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APPLICATIONS OF METAL HYDRIDES*

J. J. Reilly
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

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Department of Applied Science
Brookhaven National Laboratory
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In a companion and complementary paper[1] the properties of several metal-hydrogen systems were discussed and it will be assumed that the reader is familiar with its contents. This paper will be concerned with the practical application of metal hydrides. Primary emphasis will be given to their use as energy storage media, however, certain other applications will also be noted.

Criteria

In order to serve as a practical energy or hydrogen storage medium, a metal hydride must satisfy a number of criteria. Perhaps the most important of which is that it be easily formed and decomposed. Obviously very stable hydrides (e.g., ZrH_2, TiH_2, etc.) are not suitable and we are limited to those hydrides which will decompose at relatively low temperatures ($\leq 300^{\circ}C$). A further, and also important criterion, concerns their heat of decomposition, which even in the case of unstable hydrides, is substantial. In fact if the use of metal hydrides as energy storage media is to be feasible, the heat of decomposition must be supplied from the waste heat of the converter with which it is coupled. Thus, there must be a match between the operating temperature and waste heat output of the energy converter and the pressure-temperature characteristics of the metal hydride. For example, it appears possible to use MgH_2 as a source of hydrogen fuel for an internal combustion engine, using the high temperature exhaust heat to provide most, if not all, of the heat of decomposition. However, it would not be feasible to couple it to a fuel cell that rejects heat at 150°C. A flow diagram is shown in Figure 1 which illustrates this relationship. In this case unstable iron titanium hydride is used as the hydrogen fuel storage compound. The heat of decomposition is supplied from the waste heat of the converter by circulating its coolant through a heat exchanger in contact with the metal hydride. The heat must be supplied at a rate sufficient to satisfy fuel demand of the converter. For example, if the reservoir temperature can be maintained at 25°C by the waste heat, the hydride is readily capable of delivering H_2 fuel continuously, at high flow rates and at pressures in excess of one atmosphere. If the heat supply is insufficient the latent heat of decomposition will be supplied from the sensible heat of the surroundings; the bed will progressively cool and the H_2 flow will decrease until a balance is struck between the decomposition rate and the available heat. When the bed is exhausted it can be regenerated by following the opposite procedure, i.e., it is contacted with hydrogen at a pressure substantially above the dissociation pressure, making due allowance for hysteresis and a coolant is circulated through the bed to remove the heat of reaction.

Other criteria involve cost, safety, suitable reaction rates, reversibility, weight, and chemical and physical stability. Their relative importance will depend in some degree upon the specific application. For example, in stationary storage applications weight is not a critical parameter whereas for automotive applications it is very important.

At this time there are a number of candidate metal-hydrogen systems which are of interest for practical applications. Their properties and some pertinent data are listed in Table 1.

Specific Applications

Automotive

The use of catalyzed MgH_2 as an automotive hydrogen fuel storage compound was suggested by Hoffman et al. in 1969.[2] It was proposed that the exhaust heat of the engine be used to supply the heat of decomposition. However, despite the high hydrogen content of this material, there are two serious problems which have so far hindered its development as a practical storage compound. The most severe problem is that the heat of decomposition must be supplied at a temperature of 300°C or above. This requirement would likely incur formidable engineering problems. A less serious difficulty is that the quantity of usable waste heat is not quite sufficient to entirely satisfy the heat of decomposition and would have to be supplemented by burning a portion of the stored hydrogen. On the other hand, iron titanium hydride has a dissociation pressure well in excess of one atmosphere at room temperature and a relatively low heat of decomposition. These are important advantages which, it was suggested, would offset its low hydrogen content as compared to MgH_2.[3] It is also appropriate to note in this connection that weight comparisons are relative and while $FeTiH_2$ suffers when compared to MgH_2 or gasoline, it is quite competitive with another alternative automotive power source, electric batteries, as shown in Table 2. Indeed, the virtues of iron titanium hydride have been recognized and several hydrogen powered vehicles have been built using it as the fuel storage medium. Two of these vehicles have undergone extensive testing, a Winnebago bus which was converted to hydrogen fuel by the Billings Energy Corp. of Provo, Utah, and a small van built by Daimler Benz A.G. of Suttgart (Figure 2). Extensive performance characteristics of the Winnebago vehicle has been published[4] and are summarized in Table 3. Examination of these data reveal certain deficiencies or problem areas which no doubt will be addressed in future development efforts. The maximum hydrogen content is equivalent to a composition of $FeTiH_{1.30}$ which is rather low and probably due to the use of alloy raw materials containing a large amount of oxygen which has been demonstrated to be deleterious.[5] Further, a very simple and somewhat inefficient heat exchange system is used, i.e., passing the exhaust gas over an array of 22 stainless steel hydride containers. It should be possible, with more efficient heat exchange, to increase the amount of available hydrogen substantially so that the engine does not become starved for fuel until the bed composition is equivalent to $FeTiH_{\sim 0.1}$ rather than $FeTiH_{\sim 0.5}$. Thus, if a higher quality FeTi alloy were used having a maximum hydrogen content equivalent to $FeTiH_{1.7}$ and the heat transfer capability increased, it is quite possible to project an increase in the effective storage capacity from 7.7 Kg to 15 Kg, almost a factor of two. In this connection, the published data of Büchner, et al.,[6] indicate the performance of the Daimler Benz vehicle is somewhat improved over that of the Billings bus, however, it is very difficult to make a comparison since the vehicle weight was not given.

Nevertheless, despite its promise, complete substitution of hydrogen for gasoline can only be considered as a long-term option, because of the massive investment which would be required for its production and distribution. However, there are certain short term applications where such constraints would not operate. One particularly attractive possibility would involve hydrogen powered fleet vehicles serviced by central garages. Such vehicles, because of the almost zero pollution characteristics of hydrogen fuel, would be very desirable in congested urban or industrialized areas. The Winnebago bus, a case in point, was commissioned for this very reason by the Provo, Utah, public transit system. Opportunities also exist in the area of low pollution industrial and mine vehicles. In these latter types the weight disadvantage of the hydride (vs. liquid fuel) is not significant because such vehicles usually carry a heavy ballast; in fact, many are battery powered because of the low pollution imperative. It should also be noted that it may not be necessary to burn hydrogen exclusively in order to realize very substantial environmental and fuel (hydrocarbon) economy benefits.[3]

In the United States 95% of all private automobile trips are less than 48 km (30 miles) in length[7] and these trips account for about 60% of all vehicle miles.[8] In view of these data it appears that a vehicle capable of using both hydrogen and gasoline alternately would be a desirable compromise. Such multifueled vehicles using hydrogen exclusively for trips of relatively short range, would greatly reduce the consumption of petroleum based fuels. Further, since almost all urban trips are short, the pollution due to automotive emissions would be reduced to negligible amounts in these very same areas where they are most pronounced. For the occasional trip that exceeds the range of the on-board hydrogen storage capacity, gasoline could be used, e.g., for intercity trips. Thus, a multifuel passenger automobile was proposed[3] having almost the same weight, performance and range as the present conventional gasoline powered vehicle. The hydrogen is supplied by the decomposition of iron titanium hydride. A diagram of such a vehicle is shown in Figure 3 and its pertinent characteristics are listed in Table 4 and compared with other alternatives.

Utility Load Leveling

The storage of electrical energy through the production, storage and reconversion of hydrogen is of interest as a load leveling technique for electric utilities.[9] The entire process has been demonstrated on an engineering scale by Public Service Electric & Gas Company of New Jersey (PSE&G) and a flow diagram of this system is shown in Figure 4.[3] Hydrogen is produced electrolytically, compressed from 5 to 35 atm and stored as iron titanium hydride. Subsequently, the hydride is decomposed to supply hydrogen fuel to a fuel cell. In practice hydrogen would be produced using off-peak power, stored and then reconverted to electricity to satisfy on-peak loads. The electrolyzer was built by the Teledyne Corp., Baltimore, Maryland, and the fuel cell by the Pratt & Whitney Div. of United Technology Corp., Hartford, Connecticut. The iron titanium hydride reservoir (Figure 5) was built and tested by Brookhaven National Laboratory under a cooperative program with PSE&G. The reservoir contained 400 kg of a ferrotitanium alloy and had an effective storage capacity of 6.4 kg of hydrogen. The FeTi alloy charge was obtained from the Cannon-Muskegon Corp. of Muskegon, Michigan and was supplied in batches of ∿110 kg each at a cost of $5.15/kg. Several batches were unsatisfactory because of their high oxygen content. This adversely affected the hydrogen charging capacity because of the distortion of the pressure-composition isotherm in the direction of higher pressure. In Table 5 are listed the chemical analyses of each of the four different batches actually used. It will be noted that two batches contain manganese which was added since it was found to compensate to some extent for the high oxygen content.

The storage unit was designed to operate through a complete sorption-desorption cycle once a day. In the sorption mode, heat was removed by circulating cold water ($\sim 17^\circ C$) through an internal heat exchanger; for the reverse (desorption) reaction, heat was supplied by circulating $\sim 45^\circ C$ water through the exchanger. The system has undergone about 60 full sorption-desorption cycles without difficulty.[10] Plots of several experimental parameters vs. time for the sorption and desorption half cycles are shown in Figures 6 and 7.

While the use of iron titanium hydride in such a system as described above has been proven feasible, it is also apparent that its properties are not ideal for full scale peak shaving systems. The reference design of a 26 mw storage system that has been recently proposed[11] specifies the use of a fuel cell system which rejects heat at a temperature of $160^\circ C$. The cooling water temperature is specified as $30^\circ C$. If pure FeTi were used as the storage medium, a charging pressure considerably in excess of 35 atm would be required in order to store as much hydrogen as the PSE&G unit which had cooling water available at $17^\circ C$. Further, no advantage could be taken of the high quality heat which is rejected by the fuel cell because of the high dissociation pressure of $FeTiH_x$. Obviously a more stable hydride could be used to good advantage in this particular instance. Since it was known that the properties of the FeTi-H system could be modified by the addition or substitution of another transition metal atom, it was proposed that binary FeTi be replaced with a ternary alloy having a composition corresponding to $TiFe_{.7}Mn_{.2}$,[12] which forms a more stable hydride. A comparison of its predicted performance vs. that of FeTi is given in Table 6.

Thermal Storage

The first heat storage system involving a metal hydride was proposed by Winsche.[13] Heat derived from a low level radio-activie isotope was used to slowly decompose MgH_2 (nickel catalyzed) over a relatively long period of time. During this "charging" period the hydrogen product was stored as iron titanium hydride. The heat of formation of the latter was rejected to the surroundings. In the "discharge" mode the reactions were reversed, iron titanium hydride was decomposed using ambient heat and MgH_2 was regenerated at an elevated temperature (>300°C) The heat evolved in this step was used to produce high quality steam which performed work.

More recently, a scheme coupling solar energy with a metal hydride thermal storage system was suggested by Libowitz.[14] Solar heat is used to decompose $FeTiH_x$, or a similar hydride, at an elevated temperature and the hydrogen stored as a pressurized gas. In order to release the stored energy, the pressurized hydrogen gas is permitted to react with the previsouly dehydrided alloy at a lower temperature.

The use of a metal hydride in heat pump cycles has also been suggested.[15] A simple schematic of such a unit is shown in Figure 8. A metal hydride acting as the evaporator bed is decomposed using ambient heat, the hydrogen is compressed and sorbed in the corresponding condenser bed at a higher pressure and temperature and evolving heat. Such a device could possibly serve as a residential heat source and/or air conditioner. In order to operate continuously, the evaporator and condenser bed would have to be reversed periodically and several beds would be required. It may also be feasible, by using two different hydrides in combination with solar heat, that the compressor could be eliminated or even used to produce mechanical work.

Unfortunately, at the present time it does not appear, as pointed out by Libowitz,[16] that the storage of low quality thermal energy (e.g., solar heat) using unstable hydrides is economically feasible. This is a consequence of cost of the alloy per unit hydrogen stored and the low heat of formation. However, the assessment is not so bleak where the storage of high quality heat is concerned. In this case magnesium can be used which is relatively cheap and has an effective hydrogen storage capacity several times that of any unstable alloy hydride (Table 7). It is rather interesting to note that in this context the relatively high heat of formation and stability of MgH_2 are assets rather than liabilities. A flow diagram for a thermal storage process using MgH_2 for electric utility applications is shown in Figure 9. During the thermal charging portion of the cycle MgH_2 is decomposed at 375°C using high quality heat. Hydrogen is evolved at a pressure of 16 atm and reacted at 30°C with a ferrotitanium alloy to form a relatively unstable hydride. In order to release the stored heat, the low temperature hydride bed is heated from 30°-80° over a period of time, evolving hydrogen at a constant pressure of 10 atm. The evolved hydrogen is reacted at 335°C with the previously dehydrided Mg. The heat of reaction is used to produce high pressure steam, which is converted into electricity using a steam turbine. Steam is discharged from the turbine at 80°C and is used, with other low temperature heat sources, to provide the heat of decomposition of the ferrotitanium alloy hydride. It should be noted that the saturated steam produced in this system ($\sim$1700 psi, $\sim$322°C) is within the range produced by commercial utilities, i.e., 1450-3500 psi.

One outstanding advantage of a thermal storage system is that only in the final step is thermal energy converted into electricity. In a modern steam plant the overall conversion efficiency (heating value of fuel → electricity) approaches 40%. While in the present case the overall efficiency will be less, it is still likely to be in the 25-33% range. This value compares quite favorably to overall efficiencies estimated for other energy storage systems proposed for electric utilities.

Hydride Compressors

The hydriding and dehydriding reactions of a number of unstable metal-hydrogen systems are rapid enough to consider their use as hydrogen compressors or pumps. The pumping action is derived from the alternate decomposition and re-formation of a metal hydride using low grade heat and a heat sink to provide the driving force. The first such pump (Figure 10), using an unstable hydride was built in 1971[17] for laboratory use and is still in operation. The pumping action was obtained by the alternate decomposition and re-formation of VH_2 using hot (50°C) and cold (18°C) water. The pump has been operated at pressures ranging from 7-24 atm with a volumetric pumping rate of $\sim$50 ml/min at pressure. A more sophisticated and higher capacity compressor has recently been built using $LaNi_5H_x$; its operation is described by Van Mal in this symposium.[18]

A new departure has been suggested by Powell, et al.,[19] who are concerned with highly efficient power conversions systems. It is based on using a low temperature heat source in combination with a high temperature heat source in a closed Brayton cycle where hot compressed gas is expanded through a turbine. The novel feature of the system is the use of an unstable hydride and low temperature heat to effect the compression of the gas, thereby eliminating mechanical compressor work and substantially increasing the efficiency of the use of the high temperature heat.

Process and Laboratory Storage

The current annual production of hydrogen is $\sim 4.5 \times 10^7$ metric tons. It is primarily used in the chemical process industries for the production of a myriad of products ranging from plastics to fertilizers. It is likely that convenient storage of hydrogen would be very desirable in many processes to provide surge capacity, reserve supplies, high purity hydrogen, etc.

Iron titanium hydride is currently being used in our laboratory to provide a source of high purity hydrogen and deuterium at pressures up to 60 atm. A description of a proposed commercial laboratory cylinder is given by Lebsanft, et al.;[20] they note that it is lighter, smaller and safer than the equivalent pressurized gas cylinders and should be able to readily supply hydrogen having a purity equal to that obtained by diffusion through a palladium-silver membrane. In the United States cylinders of iron titanium hydride are currently commercially available from Billings Energy Corp., Provo, Utah.

Safety

All chemical fuels are inherently hazardous. The extent of the hazard depends upon the fuel properties, e.g., coal is much less hazardous than liquefied natural gas; the properties of liquid hydrogen would forbid its use as an ordinary common fuel even though in high technology applications large amounts have been handled without incident. On the other hand, low pressure hydrogen gas is relatively safe; in fact, "town gas," which was a major fuel in many large cities in the past, contained about 50 volume % hydrogen. With respect to metal hydrides a number of safety-related studies have been carried out.[21-25] Most were concerned with the ignition of these materials in air and these results are summarized in Table 8. In addition to these standard tests Woolley[26] reports several involving the catastrophic rupture of reservoirs containing iron titanium hydride by armor piercing incendiary bullets. Only momentary ignition occurred whereas the results of a similar test in which gasoline was substituted for $FeTiH_x$ resulted in a rather spectacular conflagration. In view of these data it may be concluded that $FeTiH_x$ is inherently less hazardous than most common, volatile fuels currently widely used.

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Table 1

Comparison of Hydrogen Storage Media

Medium	Hydrogen Content Wt %	H Storage Capacity g/ml of vol	Energy Density Heat of Combustion[a] (higher) cal/g	cal/ml of vol
MgH_2[b]	7.0	0.101	2373	3423
Mg_2NiH_4	3.16	0.081	1071	2745
VH_2	2.07		701	
$FeTiH_{1.95}$	1.75	0.096	593	3245
$TiFe_{.7}Mn_{.2}H_{1.9}$	1.72	∿0.09	583	∿3050
$LaNi_5H_{7.0}$	1.37	0.089	464	3051
$R.E.Ni_5H_{6.5}$[c]	1.35	∿0.09	458	∿3050
Liquid H_2	100	0.07	33900	2373
Gaseous H_2 (100 atm. press)	100	0.007	33900	244
N-Octane			11400	8020

[a] Refers to H only in metal hydrides.

[b] Starting alloy 94% Mg 6% Ni.

[c] R.E. refers to mischmetal, a commercial rare earth alloy.

Table 2

Energy Density Comparison
Automotive Power Sources
Actual and Proposed

Power Source	Energy Density whr/kg	Conversion Efficiency %	Net whr/kg	Ref.
Pb/acid Battery				
Present	30	70	21.0	27
Advanced	50	70	35.0	27
Li/MS Battery	150	70	105	27
$FeTiH_{1.7}$[a,b]	516[c]	30	154	
Mg_2NiH_4[a,b]	1121[c]	30	336	
MgH_2 (10% Ni)[a,b]	2555[c]	30	767	
Gasoline[a]	12880[c]	23	2962	

[a] No allowance for container weight

[b] Based on available hydrogen

i.e., $FeTiH_{1.7} \rightarrow FeTiH_{0.1}$

$Mg_2NiH_4 \rightarrow Mg_2NiH_{0.3}$

$MgH_2 \rightarrow MgH_{0.05}$

[c] Based on lower heat of combustion.

Table 3

Hydrogen Powered Bus[26]
Performance Data

Type	19 Passenger Bus
Manufacturer[a]	Winnebago Industries
Weight, less FeTi and related items	3690 kg
Weight FeTi	1002 kg
Weight Stored Hydrogen	12.6 kg
Weight Hydride Tanks	400 kg
Weight of Reinforcement	54 kg
Weight of Payload	1612 kg
Total weight	6771 kg
Available H_2 @ Sustained 80 km/hr	7.7 kg
Fuel Economy (@ 80 km/hr)	15.6 km/kg
Range @ Sustained 80 km/hr	121 km

[a] Converted to use hydrogen fuel by Billings Energy Corp., Provo, Utah

Table 4

Comparison of Passenger Vehicle Types[a]
Estimated Performance

	H_2 only	Gasoline + H_2	Gasoline only	Li/MS Electric
Vehicle wt less fuel related items, kg	1815	1815	1815	1816
$FeTiH_{1.7}$ wt kg	862	171		
Fuel Tank and Support wt kg	215	43		
Gasoline wt kg		45	56	
Battery wt kg				1264
Total wt kg	2892	2074	1871	3080
Propulsive[b] Energy kw hr	133	27(H_2) 139	172	133
Estimated Range km[d]	232	385[c]	370	232

[a] Frame similar to EPA 1815 kg (4000 lb) inertia weight class.

[b] Based on energy densities and conversion efficiencies listed in Table 2.

[c] 62 km on H_2 only, 323 km on gasoline.

[d] Based on weight-range data given by Brogan.[28]

TABLE 5

PSE & G RESERVOIR

ALLOY ANALYSES

WT. %

	Batch #			
	1	2	3	4
Fe	52.7	51.1	51.3	50.7
Ti	46.0	47.0	46.2	45.5
Mn	-	-	1	2
O	0.29	0.39	0.27	0.31
C	0.015	<0.01	<0.01	<0.01

Table 6

Comparison of Ferro-Titanium Alloy Storage Systems

	PSE & G Demonstration	Full Scale Plant Current Design	Full Scale Plant Advanced Design
Alloy	FeTi	FeTi	$TiFe_{0.7}Mn_{0.2}$
Wt % Hydrogen Stored	1.57	1.15	1.60
Charging Press. atm.	35	30	10
Discharge Press. atm.	2	2	2
Hot Fluid Temp. °C	45	160	160
Cold Fluid Temp. °C	17	30	30

Table 7

Thermal Energy Storage Two Bed System

	MgH_2 (Cu catalysed)	$TiFe_{.8}$ $Mn_{.2}$ $H_{1.8}$
ΔH_f from the alloy	-18.5 kcal/mol H_2	∿-8 kcal/mol H_2
Effective H Storage Capacity	6.4 wt %	1.6 wt %
Estimated cost	1.98/kg[a]	3.85/kg[b]
Thermal Storage Capacity	0.69 kWh/kg	0.17[c] kWh/kg
$ kWh Stored Thermal	2.87	22.56[c]
$ kWh Stored Electrical (33% off)	8.70	68.36[c]

Overall Cost of Materials	
$/kWht	25.43
$/kWhe	68.36

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[a] Cost of Mg - $1.98/kg; Cu = $1.54/kg

[b] Projected

[c] Based on ΔH_f for MgH_2

Table 8

Ignition Temperature of Various Materials in Air

Material	Particle Size µ	Bulk Powder	Dust Cloud	Ref.
FeTi	74-149	No ignition		24
FeTi	<74		490	24
$FeTiH_x$	74-149	188		24
$FeTiH_x$	<74		420	24
$LaNi_5$	<74		420	25
$LaNi_5H_x$	12 (Avg.)	192	320	25
U	<40	100	25	23
UH_3	<12	25	25	23
Zr	<12	190	25	23
Zr	<40	300	350	23
ZrH_2	<30	340	430	23

Figure Captions

1. Schematic showing integration of a metal hydride (e.g., $FeTiH_2$) with an energy conversion device (internal combustion engine, fuel cell, gas turbine, etc.).
2. Hydrogen powered vehicles; a) Winnebago 19 passenger bus converted to hydrogen fuel by Billings Energy Corp., Provo, Utah;[4] b) Mercedes Benz van.[6] In both cases iron titanium hydride is used for on board storage of hydrogen.
3. Multifuel vehicle capable of using H_2 or gasoline fuel either alternately or simultaneously. Hydrogen is stored as iron titanium hydride (see Table 4). The heat of decomposition is extracted from the engine coolant.
4. Flow diagram of peak shaving demonstration plant built by Public Service Electric and Gas Corp. (PSE&G).[3]
5. Iron Titanium Hydride Reservoir used in PSE&G pilot plant[3] (see Table 5).
6. Hydrogen in reservoir and bed temperature vs. time in charging step--PSE&G reservoir.[3]
7. PSE&G reservoir pressure and bed temperature during discharge.[3]
8. Simple heat pump flow diagram. Heat is used at ambient temperature to decompose hydride in evaporator bed. The evolved hydrogen is compressed and reacted with dehydrided metal at a higher temperature and pressure. The flows are reversed when the evaporator bed is exhausted and the condenser bed is saturated.

9. Flow diagram for MgH_2 thermal storage system for utility application.
10. Gas circulation pump powered by the decomposition and regeneration of vanadium dehydride.[17]

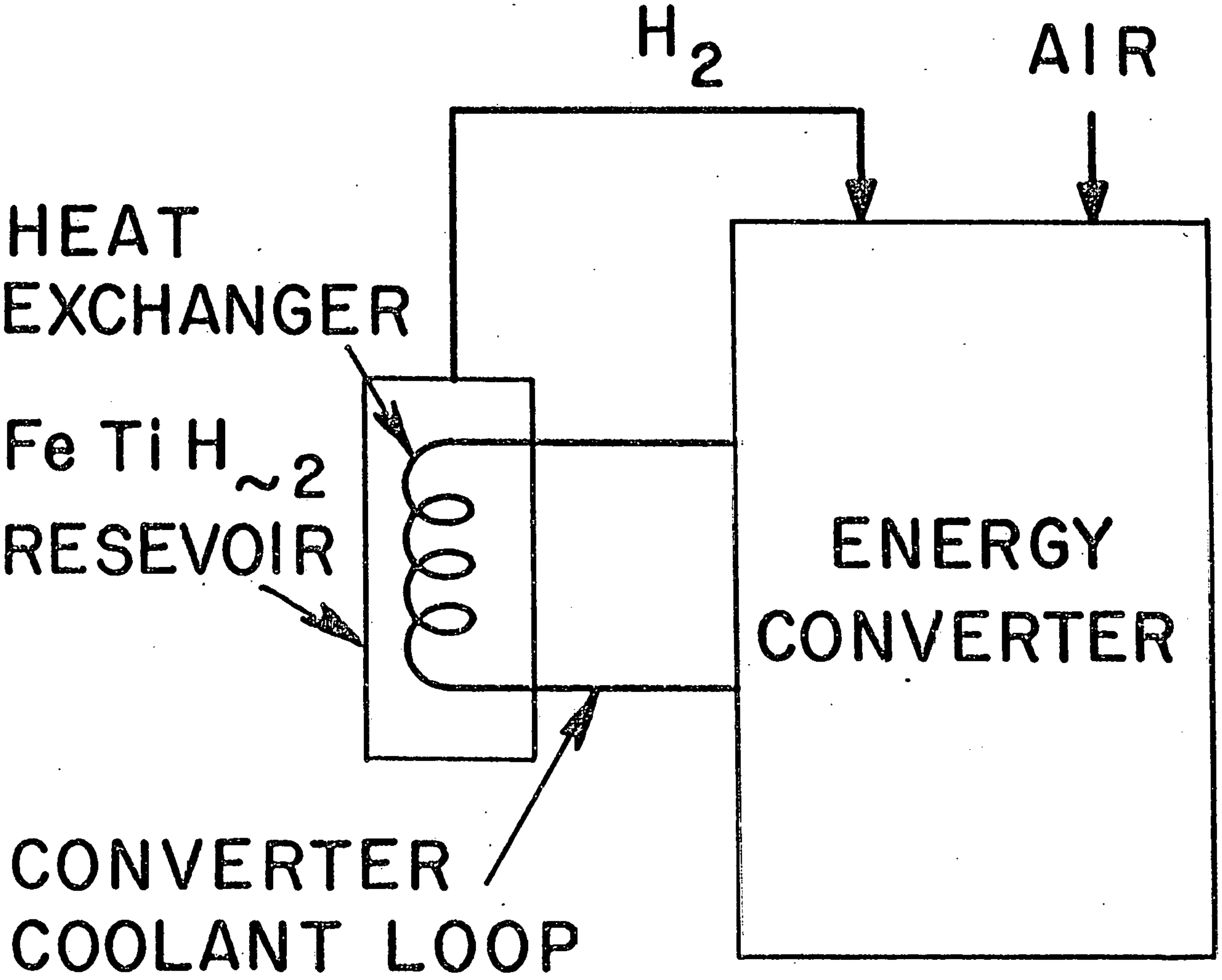


Figure 1. Schematic showing integration of a metal hydride (e.g., $FeTiH_2$) with an energy conversion device (internal combustion engine, fuel cell, gas turbine, etc.).

a) Winnebago 19 passenger bus converted to hydrogen fuel by Billings Energy Corp., Provo, Utah[4]

b) Mercedes Benz van[6]

Figure 2. Hydrogen powered vehicles. Iron titanium hydride is used in both cases for on board storage of hydrogen.

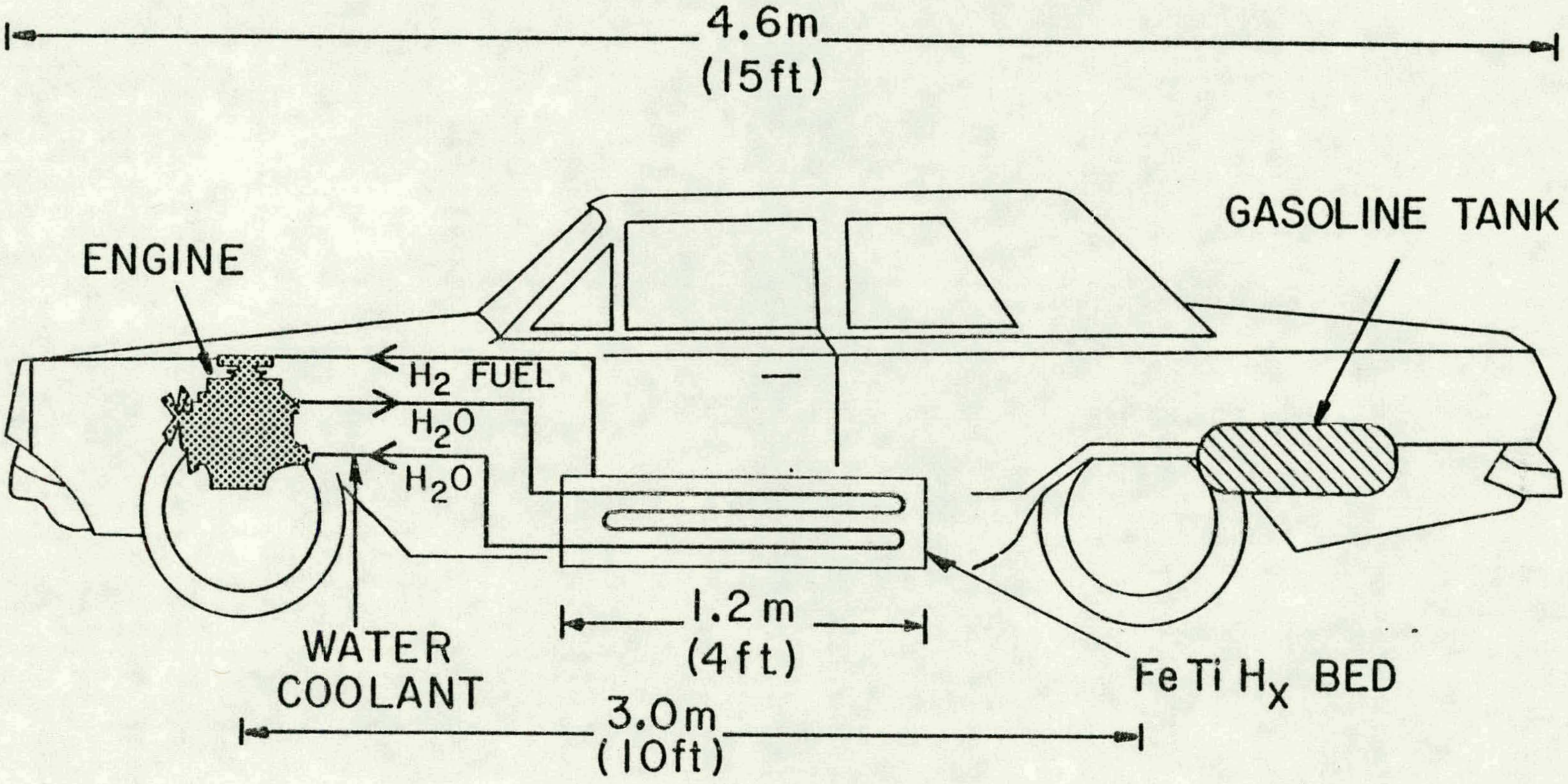
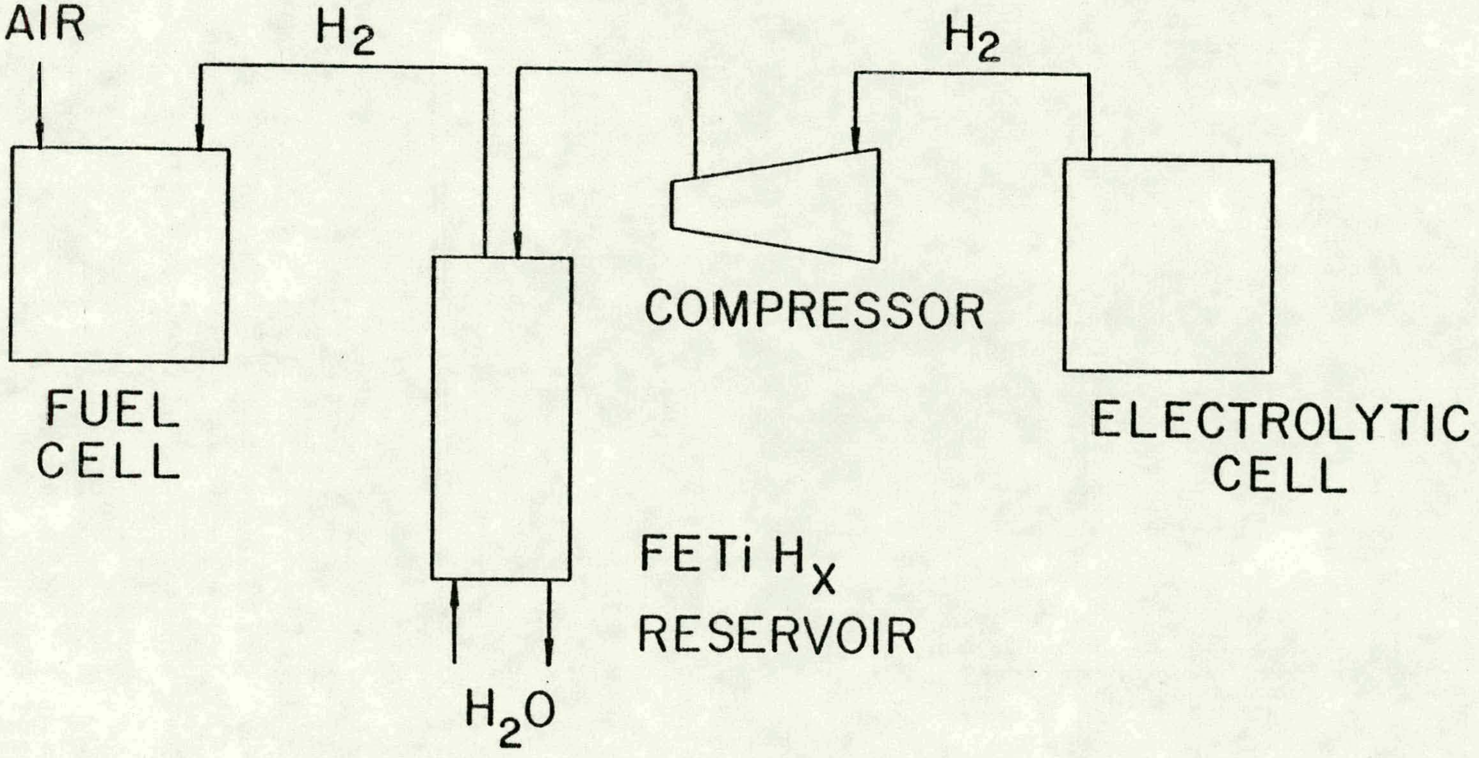


Figure 3. Multifuel vehicle capable of using H_2 or gasoline fuel either alternately or simultaneously. Hydrogen is stored as iron titanium hydride (see Table 4). The heat of decomposition is extracted from the engine coolant.



PSE + G PEAK SHAVING DEMONSTRATION

Figure 4. Flow diagram of peak shaving demonstration plant built by Public Service Electric and Gas Corp. (PSE&G).[3]

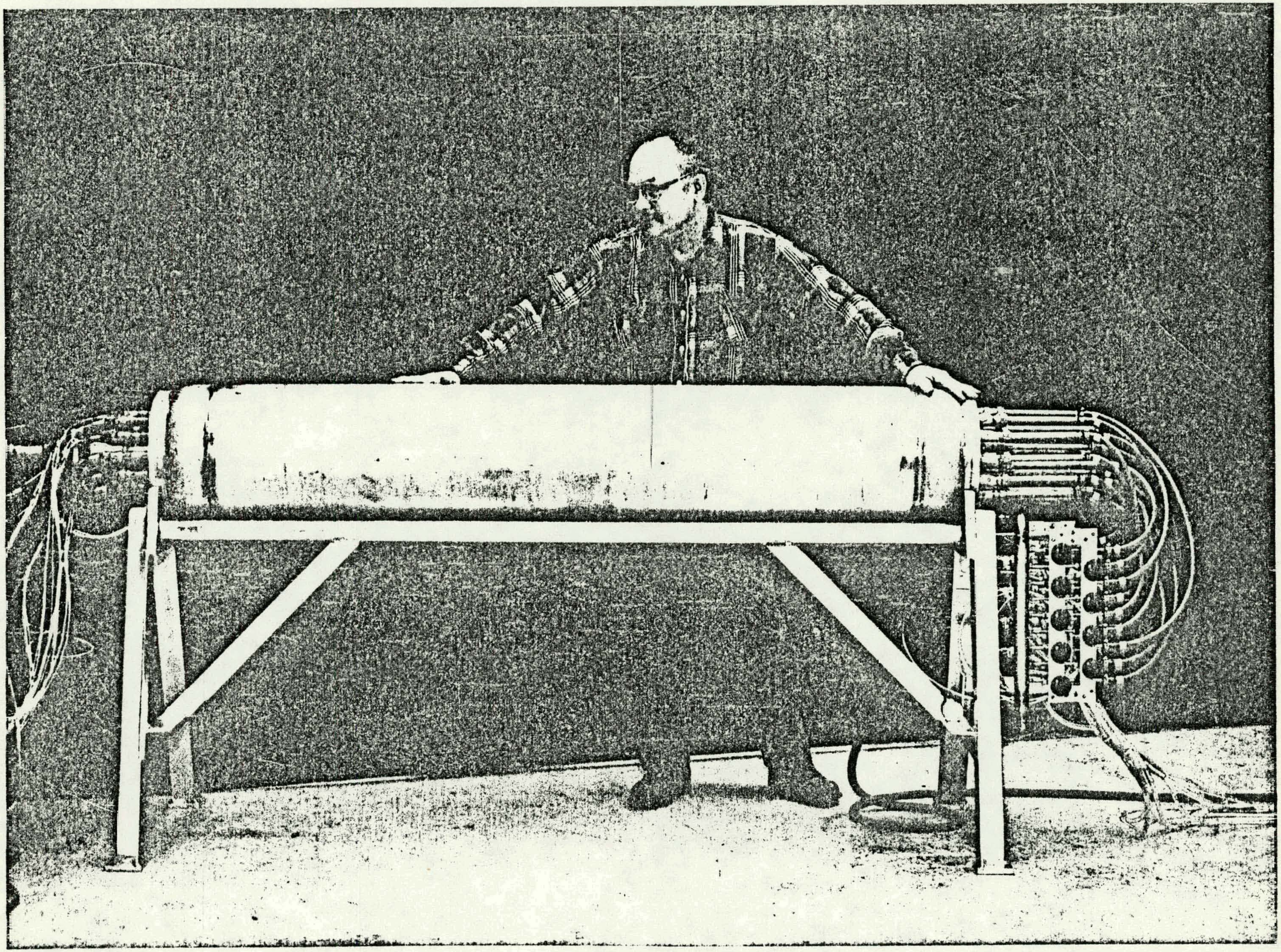


Figure 5. Iron Titanium Hydride Reservoir used in PSE&G pilot plant[3] (see Table 5).

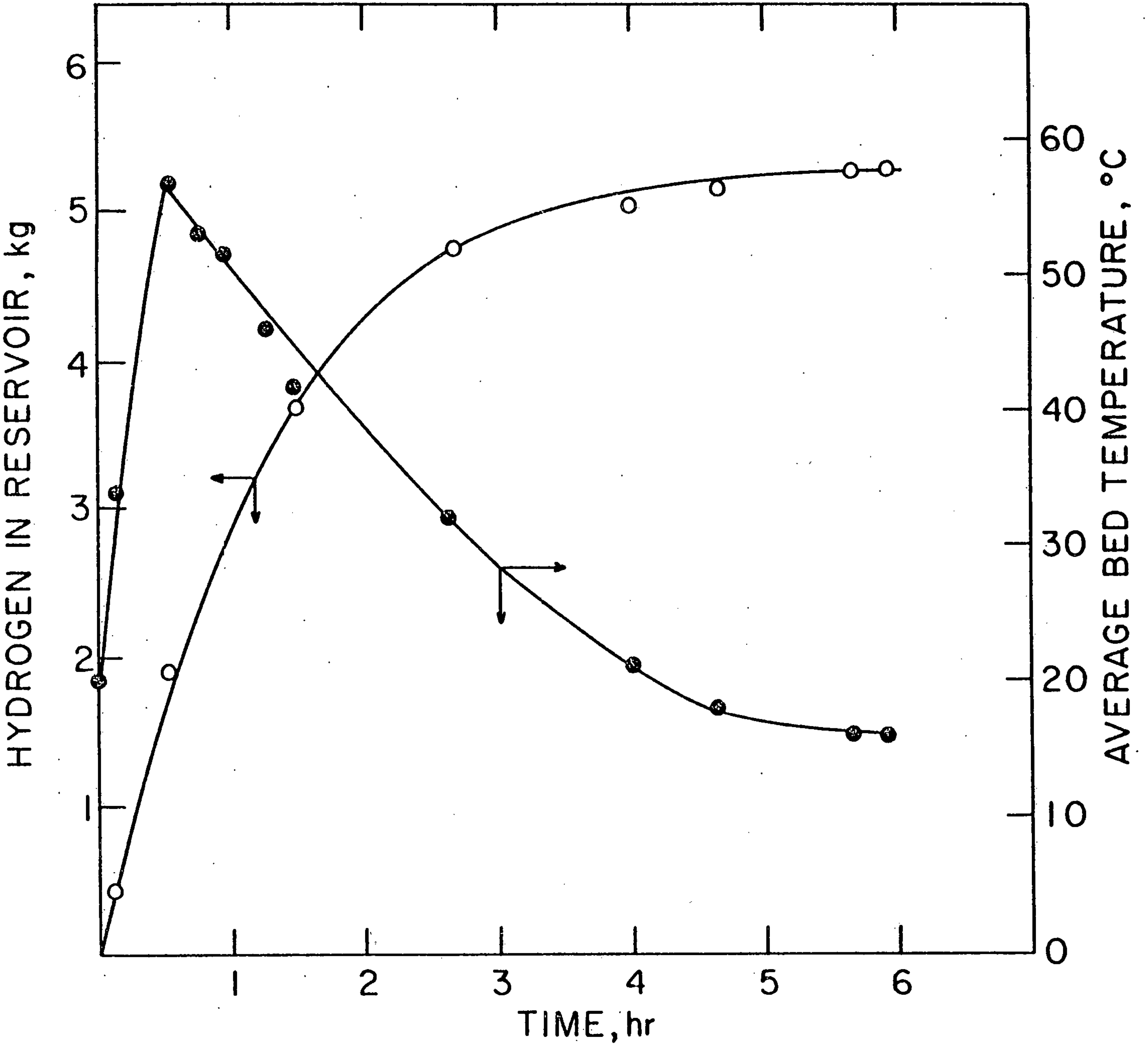


Figure 6. Hydrogen in reservoir and bed temperature vs. time in charging step--PSE&G reservoir.[3]

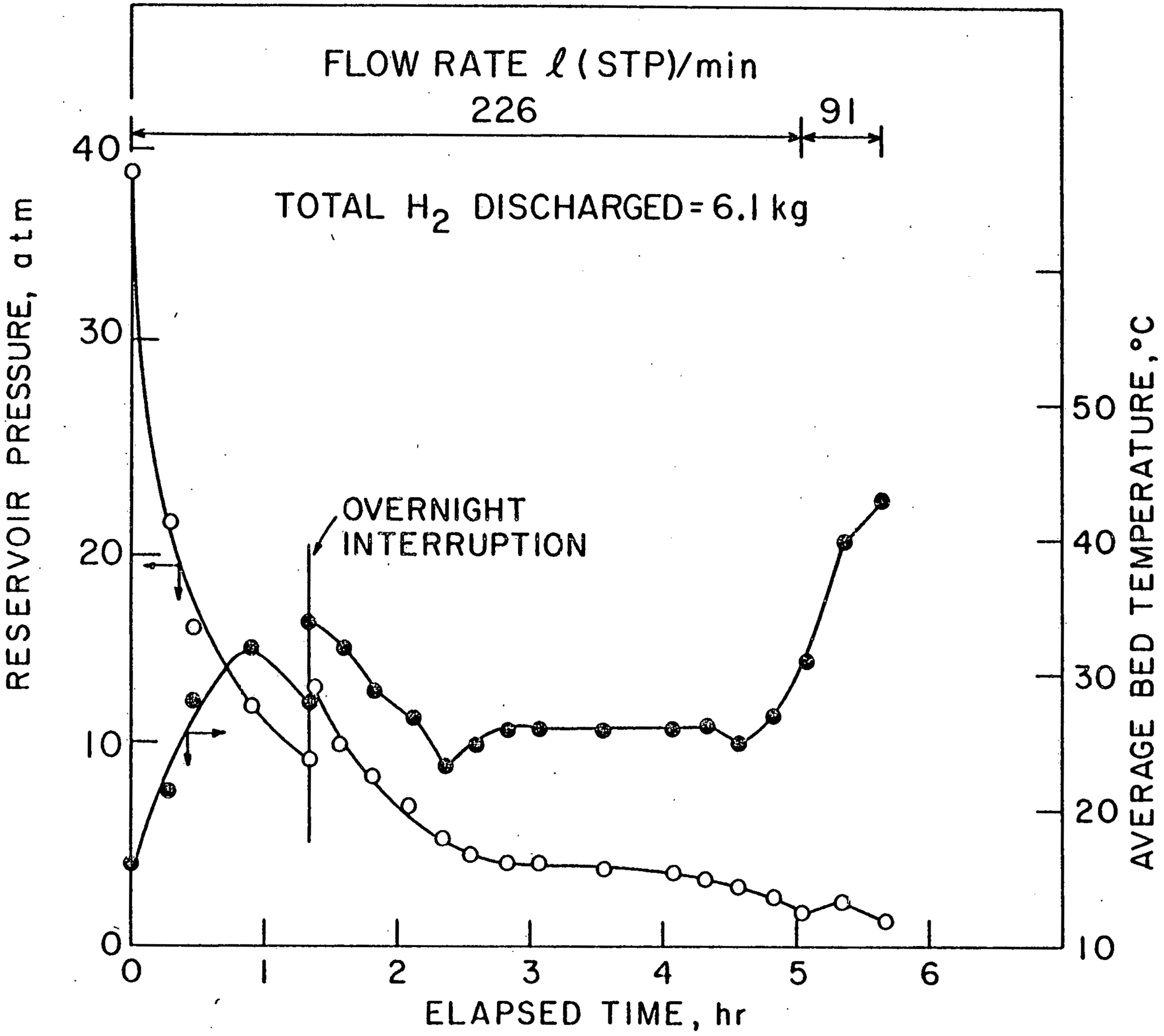


Figure 7. PSE&G reservoir pressure and bed temperature during discharge.[3]

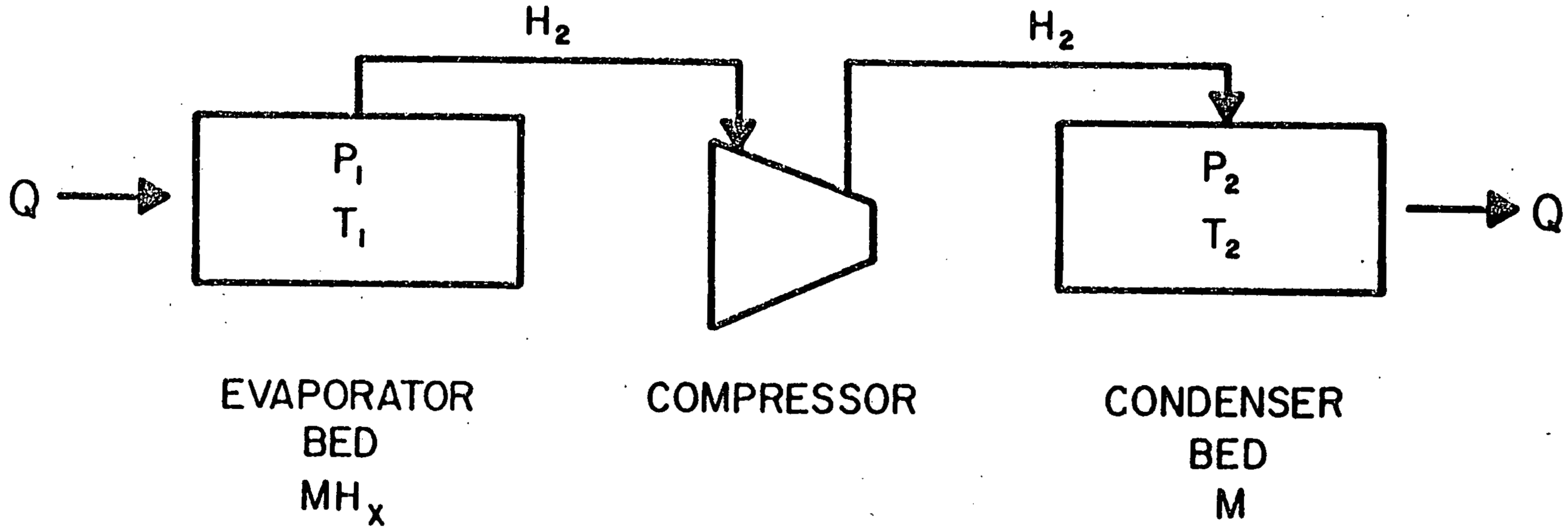


Figure 8. Simple heat pump flow diagram. Heat is used at ambient temperature to decompose hydride in evaporator bed. The evolved hydrogen is compressed and reacted with dehydrided metal at a higher temperature and pressure. The flows are reversed when the evaporator bed is exhausted and the condenser bed is saturated.

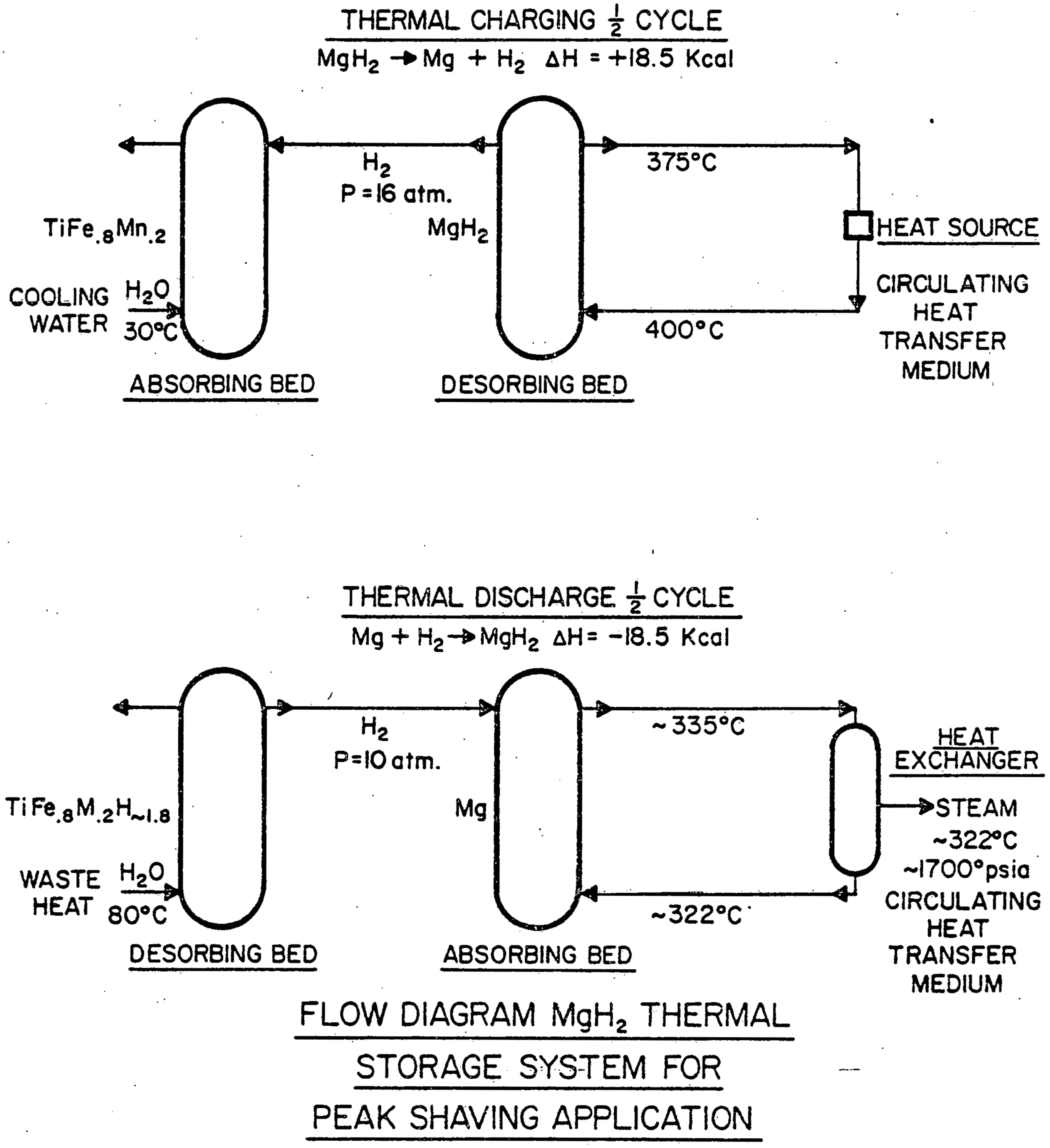


Figure 9. Flow diagram for MgH_2 thermal storage system for utility application.

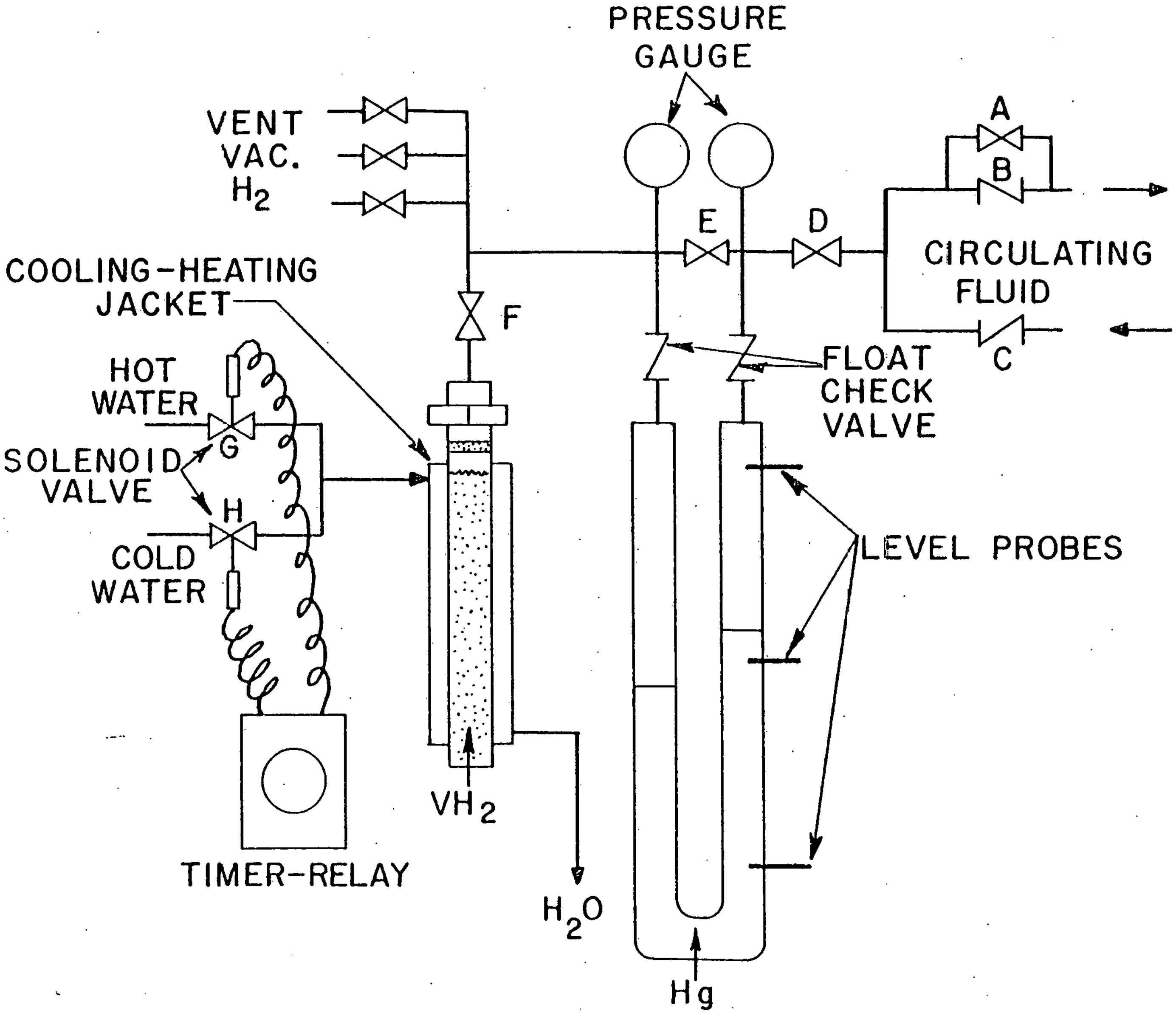


Figure 10. Gas circulation pump powered by the decomposition and regeneration of vanadium dehydride.[17]