

Hydrogen-electric power drives would consist of most or all of these: chilled hydrogen gas tank, liquid oxygen tank, a bank of fuel cells, dc/ac inverter, ac drive motors, solid state ac speed control, dc sputter-ion vacuum pumps, steam turbine generator set and steam condenser. Each component is described. Optional uses of low pressure extraction steam and warm condensate are listed. Power drive applications are listed. Impact on public utilities, fuel suppliers and users is discussed.

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## Introduction

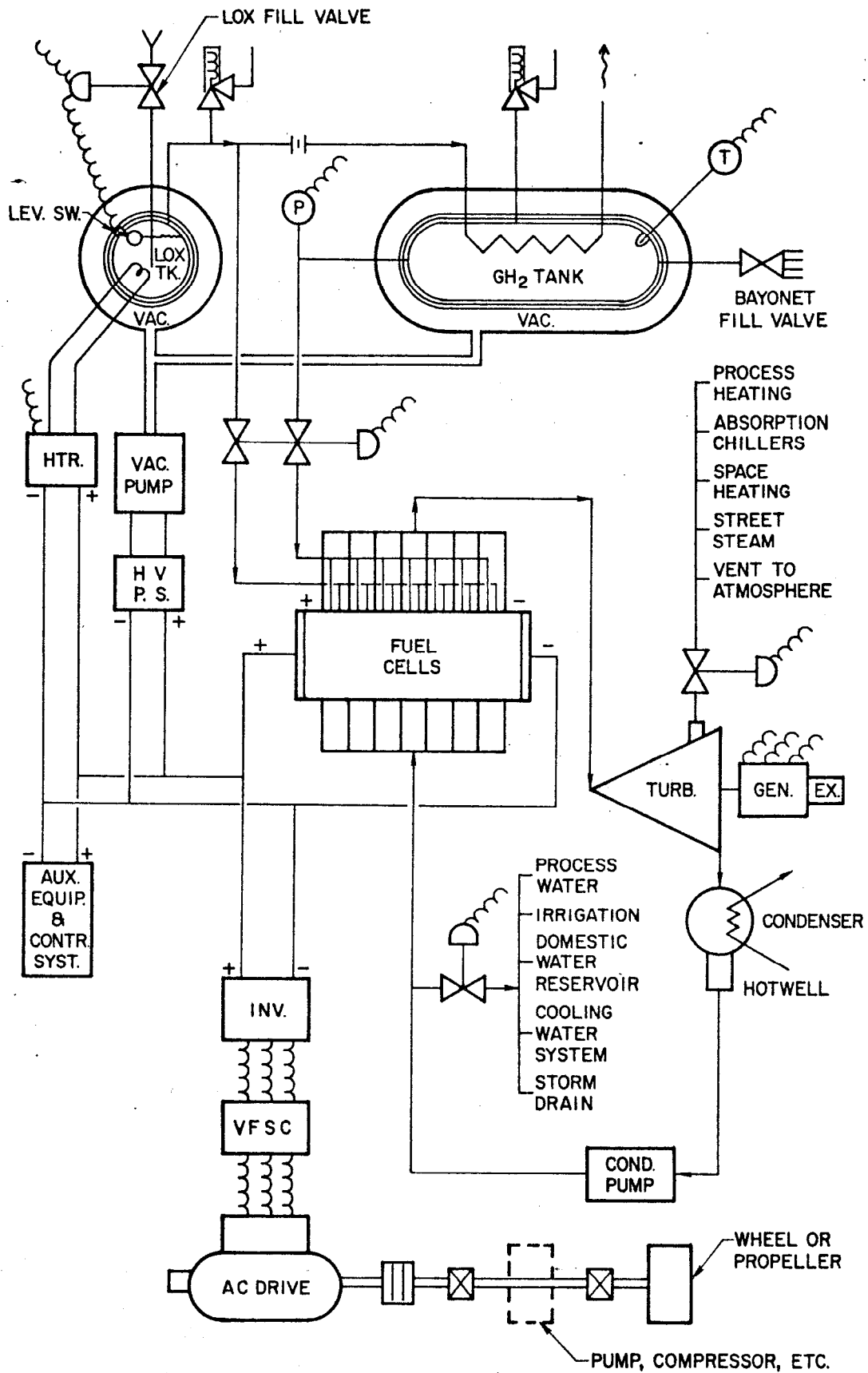
Hydrogen-electric power drives would consist of most or all of the following:

1. Chilled hydrogen gas tank
2. Liquid oxygen tank (LOX)
3. Hydrogen-oxygen-fired fuel cells
4. dc/ac solid state inverter
5. ac motors for driving wheels, propellers or rotors
6. Solid state variable frequency ac motor speed controls
7. dc sputter-ion vacuum pump to evacuate thermal insulating jackets of chilled hydrogen and LOX tanks
8. Steam turbine-generators using fuel-cell exhaust steam

Figure 1 shows the overall schematic. Control lines are not shown.

Figure 2 shows typical design details for fuel cells that can be operated at elevated pressures and temperatures.

Bulk storage of fuel for a bank of fuel cells can be adequately provided by storing oxygen as a liquid (LOX) and using its boil-off to chill hydrogen stored as a gas. The hydrogen and LOX tanks can be isolated thermally using evacuated tank jackets. Fuel cells designed to fire only electrolytically pure hydrogen and oxygen should be simple and low cost. If these are designed to operate at elevated pressures and temperatures the leaving steam can be used to power a condensing steam turbine generator set. A portion of the condensate can be used to cool the fuel cell electrolyte. Excess low pressure extraction steam and/or warm condensate equal in mass flow to the oxygen and hydrogen consumed in the fuel cells, can be used to further improve the overall thermal efficiency of the power drives.



**FIGURE 1**

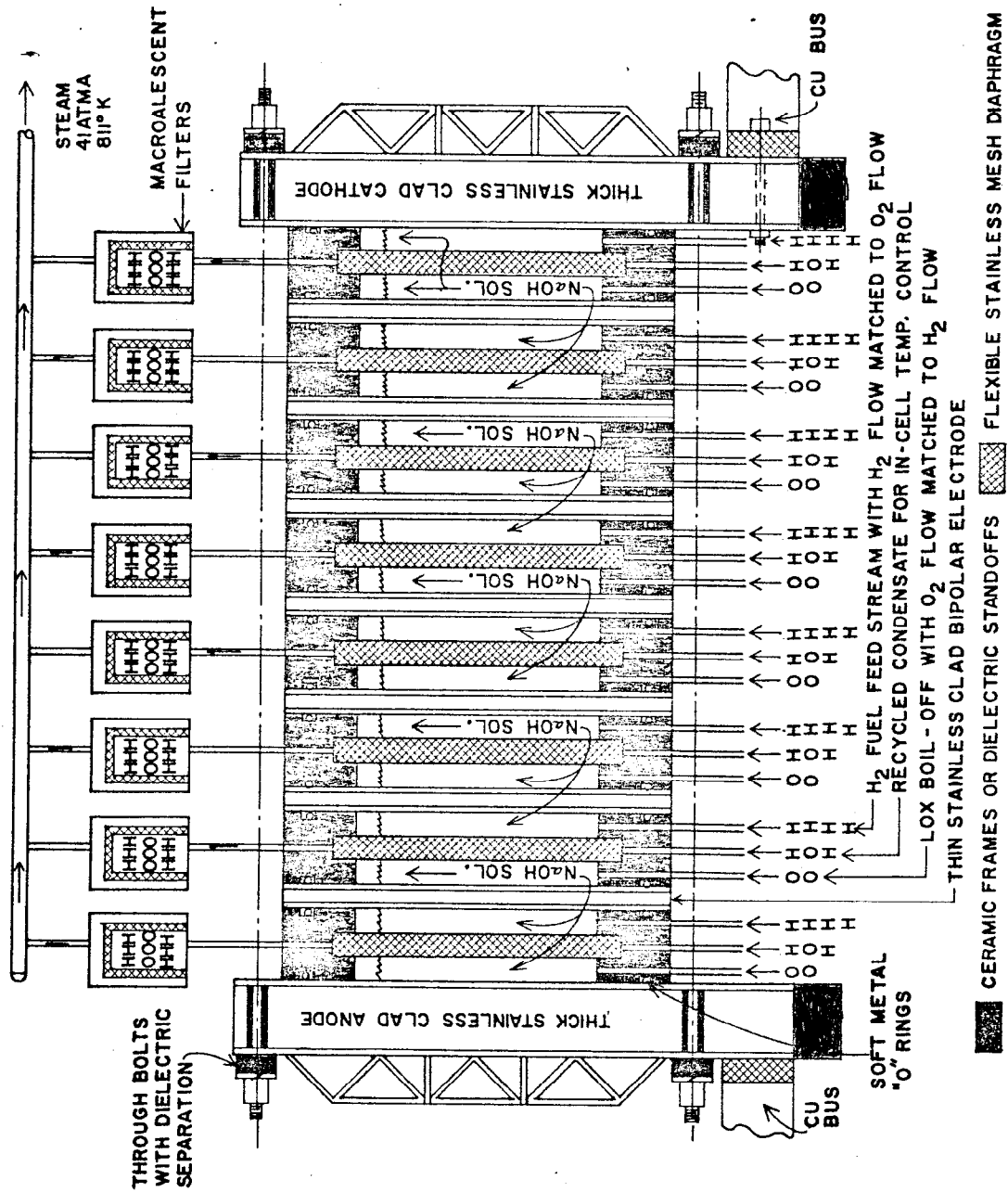


FIGURE 2

## Components and Subsystems

### 1. Chilled Hydrogen Gas Tank

The specific weight of hydrogen contained as gas in a tank can be increased at any pressure by a factor of three if the gas tank is chilled using LOX boil-off as coolant. This is important for mobile equipment such as trains, buses, trucks, cars, boats, ships or aircraft. Thermal insulation of the tank is provided by a hard vacuum jacket, and multilayered wraps of super insulation can be added to further reduce heat gain from ambient. Tank construction should allow for a 3 to 1 increase in pressure, obviating need for venting except in emergency.

### 2. Liquid Oxygen Tank

The specific volume of oxygen contained as liquid in a tank can be increased at any pressure by a factor of over 250 as opposed to storing it as a gas. This also permits the reduction of hydrogen gas tank volumes, as mentioned above, both of which are important in mobile equipment. Thermal insulation of the LOX tank is provided by a hard vacuum jacket, and multilayered wraps of superinsulation can be added to further reduce heat gain from ambient. Tank construction should allow for a pressure increase to 125 atma (atmospheres absolute) prior to venting, to permit reasonable lapses between use of power-driven vehicles or equipment, and yet avoid rupture in an emergency.

### 3. Hydrogen-Oxygen-Fired Fuel Cells

Chilled hydrogen gas and LOX together are worth more than hydrogen gas alone or any commonly used combustible liquid or gaseous fuel. This is because by using fuel-cells and other hydrogen-age equipment the thermal efficiency of power drives can be higher by factors of 2, 3 or 4. Fuel cells designed to fire only electrolytically pure oxygen should be the most efficient and least costly. Since output volts must be constant by definition, current would be controlled by load feedback to a combined regulator for the admittance of hydrogen and oxygen as gases. Fuel cells designed to operate at up to 70 atma and at up to 800<sup>o</sup>K can

discharge steam suitable for use in modern steam turbines.

#### 4. Direct Current to Alternating Current Inverters

These are of the solid-state, very efficient type which are commercially available, and can be modified as necessary to fit almost any conceivable configuration imposed by the intended mobile or stationary end-use.

#### 5. Alternating Current Drive Motors

The use of ac drive motors is easily justified by the obviation of brush assemblies. Direct current equipment is severely limited as to size, which is not so for alternators. Also dc/ac inverters as described above are compact units sold at reasonably low cost. Alternators can be built right into the hub of driven wheels or propellers in many cases, and the use of two bearings will apply to all other cases. The arrangement is most practical and will be discussed next.

#### 6. Driven Alternator Speed Control

These are the solid-state, very efficient, variable frequency type. In the past most schemes for variable speed drives suffered from a narrow control range and a tendency to reject as much heat as was not used at the lower speeds requiring extensive cooling systems. The use of solid-state ac motor variable speed control has turned this around so that modulated speed control range is at a maximum, and necessity for heat rejection is at a minimum. This fact makes hydrogen-electric power drives all the more attractive.

#### 7. Direct Current Sputter-Ion Vacuum Pumps

The vacuum jackets of the hydrogen gas tank and the LOX tank must be evacuated to a hard vacuum to sharply curtail heat gain from ambient. The sputter-ion type is used because it has a unique advantage over the other types. At a lower jacket pressure these vacuum pumps draw less power. In sterile evacuation as is under consideration, these pumps bottom out at close to  $10^{-8}$  Torr. Such vacuum systems need auxiliary

pumping to about  $10^{-5}$  Torr to prevent pump burnout and permit use of subsized power supplies. Rough pumping using LOX cooled absorbers will accomplish this.

#### 8. Steam Turbine-Generators Using Fuel Cell Exhaust Steam

If fuel cells have 0.0% efficiency, all heat released by  $O_2 + 2H_2$  reactions will go into the electrolyte and none of it leaves as electricity. If fuel cells have 100.0% efficiency, all heat will leave as electricity and no heating of the electrolyte occurs. A practical design will combine fuel cells with steam-turbine generators using the aphodid cycle but not requiring an aphodid burner. The recycled portion of the turbine mass flow would be introduced into the fuel cell electrolyte to provide intimate cooling to tolerable temperature levels. Fuel cell design would permit exhaust steam to be at sufficiently high temperature and pressure as is used in modern steam turbines. There is no need for regenerative feedwater heating. The mass flow of hydrogen and oxygen fed into the fuel cells must be continuously removed from the system, either as low pressure steam, or as warm condensate, or both. Table 1 lists the approximate parameters.

#### Optional Uses of Low Pressure Extraction Steam

As noted it is necessary to condense total steam exhausting from turbines to achieve maximum electrical output for a given hydrogen-electric power drive. Condensers will be cooled using ambient air, cooling tower water, river water or seawater. This arrangement allows warm condensate removed from the system to be reused as process water, for irrigation, domestic water reservoir makeup, in cooling water ponds or to be rejected to storm drains. Alternately, low pressure steam at 6 atma pressure could be extracted for use in process heating, absorption type water chillers, space heaters, for resale as street steam or vented to the atmosphere. The disposal of steam/condensate mass flow equal to fuel cell hydrogen/oxygen input will be based on the economics of each application. Figure 2 shows the overall block diagram of end use.

Table 1

Fuel Cell Efficiency Percent	Fuel Cell Output kW	Theoretical Steam Enthalpy W/g	Actual Steam Enthalpy W/g	Aphodid Cycle Flow kg/Hr	Total Steam Flow kg/Hr	Total Condensing Output kW	Condensing Mode Output kW	Condensing Mode Efficiency Percent	Extracting Mode Output kW	Extracting Mode Efficiency Percent
0	0	3.94	1.12	25,637	35,637	13,102	13,102	33	9,426	24
10	3,941	3.55	1.12	22,091	32,091	11,798	15,739	40	12,063	31
20	7,882	3.15	1.12	18,454	28,454	10,461	18,343	47	14,667	37
30	11,823	2.76	1.12	14,909	24,909	9,158	20,981	53	17,305	44
40	15,764	2.36	1.12	11,274	21,274	7,821	23,585	60	19,909	51
50	19,705	1.97	1.12	7,728	17,728	6,518	26,223	67	22,547	57
60	23,646	1.57	1.12	4,091	14,091	5,181	28,827	73	25,151	64
70	27,587	1.18	1.12	546	10,546	3,877	31,464	80	27,788	71
80	31,528	0.79	0.79	0	10,000	0	31,528	80	0	80
90	35,469	0.39	0.39	0	10,000	0	35,469	90	0	90
100	39,410	0.00	0.00	0	10,000	0	39,410	100	0	100

Notes:

1. Fuel Cell Output is based on 1,000 Kg/Hr., H<sub>2</sub> feed gas & 9,000 Kg/Hr O<sub>2</sub> feed gas.
2. Actual steam enthalpy is based on 41 atma, 811°K which requires aphodid cycle flow to cool fuel cells at low and intermediate fuel cell efficiencies.
3. Total steam flow is equal to 10,000 Kg/Hr from fuel cells plus aphodid cycle flow.
4. Condensing mode output is based on no extraction of low pressure steam.
5. Extracting mode output is based on 10,000 Kg/Hr extraction of low pressure steam.
6. Steam-turbine-generator engine & electrical efficiency is taken as 75%.
7. Tabulated efficiencies are thermal efficiencies.
8. For small plants or many mobile plants a turbine-generator set would not be justified and electrical generation efficiency would be that of fuel cells.
9. To the extent that extracted low pressure steam or warm condensate is reused the value of the H<sub>2</sub> and O<sub>2</sub> feed streams is increased and overall thermal efficiency is increased toward the limit of 100%.
10. Steam rates used are 2.72 g/W-hr condensing and 5.44 g/W-hr non-condensing
11. At fuel cell thermal efficiencies of 80% or above effluent would be water.



## If LOX Helps Reduce Bulk Storage, Why not LH<sub>2</sub>?

LH<sub>2</sub> is used in rocketry. It might be justified in very high performance military aircraft. Its use in commercially owned vehicles, ships or planes which visit urban centers is not only unjustified, but unnecessary. The LOX cooled H<sub>2</sub> gas, as discussed in (1) above, insures that cars, for instance, would not need to be refueled more often than at the present time. For trains, trucks or buses, commercial shipping or airlines, the use of neon refrigerators would allow a 9 to 1 reduction in H<sub>2</sub> gas volume at any pressure which, in turn, insures that any leaked H<sub>2</sub> gas is bouyant in ambient air and will safely rise away. This is not true of leaked LH<sub>2</sub> which boils vigorously into gas within the detonate-and-burn range which requires only 1/10 joule of energy for ignition. It is not possible to vent an explosion properly, and accidents in urban areas could be catastrophic.

### Hydrogen-Electric Power Drive Applications

These include:

1. Cars, trucks and buses
2. Train locomotives
3. Helicopters and other propeller driven aircraft
4. Boats, hydro-foils and ships
5. Public utility power plants
6. Industrial plants using rotating machinery
7. Scientific laboratories using dc power
8. Military tanks and mobile cannon
9. Submarines and undersea laboratories
10. Remote power consuming centers

The immediate advantage in using hydrogen-electric power drives would be to double the thermal efficiency of stationary power plants and to triple or quadruple the thermal efficiency of many mobile power plants.

### Impact on Public Utilities, Fuel Supplies and Users

These should be minimal. There is the primary cost of free energy source power plants to produce chilled hydrogen gas and LOX, but this will be offset by not building obsolete nuclear power plants or

buying at increasing cost the dwindling supplies of coal and petroleum fuels. The inefficiencies of energy production at the front end is offset by the use of replenishable free energy sources so that  $H_2$  and  $O_2$  gases can be sold competitively with respect to nuclear or fossil fuels. Public utilities hold franchises and will benefit from the lower capital costs of hydrogen-electric driven power plants as nuclear and fossil fuels continue to become more expensive. Fuel suppliers have the necessary tanker and pipe line capability to bring chilled hydrogen gas and LOX to major power consuming centers as they presently are doing with nuclear and fossil fuels. There would appear to be no justification for trying to replace these experienced suppliers of fuel. Our entrance into our Hydrogen Age should count heavily on their continuance using as much as possible of the extant piping and equipment. Users should find the gradual conversion to a hydrogen fuel based economy exciting. The choice between owning or leasing hydrogen-electric power drives will be a continuing exercise to good minds at any and every level of load. Small  $H_2/O_2$  fuel at less than laboratory proven efficiency or large units augmented by aphodid cycle turbine-generator sets with reuse of exhaust steam or warm condensate can result in power plants of the highest of attainable thermal efficiency.

#### Hydrogen-electric cars

Passenger cars could be constructed using wrap around chilled  $H_2$  tanks to also serve as impenetrable bumpers and running boards with tanks dash-pot mounted to protect passengers against serious injuries during an accident. Power-drive equipments are compact and can be arranged in a very low head room compartment located under passenger compartment floor which will place centers of gravity very close to road beds and make such vehicles almost impossible to tip over. Hydrogen-electric cars would be very quiet, very fast, very safe and highly efficient. H-E cars would require fan cooled condensers and condensate recirculating pumps to prevent unusably high operating temperatures within the fuel cells much as in present day vehicles.