

Design for the cold start-up of a man-portable fuel cell and hydrogen storage system

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Abstract

The feasibility of developing a man-portable power supply having a maximum power of 500 W, a stored-energy capacity of 2000 W h and operating in environmental temperature conditions ranging from -40 to $+40$ °C is explored. The design is based on combining an alkaline fuel cell stack and a hydrogen storage system that uses a chemical hydride. Two chemical hydrides, namely calcium hydride and lithium aluminum hydride are examined as possible storage media. The results indicate that the latter hydride would be some 25% lighter than the calcium hydride system, that the combined fuel cell and hydride system could be readily started and would function satisfactorily in an environment of -40 °C. The power supply, based on the lithium aluminum hydride storage medium, would satisfy the required power specifications; the man-portable system would weigh approximately 3.4 kg with a volume of 13.2 l.

Introduction

An exploratory investigation into the systems development of a new type of portable power supply is described. The basic components of the proposed device are the alkaline fuel cell stack and a hydrogen (H_2) storage system in which the H_2 is stored in the granular form of a chemical hydride. The packaging of these components, schematically represented in Fig. 1, is to provide a man-portable power supply capable of cold start-up in an environment of -40 °C. The nominal requirements for the power supply considered in this investigation are summarized in Table 1. These requirements are unique and the design is dependent upon the particular operating characteristics of the alkaline fuel cell combined with the specific H_2 storage system. References 1–3 provide a broader insight into the global trends of fuel cell development and their respective areas of potential commercialization in the future. Certainly, the man-portable power supply design presented could begin to address numerous commercial opportunities with this technology.

The two classic *problems* of H_2 technologies have been the development of an *economical high performance fuel cell stack* and a *H_2 storage system* that are both lightweight and economical and could be integrated with the fuel cell to supply H_2 as required by the fuel cell stack. The alkaline fuel cell is known to be capable of high performance. To overcome the other difficulties, the proposed system takes advantage of a unique property of the alkaline (or more exactly, of a basic) electrolyte fuel cell, namely that water is produced at the hydrogen electrode or anode of this fuel cell type. This allows the H_2 supplied to the anodes of this fuel cell stack to

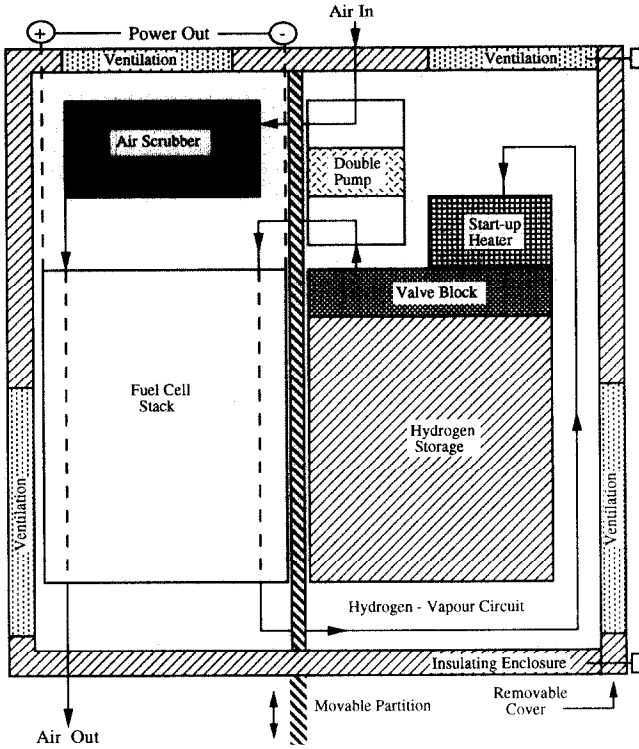


Fig. 1. Schematic of power supply.

TABLE 1

Specifications for the power supply

Maximum power (W)	500
Stored energy (W h)	2000
Discharge period (h)	24
Operating temperature (°C)	-40 to +40
Desired weight (kg)	4.6
Recharge	mechanical
Operating cost	low

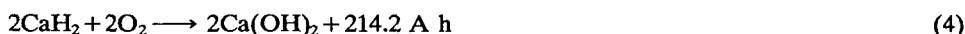
enter dry and to exit moist, having picked-up some of the water produced in the fuel cell stack. As illustrated in Fig. 1, the moist H_2 (H_2 /vapor circuit) flows to the hydride storage system and reacts to produce more H_2 . The design of the H_2 storage system is such that all of the moisture picked-up in the passage of the H_2 stream through the fuel cell stack reacts with the chemical hydride to produce H_2 . The H_2 stream is pumped through the fuel cell stack whatever number of times are required to remove the water produced by the fuel cell stack so that the system operates in a steady state. That such a system can operate in a steady state can be seen by considering the reaction mechanisms of the alkaline fuel cell stack and the H_2 storage system. At the anode of an alkaline fuel cell stack:



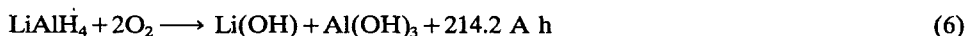
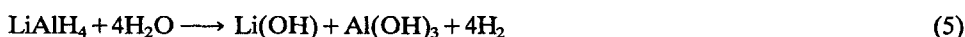
and, at the cathode:



The reaction in the H_2 storage system depends on the particular chemical hydride used. In this investigation two hydrides, namely calcium hydride (CaH_2) and lithium aluminum hydride (LiAlH_4) are considered. Their respective reactions within the storage system as well as the net reaction for the combined fuel cell stack and H_2 storage system for each of two hydrides are given by eqns. (3)–(6). For calcium hydride:



and, for lithium aluminum hydride:



It should be noted for both storage mediums, that the water produced within the fuel cell stack is entirely consumed within the hydride storage system so that no water leaves the system. This is particularly important for the system under consideration because the design specifications requires it to operate in an environment at -40°C . Furthermore, for the fuel cell stack to produce the same number of A h, two moles of CaH_2 or 84.2 g are required, as compared with one mole of LiAlH_4 or 39.9 g if the latter storage medium is adopted. Other differences between these two hydrides will be discussed in subsequent sections.

Design system components

Prototypes of each of the system components have been build and/or tested. Based on measurements made on each of these prototype systems, projections of the size and weight of the components required for the power supply can be extrapolated as a result of the modular structure of the hardware. Given that the characteristics of the individual components have been established, the design of the total system to address the required specifications can be undertaken.

The KOH fuel cell stack

Studies of different catalysts for the reduction of O_2 and the oxidation of H_2 at the catalyst interface have been conducted [4, 5]. Utilizing the Butler–Volmer equation, with the Tafel parameters recorded in Table 2 and neglecting the effects of mass-transfer polarization, it is possible to calculate the *best limits* of kinetic performance of a KOH fuel cell; if all platinum is assumed to be fully utilized, a current density of 1 A/cm^2 at a cell voltage of 0.7 V is achievable [6]. Correlation of these projected theoretical performances based on platinum usage with the measured performance characteristics of an actual cell indicates a 15% utilization of the platinum in a small prototype stack having an electrode area of 25 cm^2 . Additional comparisons with a larger, eleven-cell stack indicated a further decline in the platinum usage to but 4%; a reduction attributed to mass-transfer polarizations which were corrected by a doubling

TABLE 2

Electrolyte-electrocatalyst characteristics at 65 °C^a

6 N KOH-platinum	Exchange current (mA/cm ²)	Tafel slope (V/dec)
H ₂ oxidation	0.463	0.099
O ₂ reduction	4.440×10^{-6}	0.068

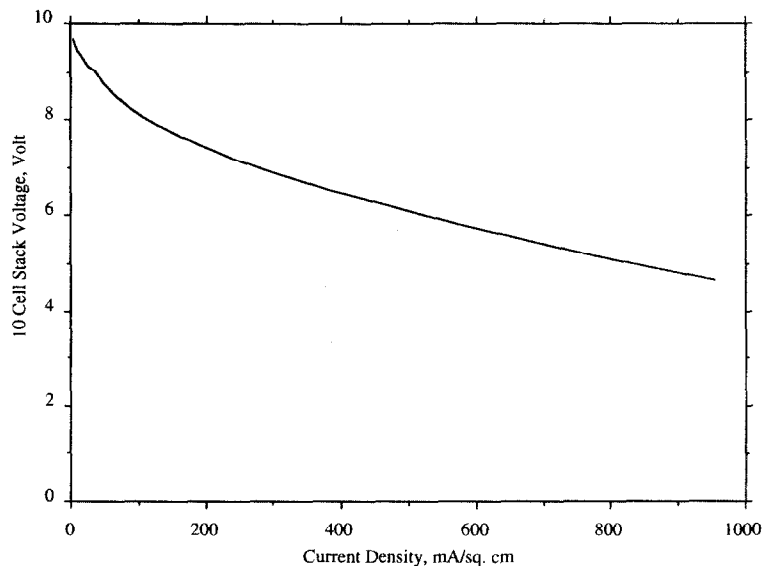
^aSee ref. 4.

Fig. 2. Predicted voltage-current relation for a ten-cell stack at 65 °C; 1 ATA; anode platinum loading: 0.72 mg/cm²; cathode platinum loading: 1.44 mg/cm²; crystallite diameter: 2.6 nm; electrode: 105 cm²; electrode separation: 2.5 mm, and area usage: 10%.

and a fivefold increase respectively in the circulation rates of the air and H₂. These adjustments improved the percentage utilization of the platinum to 10%.

From these test results [6, 7], the voltage-current characteristics and the power curve predicted for the fuel cell stack, as specified in Table 1, are presented in Figs. 2 and 3. The associated details of the stack parameters, electrocatalyst loadings, operating conditions and the weight of the itemized components which constitute the fuel cell stack are summarized in Table 3. The total weight of the proposed fuel cell stack is 1347 g.

Hydrogen storage system required

Based on the fuel cell stack details provided in Table 3, the theoretical H₂ consumption can be evaluated. From the reaction mechanisms given by eqns. (3) and (4), and (5) and (6), one mole of H₂ produces 53.55 A h, so that for the ten-cell stack producing 83.4 W at 8.16 V, the required consumption rate of H₂ is therefore estimated to be 0.7 l/min. While this is the rate at which H₂ would have to be supplied

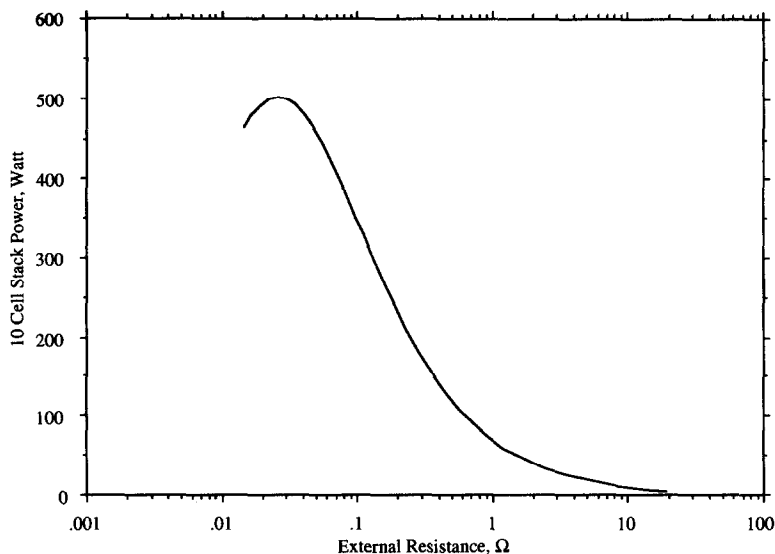


Fig. 3. Predicted ten-cell stack power performance for the characteristics identified in Fig. 2.

by the chemical hydride and consumed within the fuel cell, the circulation rate of the H_2 through the stack is required to be five times that of the theoretical consumption rate to correlate with the designed 10% platinum utilization i.e. a circulation rate of 3.5 l/min is specified.

The chemical hydrides are enclosed in a volume and incorporated within a designed membrane. Using these membranes, a gas stream containing moisture can be pumped through the enclosure so that the moisture reacts with the hydride to produce H_2 at a controlled rate.

To test the H_2 storage systems, a *fuel cell simulation* unit was used. The test system is shown schematically in Fig. 4. The *simulator* is simply intended to simulate the H_2O produced at the anodes of the KOH fuel cell stack. This was done by circulating the H_2 stream through the volume that contained both the liquid and vapor phases of H_2O . The amount of $H_2O(v)$ picked-up by the circulating stream was controlled by controlling the temperature of the water bath and the rate of circulation.

The storage systems were nominally designed to produce H_2 at a rate of $90 \text{ cm}^3/\text{min}$ and a pressure of 10 mm Hg. The results obtained with the preliminary CaH_2 storage system are presented in Fig. 5. For this hydride, the temperature bath was maintained at 60°C and the circulation rate held constant at 4 l/min. It was unnecessary to change this circulation rate because, as may be seen from Fig. 5, this storage system provided more than the nominal flow rate throughout the experimental period. Notice also that 84% of the theoretical maximum amount of H_2 was recovered before the flow rate fell below the nominal value.

Based on the results shown in Fig. 5 and the analogous results for $LiAlH_4$, a H_2 storage system for each of the hydrides was designed. The system is shown schematically in Fig. 6. It is based on the hydride being contained in two cylindrical cartridges. When the power supply is operating, the H_2 would be supplied by a single cartridge. During this period, the expended cartridge could be replaced. The valving would be such that when one cartridge was exhausted, a lever could be turned and the H_2 flow

TABLE 3
Parameters and weight of components for a 500 W alkaline fuel cell stack

Stack parameters	Operating conditions		Electrocatalyst	Weight of components	
Number of cells	10	Temperature (°C)	Anode (mg Pt/cm ²)	0.72	Electrodes (g)
Area of each electrode (cm ²)	105	Pressure of gases (atm)	Cathode (mg Pt/cm ²)	1.44	Frames (g)
Power continuous (W)	83.4		Crystallite size (nm)	2.6	Fasteners (g)
Energy supply in 24 (W h)	2002		Electrode separation (mm)	2.5	Electrolyte (g)
Volts per cell (V)	0.816		Platinum usage (%)	10	Interconnection (g)
Current density (mA/cm ²)	97.3				Total weight of fuel cell stack (g)
Total volume (cm ³)	1438				
Total surface area (cm ²)	778				

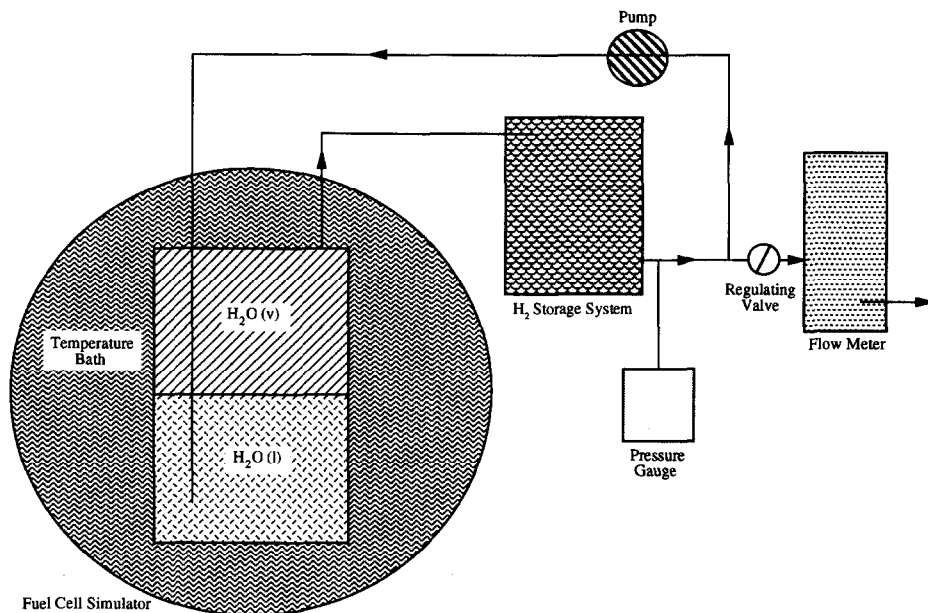


Fig. 4. Schematic of system for monitoring pressure and flow rate of H_2 produced from H_2 storage system when operated with a fuel cell simulator.

would be switched to the fresh cartridge. This arrangement would permit the power supply to be used on a continuous basis.

For purposes of comparison, the size of the cartridges used in the H_2 storage system has been held constant for the two H_2 storage media being considered. The cartridges can be constructed so that the hydride stored within has an indefinite shelf life. The quick connections would be such that minimal contamination of the system by O_2 would result from changing the cartridges. Other comparisons between the two-hydride storage systems are provided in Table 4. When CaH_2 is used as the storage medium, 12.2 hydride cartridges are required for 24 h of operation at the rated power, or in other words, a cartridge would have to be changed every 118 min. By contrast, if the H_2 storage medium is $LiAlH_4$, only 5.7 cartridges are required and the interval between the cartridge changes would be 4.2 h or 252 min. Further, the weight of the storage system, including a sufficient number of hydride storage cartridges for 24 h of operation at the rated power, is significantly less when $LiAlH_4$ is used as the storage medium. The weight of the storage system for this storage medium is estimated as 1.04 kg, whereas for CaH_2 the corresponding weight is estimated to be more than twice as large, approximately 2.2 kg.

Circulation of hydrogen and air

The required circulation rate for H_2 has already been established at five times the theoretical consumption rate, or 3.5 l/min. The O_2 for the fuel cell stack is to be drawn from air. Since the overall reaction for the fuel cell stack is:



the theoretical consumption rate for O_2 is 0.35 l/min.

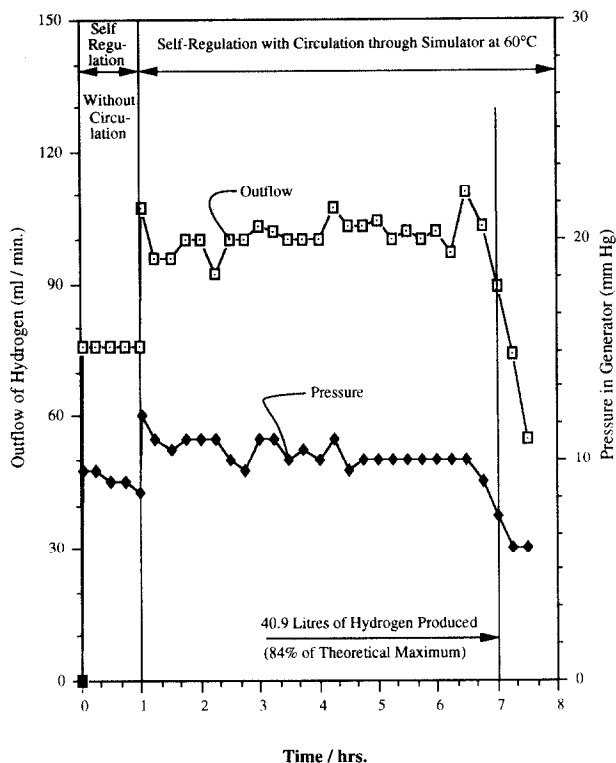


Fig. 5. Performance of present CaH_2 storage system.

It was also established in laboratory experimentation that circulating the O_2 at twice the theoretical consumption rate provided the fuel cell performance consistent with the fuel cell stack design. Thus the required O_2 circulating rate would be 0.7 l/min, and since O_2 is approximately 20% of air, the circulating rate of air would also be 3.5 l/min. The air would be drawn through a small bed of CaO granules to remove the CO_2 , estimated at a 0.03% content of air. The reaction is given by:



where 1 g of CaO can ideally remove the carbon dioxide from 800 l of air at standard temperature and pressure. This translates into 6.3 g of CaO required for each 24 h of power supply operation. Using soda lime as the absorption material which contains 27% of the active component by weight, the total weight of the scrubbing system for the power supply is estimated to be 24 g for a full 24 h operational period. The capacity of this type of scrubber to remove CO_2 has been tested and found to be very effective.

On the circulating requirements of both air and H_2 , pump characteristics have been evaluated; the power consumption for this purpose is small, and a single electrical motor driving a double pump would maintain a minimum flow rate of 3.5 l/min for both gases.

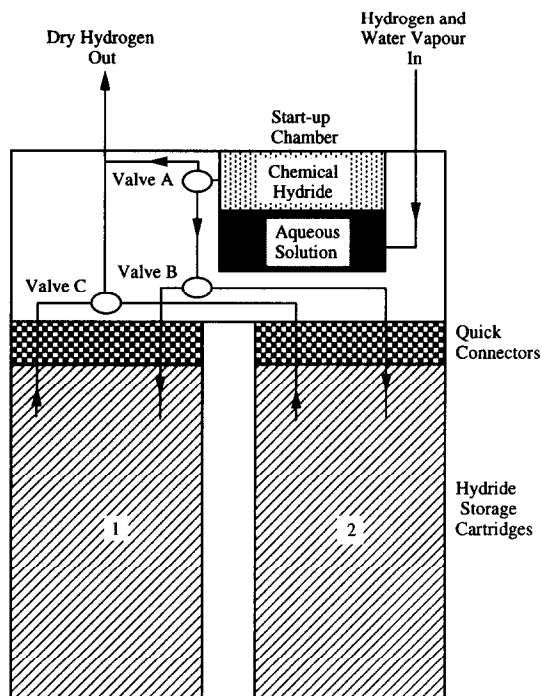


Fig. 6. Diagram of hydrogen storage and start-up system.

TABLE 4

H₂ storage system using CaH₂ or LiAlH₄ for fuel cell stack

	Using CaH ₂	Using LiAlH ₄
Stack parameters		
Fuel cell stack (W)	83.4	83.4
Energy supplied in 24 h (W h)	2002	2002
Total H ₂ supplied (l)	1008	1008
Amount of hydride (g mol)	26.2	10.3
H ₂ recovery (%)	85	98
Fuel (for 24 h) (g)	1112	390
Weight of components		
Valve block and connectors (g)	250	250
450 ml cartridge (empty) (g)	69	69
Hydride loading/cartridge (g)	91	69
Number of cartridges required for 24 h	12.2	5.7
Weight of cartridges and contents (g)	1952	787
Total weight of hydride system for 24 h operation (g)	2202	1037

Operation at normal and higher temperatures

The specifications require that the power supply operate under environmental conditions in which the temperature is as high as +40 °C. The fuel cell stack is designed such that it is intended to operate with the electrolyte encapsulated. The question that then arises is whether special cooling will be required for the stack;

however, as may be seen by the following considerations, no additional cooling is anticipated.

An environment at +40 °C is the most severe thermal condition that the system is to experience and is therefore the specific situation considered. Under steady-state conditions, the power dissipated, P_d , in the stack is given by:

$$P_d = (V_o - V)I \quad (9)$$

where V_o is the open-circuit voltage, V is the voltage produced by the stack and I is the current. For the electrodes, V is rated at approximately 1.0 V/cell. Under normal steady-state operating conditions of the stack, as outlined in Table 3, the power dissipated, P_d , approaches 18.8 W.

There are two modes for the cooling of the stack. One is the required circulation of air through the stack that would remove an amount of energy equivalent to some 17% of P_d . The second is the natural convection from the stack surface which can be shown [6, 8] to account for the balance of the P_d under steady-state conditions. While complete details are not provided, the key conditions of operation employed in the analysis are (i) the preferred steady-state operating temperature in the stack is set at 80 °C; (ii) the calculated surface temperature of the stack is 73.3 °C, and (iii) the temperature of air inside the insulating enclosure is 43.3 °C.

It has been assumed that the circulating H_2 does not alter the energy balance, so that this flow would therefore enter and exit the stack at 80 °C. In this context it should be noted that the temperature of the H_2 leaving the reaction chamber can attain a temperature of 150 °C. Through a suitable choice of flow pathway the gas would be cooled prior to entering the stack at 80 °C. Furthermore, it has been assumed that the thermal energy arising from the reaction in the H_2 storage system does not raise the temperature of the fuel cell when the power system is in an environment at 40 °C. At this condition, the insulating partition separating the fuel cell stack from the H_2 storage system would be in place and the H_2 storage system would be fully ventilated, see Fig. 1. If necessary, the outer surface of the insulating container can be removed; however, this latter measure should not be necessary.

System operation at low temperatures

The specifications for the power supply also require operating in an environment with temperatures as low as -40 °C. To provide power at this extreme condition, it is necessary either to maintain the system operational at some low rate or for the system to be started after being cooled to this temperature. The former is likely to be expensive, so that the feasibility of the latter possibility has been more fully investigated.

To this end, three principal tasks need to be performed: (i) to identify aqueous mixtures that remain liquid at -40 °C and which are also stable at 40 °C; (ii) to demonstrate that such aqueous mixtures when brought into contact with the H_2 storage medium (i.e., the chemical hydrides) at -40 °C will induce the reaction to liberate H_2 , and (iii) to demonstrate that the H_2 , once admitted to the fuel cell which itself has been cooled to -40 °C can, with the fuel cell, deliver power to an external load.

Experimentation

Apparatus

The tasks identified for the low temperature cold start-up can only be accomplished by experimental investigation; thus, it was necessary to construct the following items of specialised apparatus:

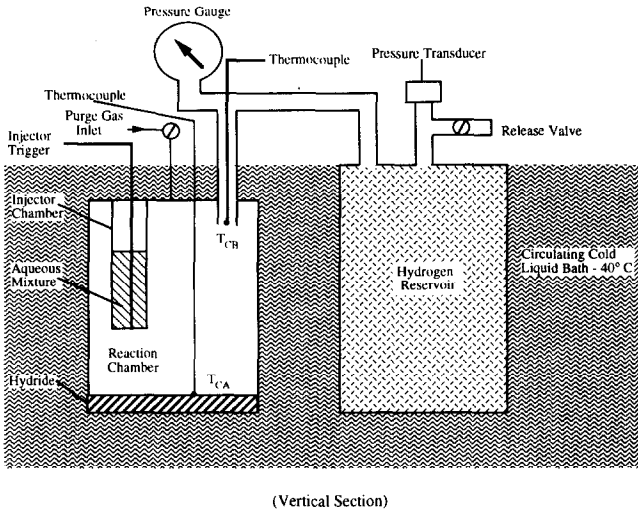


Fig. 7. Schematic of reaction chamber and hydrogen reservoir.

- (i) An environmental chamber was assembled that consisted of a liquid bath and cooling system. Objects could be immersed in the liquid bath and cooled to -40°C .
- (ii) A reaction chamber-reservoir system, schematically shown in Fig. 7, was constructed that could be totally immersed in the liquid bath of the environmental chamber. The reaction chamber was to accommodate a sample of a chemical hydride in the form of a dried powder placed on the floor of the chamber, and a sample of an aqueous liquid mixture to be held in a separate injector. Triggering the injector would permit the liquid mixture to drain from its container into direct contact with the hydride. The temperature of the reactants and the gas leaving the chamber are monitored with thermocouples T_{CA} and T_{CB} respectively. The H_2 gas leaving the reaction vessel entered the reservoir; the pressure in both the reaction chamber and the reservoir were monitored.
- (iii) A container was constructed of sufficient size to accommodate a fuel cell stack. The container was lined with polyethylene sheet and sealed with a styrofoam lid with access for the O_2 and H_2 feed lines and the leads for the electrical power produced. The entire assembly could then be immersed in the liquid bath of the environmental chamber; additional cooling of the contents of the container could also be achieved by discharging vapor from liquid N_2 onto the contents when immersed in the liquid bath. Thermocouples were also placed at relevant locations.

Experimental procedure and results

To assess whether the KOH electrolyte and other aqueous mixtures could be used to start the power supply, their phase at -40°C had to be determined. The aqueous mixtures are listed in Table 5; all being liquids at room conditions.

A sample of each was placed in a test tube and the test tubes immersed in the liquid bath of the environmental chamber. Their temperature was monitored as they were cooled and their phase examined visually by retracting each test tube from the bath as temperatures of -35 , -40 and -45°C , respectively, were attained. The results are summarized in Table 5; the 6.85 N KOH and the 46 vol.% H_2O mixture

TABLE 5
Results of freezing tests on mixtures

Mixture	Temperature (°C)		
	-35	-40	-45
6.85 N KOH	liquid	liquid	liquid
Ethylene glycol-water, 50-50 vol.%	liquid	white slosh nonflowing	white slosh nonflowing
Ethylene glycol-water, 54-46 vol.%	liquid	liquid	liquid (viscous)
CaCl ₂ -water, 3.84 M	white solid	white solid	white solid
AlCl ₃ -water, 2.50 M	liquid (greenish)	liquid (greenish)	liquid (viscous)

of ethylene glycol and water remained liquid, even at -45°C . Thus, these substances are candidates for the fuel cell electrolyte and for use in starting the power supply at -40°C , respectively.

Subsequently, this aqueous mixture was used to examine the reactivity at -40°C of the two hydrides, CaH_2 and LiAlH_4 utilizing the apparatus shown in Fig. 7. The aqueous mixture was enclosed in the injector chamber and a sample of the particular hydride to be examined was placed in the base of the reaction chamber. Dry N_2 was used to purge the system of any O_2 and the chamber was maintained at slightly greater than atmospheric pressure during the cooling process in order to minimize the leakage of O_2 into the system. After the reaction chamber and its contents had been cooled to -40°C the N_2 pressure was released bringing the chamber to atmospheric pressure. The injector was triggered from outside the chamber, thereby allowing an aqueous mixture to drain onto the hydride. The results obtained are summarized in Table 6; the LiAlH_4 reacted very rapidly indeed producing H_2 at a temperature of 150°C as it discharged from the reaction chamber. This means that the H_2 entering the fuel stack will already be heated and can assist in the warming-up and starting of the fuel cell stack.

To examine the characteristics of the fuel cell reactions and performance when the fuel cell is cooled to -40°C the complete system was positioned in the fuel cell container and immersed within the liquid bath of the environmental chamber. The measured open-circuit voltage of a fuel cell when utilizing the 6.85 N KOH electrolyte remained approximately constant throughout the falling temperature range, i.e., from room temperature down to -40°C . However, when power was drawn from the fuel cell at -40°C its response was considerably impaired. A curve illustrating the voltage-current characteristics of a fuel cell that had been cooled to less than -40°C before being loaded is shown in Fig. 8. This result indicates that a fuel cell that is initially cooled to -40°C should preferably be warmed to a higher temperature before being loaded. This warming process is feasible in the system under consideration because of the very rapid reactivity of certain of the chemical hydrides at these temperatures. These characteristics can beneficially be incorporated into the design of the power supply system.

TABLE 6

Comparison of experimental results of reacting CaH_2 and LiAlH_4 at -40°C with excess 54–46% mixture of ethylene glycol–water to generate hydrogen^a

Hydride	Quantity reacted (g)	Theoretical hydrogen at standard temperature and pressure (l)	Delay before reaction started (s)	Duration of initial reaction (s)	Maximum measured temperature in reaction chamber ($^\circ\text{C}$)	Maximum measured outflow gas temperature ($^\circ\text{C}$)	Time to reach 90% of initial maximum pressure (s)	% of theoretical maximum pressure after cooled to -40°C (30 min)	Volume of mixture (cm^3)
CaH_2	4.005	4.272	52	90	55	-15	42	67	18 ^a
LiAlH_4	1.815	4.286	32	~2	~200 off scale	~150	~1	96	15 ^a

^aIn the case of CaH_2 , there was 2.4 times the amount of water needed and in the case of LiAlH_4 , there was 2 times the amount of water needed.

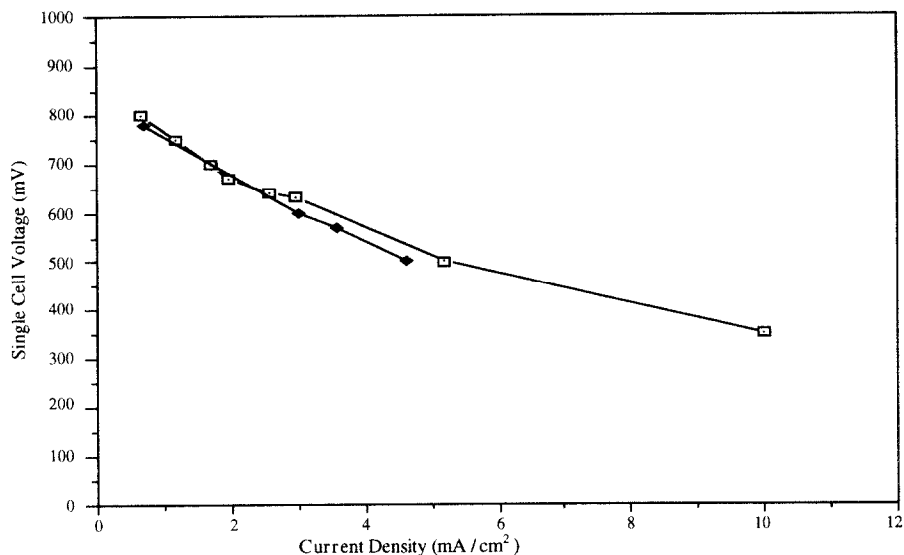


Fig. 8. KOH fuel cell performance at -40°C , repeated measurements (\blacklozenge , \square); nominal electrode area: 50 cm^2 ; catalyst loading: anode 0.72 mg/cm^2 , cathode 1.44 mg/cm^2 ; crystallite size: $2.0\text{--}2.5\text{ nm}$; pressure H_2 : 1 atm ; pressure O_2 : 1 atm , and temperature: -40.3°C .

Starting-up the power supply

It has been shown that an ethylene glycol-water (46 vol.% H_2O) remains liquid at below -40°C and that, when it is brought in contact with either CaH_2 or LiAlH_4 at -40°C , a reaction occurs that liberates H_2 . The LiAlH_4 is much more attractive than CaH_2 as a storage medium because it reacts very rapidly at -40°C and gives rise to H_2 at a temperature of 150°C . This high temperature H_2 may be of significant benefit in starting the remainder of the system because the performance of the KOH fuel cell at -40°C is considerably impaired. Probably the design of the system should be such that the fuel cell is warmed to above -40°C before it is started. However, the fact that the KOH cell does produce power at -40°C and does maintain its open-circuit voltage constant throughout the temperature range from 20 to -40°C is of importance because this power and voltage can be used to operate other system components, such as the circulation pump, during the start-up.

Thus, to start the power supply, the H_2 storage system would be constructed so that a small quantity of ethylene glycol-water solution is contained within a small canister that is held in the switching valve block (see Fig. 6). By a trigger mechanism the contents are poured onto a compartment containing the fuel. This compartment will be covered by a membrane that allows the solution to come in contact with the CaH_2 or the LiAlH_4 at a controlled rate. The hot H_2 gas released would flow through the two-way valve A to the fuel cell stack. As may be seen from Fig. 8, if the fuel cell stack were initially at -40°C when the warm H_2 gas entered, the fuel cell stack described in Table 3 would produce 2.6 W at 5 V . This voltage and power input to the pump tested could produce a H_2 flow rate of 1 l/min at a pressure of 5 mm Hg .

The fuel cell stack and the circulation pump could be operated in this manner until the system had been brought to the desired temperature. Valve A would then be operated to direct the flow of H_2 from the start-up chamber through the two-way

valve B to cartridge 1. Two-way valve C would be set so that the hydrogen flow from cartridge 1 would be directed to the fuel cell stack. When this cartridge of hydride was exhausted, two-way valve B would be switched so that the H_2 flow from the start-up chamber would be fed to cartridge 2 and the two-way valve C set so that the flow from cartridge 2 was directed to the fuel cell stack. The flow would continuously be passed through the aqueous solution of the start-up chamber; the moisture picked-up therein would allow excess H_2 to be generated so that the load on the fuel cell could be changed at will.

After the initial start-up period, the H_2 stream leaving the start-up chamber enters one of the hydride storage cartridges. Any products from the ethylene glycol-water reaction in the start-up chamber would therefore be expected to be removed during the flow of the H_2 stream through the hydride bed. Also, once the hydride storage cartridge is spent (no further H_2 generated), the cartridge is removed for recycling. This procedure would eliminate any build-up of the ethylene glycol products in the storage system. If the products from the initial start-up of the system prove to be a difficulty, a simple adsorption component can be added; this addition is however not considered to be a likely necessity.

During the start-up at low temperatures, the movable partition identified in Fig. 1 which is used to insulate the fuel cell stack from the H_2 storage system would be retracted so that the energy dissipated in the H_2 system can be used to warm the environment of the fuel cell stack.

Operation of the power supply at low temperatures

Once the power supply has been started and the H_2 storage system has been brought on-line, it will be desirable to increase and maintain the temperature within the insulating environment at the normal operating temperature of the fuel cell stack, namely $80\text{ }^\circ\text{C}$. When operating in an environment with outside temperatures as low as $-40\text{ }^\circ\text{C}$ there is a possibility of this air cooling the fuel cell to well below its normal operating condition. Design investigations have been undertaken which confirm that even when the power supply is in an environment of $-40\text{ }^\circ\text{C}$ that the system would have to be ventilated in order for it to operate at steady state. The relevant conditions for this projected result include that the insulating container be constructed of 1 cm thick polystyrene material, that the movable partition be retracted so that the heat emanating from the H_2 storage system be retained within the insulating container. The result applies to the use of either hydride: for $LiAlH_4$ the heat of reaction had to be experimentally determined and was found to be $-109 \pm 4.2\text{ kJ/mol } H_2$, which is close to the value for CaH_2 of $-113\text{ kJ/mol } H_2$ obtained from the literature [9].

Water management

As indicated previously, the electrolyte will be encapsulated and the O_2 will be drawn from circulated air. Ideally, under steady-state conditions, the water produced by the fuel cell stack exactly balances that consumed in the H_2 storage system; however some water vapor may be lost at the cathode to the circulated air. The H_2 storage system (Fig. 6) is designed to allow compensation to be made for any water lost in this fashion. As may be seen in this Fig., even after the start-up phase has been completed, the H_2 - $H_2O(v)$ returning from the fuel cell stack will continue to pass through the start-up chamber. The flow of this stream through this chamber is planned

TABLE 7

Estimate of the weight of the power supply

Fuel cell stack (see Table 3 for details) (g)	1347
Pump (3.5 l of air/min; 3.5 l of H ₂ /min) (g)	250
Air scrubber for 24 h operation (g)	24
Start-up heater (g)	150
Interconnections (g)	125
Insulated enclosure and supporting structure (g)	500
H ₂ storage system for 24 h	
CaH ₂ storage (see Table 4 for details) (g)	2202
LiAlH ₄ storage (see Table 4 for details) (g)	1037
Total weight of power supply and fuel for 24 h	
with CaH ₂ storage (kg)	4.6
with LiAlH ₄ storage (kg)	3.43

to be through the spent hydride that was consumed in the start-up. The moisture in this bed can be varied as required and thus moisture can be added to the H₂ stream as required. An estimate has been made of the water required for this purpose for 24 h of operation. This weight is included in the estimated weight of the start-up heater (see Table 7).

Weight and material cost for the proposed power supply

The estimated weight of each of the components and the total weight of power supply, including the fuel for 24 h of operation have been listed in Table 7. These calculations have been performed for two different H₂ storage mediums, CaH₂ and LiAlH₄. We note first of all that the estimated weight of the power supply using either storage medium is within the specifications. Secondly, when the H₂ storage medium is LiAlH₄, the estimated weight of the power supply is 25% less as compared with the CaH₂. This makes the comparison of the cost of the two storage mediums an important question, which is addressed below. Thirdly, the weight of the structural members have been included in the estimated weights so that if the components can each meet their projected performance, it should be possible to construct a power supply with the desired characteristics.

An analysis of the possible error in our estimation of the weights of the different components indicates that the least confidence could be placed on the maximum power calculation for a fuel cell stack since the greatest extrapolation had to be exercised in this calculation, and the calculation is sensitive to the value of the parameters. However, if the prototype of this design indicates that the system has been undersized, corrective measures could be taken by simply increasing the cross-sectional area of the electrodes. This would have little effect on the continuous operation of the system. To provide the continuous power (83.4 W), the current density would be reduced when the cross-sectional area was increased and the voltage per cell would go up. The net change in the remainder of the system would be expected to be only a few percent. In summary, we would doubt that the error in the sizing of the system could possibly exceed 25%. Thus, the proposed system could meet the weight specification if the H₂ storage medium was LiAlH₄.

An estimate of the manufacturing cost of the system can not be given at this stage of the development of the system. The cost of the materials for the system, excluding the fuel, is estimated to be 120 to US \$130, including the cost of the electrocatalyst, the current collectors, the water proofing for the electrodes, etc. The cost of the fuel for continuous operation is estimated at 2.0 to 2.5 cents/W h for either CaH_2 or LiAlH_4 , assuming they can be purchased in bulk. The LiAlH_4 is more expensive on a per gram basis, however, it contains more H_2 , it has a greater reactivity which results in a recovery of 98% of the theoretical H_2 content, as compared with approximately 85% for CaH_2 . As a result, the cost of the H_2 is approximately the same for the two storage mediums. The material cost of the scrubber for 24 h of operation is estimated to be 48 cents.

Since the LiAlH_4 gives rise as to a lighter system, has a better reactivity at -40°C and costs approximately the same as the CaH_2 , the storage medium of choice would be LiAlH_4 . The system could be assembled as indicated in Fig. 9, and with the insulating container added, the total volume of the system is estimated at 13.2 l.

In summary, after allowing for the possible error in the projections required to design the power supply to meet the maximum power specifications, the indications are that a man-portable power supply could be built to meet the specifications outlined in Table 1. Extensive evaluation of the performance of the power supply under field conditions will be required to confirm the reliable thermal management, the full operational aspects and life of components within the defined temperature range, as

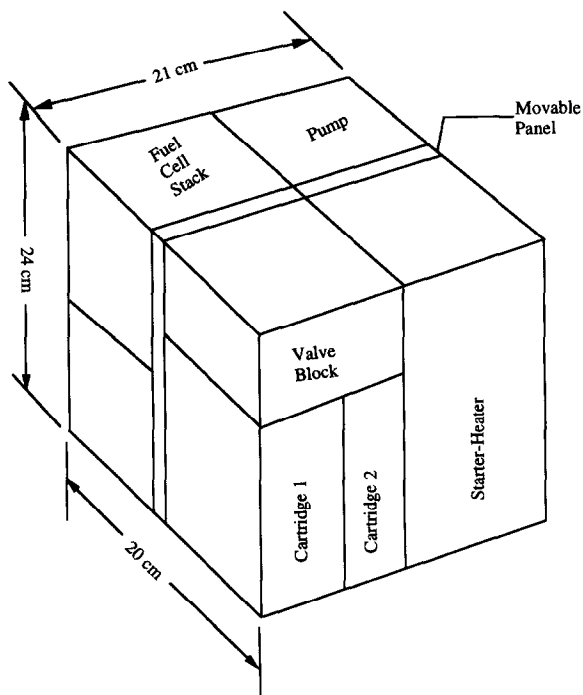


Fig. 9. Estimated overall dimensions of system. An additional insulating enclosure (~ 1 cm in thickness) will be added.

well as further optimization of the total volume. Finally, it should be emphasized that the power supply is particularly safe in that the H_2 is contained within the chemical hydride at ambient conditions and is only produced when required to be consumed within the fuel cell.

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