13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Solid State (Metal Hydride) Refrigerant Based Air Conditioner and Freezer Systems

Bamdad Bahar[a*], William TomHon[a], Matt Golben[a], Jacob Zerby[a], Mark Golben[a]

[a]*Xergy Inc., 299A Cluckey Dr., Harrington DE 19952, USA*

Abstract

Chlorine and Fluorine containing refrigerant based heat pumps currently consumes over 2,000 Trillion-Watt hours per year of electric power [1]. Current refrigerants used in these devices have climate harming "Global Warming Potentials" (GWP) that are thousands of times higher than that of CO_2 gas. This paper explores a novel heat pump technology based on solid-state (metal hydride based) refrigerant employing hydrogen compression. This paper provides performance data for solid state refrigerant heat pumps for air conditioning (AC) and Ultra Low Temperature (ULT) freezer systems. Operational data, lessons learnt, and optimal practices needed to deploy these systems are reviewed. Key components in the system are analyzed, including the metal hydride heat exchangers, (electrochemical and other) Hydrogen compressors, and system controls.

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Keywords: Metal Hydride; Solid State Refrigerant; Electrochemical Compression; Hydrogen; Air Conditioner; Ultra-Low Temperature Freezer

1. Introduction to Solid-State refrigerant (Metal-Hydrogen Sorption Systems)

A refrigerant is a substance used in a heat pump or refrigeration cycle that typically undergoes phase transition with favorable thermodynamic properties that enables heat absorption or rejection upon phase transition. Chlorine and Fluorine containing refrigerant based heat pumps currently consumes over 2000 Trillion-Watt hours per year of electric power [1]. Current refrigerants used in these devices have climate harming "Global Warming Potentials" (GWP) that are thousands of times higher than that of CO_2 gas. Therefore, alternatives to current refrigerants are critically needed to address the shortcomings of current refrigerants.

Solid state refrigerants hold the potential to provide a highly efficient, low cost, recyclable, environmentally friendly alternative to traditional refrigerants. Metal hydrides (MH) are a class of solid-state refrigerants. Metal hydrides are metallic compounds, in which one or more hydrogen centers have nucleophilic, reducing, or basic properties. For heat pumps, we utilize the reversible heat-driven reaction of a hydride-forming metal/alloy, or intermetallic compound (IMC) with hydrogen gas. Hydrogen changes phase from a gas to a solid metal alloy with very favorable thermodynamic properties.

$$M(s) + xH_2(S) \rightleftharpoons MH_x(s) + Q \quad (1)$$

In Eq.1, M is a metal or alloy (e.g., vanadium (V) or a body-centred cubic (BCC) solid solution based upon it), or an IMC (typically with linear (AB_2) or trigonal bipyramidal (AB_5) molecular geometries); (s) and (g) relate to solid and gas phases, respectively, and Q is the reaction enthalpy. The overall process performance is strongly dependent on the intrinsic features of metal hydride reaction including its thermodynamic and kinetic

* Corresponding author. Tel. +1 (302)-629-5768.
E-mail address: bamdad.bahar@xergyinc.com

characteristics, as well as composition, structure and morphology of the solid phases (M, MH_x) involved in the process. These features are mainly related to fundamental aspects of hydride materials.

Equilibrium of the metal-hydrogen reaction is characterized by an interrelation between hydrogen pressure (P), concentration of hydrogen in the solid phase (C) and temperature (T). PCT diagrams can be generated to characterize specific hydride-forming materials. These provide the thermodynamics of its interaction with gaseous hydrogen. At low hydrogen concentrations ($0 \leq C < a$) hydrogen atoms form an interstitial solid solution in the matrix per Henry–Sieverts law. When the value of C exceeds concentration of the saturated solid solution, precipitation of the hydride (β-phase with hydrogen concentration) occurs. The system then exhibits a first order phase transition at a constant hydrogen pressure, $P = P_P$ ($a \leq C \leq b$). This pressure is called the plateau pressure (P_P) in the metal–hydrogen systems. The process is almost exactly (100%) reversible, with slight differences as the concentration changes. This is termed hysteresis and is a source of efficiency loss (<5%).

Depending on the type and composition of the hydride-forming material, the equilibrium hydrogen pressures vary in a very broad range, from below 1 bar to exceeding 1 kbar at room temperature. Most of the lower pressure compression alloys (P_H < 200 bar at T_H < 150 °C) belong to the AB_5-type intermetallic compounds while significantly higher, >1 kbar, hydrogen pressures can be generated using AB_2-type compounds. Current prototype systems have been built using a wide variety of commercial AB_5 compounds, although in the future, the high thermal exchange capacity of AB_2 could lead to smaller heat exchangers.

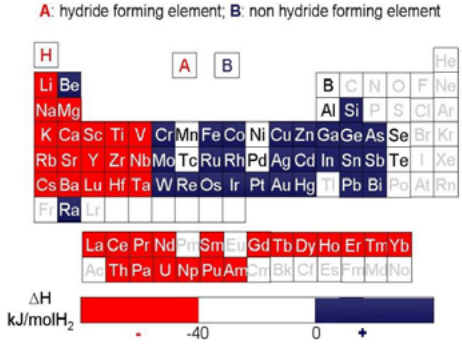
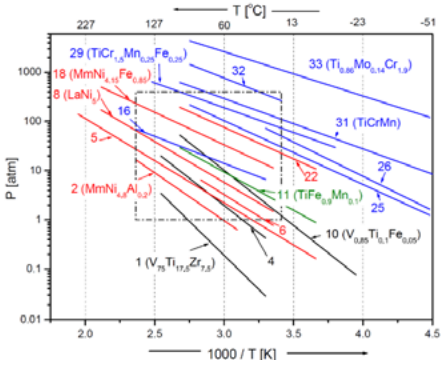


Fig. 1. Hydride and non-hydride forming elements in the periodic system of elements [2].

Proper hydride selection is critical to designing useful metal hydride heat exchangers. Figure 2 (right) provides equilibrium characteristics of the interaction of hydride-forming alloys suitable for Hydrogen. The data is sorted in the ascending order for desorption plateau pressure. Figure 2 (left) provides Van't Hoff plots for selected hydride-forming alloys suitable for hydrogen.



Index	Formula	SR Designation	-ΔS° (J/(mol-H_2*K))	-ΔH° (J/(mol-H_2))
1	$V_{75}Ti_{17.5}Zr_{7.5}$	R-2120	145.1	52.98
2	$MmNi_{4.6}Al_{0.2}$	R-2410A	111.3	37.20
4	$V_{75}Ti_{10}Zr_{7.5}Cr_{7.5}$	R-2300	132.3	42.23
5	$LaNi_{4.8}Sn_{0.2}$	R-2560B	104.3	32.83
6	$Mm_{0.7}La_{0.3}Ni_{4.7}Sn_{0.3}$	R-2660	111.2	32.80
8	$LaNi_5$	R-2500	110.0	31.80
10	$V_{0.85}Ti_{0.1}Fe_{0.05}$	R-2310	148.0	42.90
11	$TiFe_{0.8}Mn_{0.1}$	R-2700	107.7	29.70
16	$Zr_{0.7}Ti_{0.3}Mn_2$	R-2860	85.0	21.00
18	$MmNi_{4.15}Fe_{0.85}$	R-2440B	105.4	25.00
22	$Ca_{0.2}Mm_{0.8}Ni_5$	R-2420	109.5	24.50
25	$TiCr_{1.8}Mo_{0.01}$	R-2816B	113.0	24.80
26	$TiCr_{1.9}$	R-2810	122.0	24.80
29	$TiCr_{1.6}Mn_{0.25}Fe_{0.3}$	R-2843A	101.6	19.32
31	TiCrMn	R-2840	106.0	19.60
32	$ZrFe_{1.8}Ni_{0.2}$	R-2904	119.7	21.50
33	$Ti_{0.86}Mo_{0.14}Cr_{1.8}$	R-2816A	117.0	17.20

Fig. 2. Van't Hoff plot and enthalpy and entropy of formation of hydride complex for selected sorbent refrigerants (SRs) [2]

Hydrogen compression is critical for a metal hydride refrigerant based heat pump cycle. Hydrogen can be compressed using mechanically driven, electrochemically driven or metal hydride (heat driven) compressors. For durable performance, hydride systems must remain dry and hydrogen gas streams must be pure and free of contaminants. Much like other refrigerant systems, the type of compression employed must be mated with the specific type of hydride selected and the overall requirements of a specific heat pump application. One of the first modern metal hydride heat pumps (MHHPs) was built in 2014 (Figure 3). Hydrogen compression ratio (P_H/P_L) for hydrides can vary in the range 10–50.

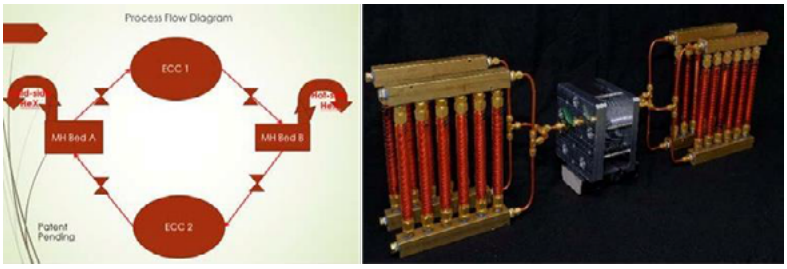


Fig. 3. (a) A schematic for a potential ECC-based MHHP. (b) Picture of prototype ECC-based MHHP

Initial development of the electrochemical compressor-based metal hydride system was conducted with commercially available hydride cylinders with heat exchanger capability. Two designs differing in the placement of the heat exchanger coil and the aspect ratio of the units were tested: exterior-wrapped tubes brazed to the high aspect-ratio hydride containing cylinder (Figure 4a), and a coiled tube placed inside a lower aspect ratio hydride cylinder (Figure 4b). Both designs showed significant deficiencies in heat exchange capability.

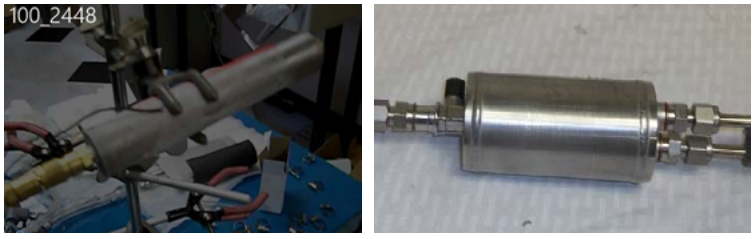


Fig. 4. Hydride cylinders with heat exchanger capability (a) high aspect-ratio hydride with potential for exterior wrap-around coil and (b) (b) a coiled tube placed inside a lower aspect ratio hydride cylinder.

Figure 5 shows results for COP vs operating voltage. While low voltages (<0.1 V) provide the greatest benefit to COP, low voltage systems have a lower current and H_2 flow and thus require larger, more expensive systems to maintain a constant temperature. Conversely, faster heating can be achieved with smaller systems by operating at higher voltages represented (>0.2 V).

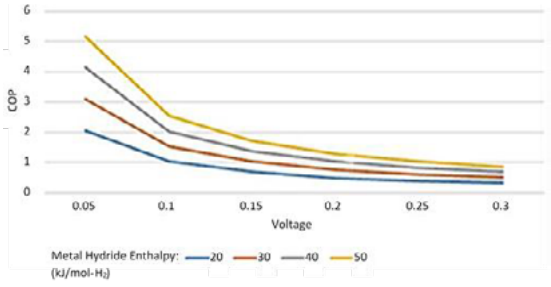
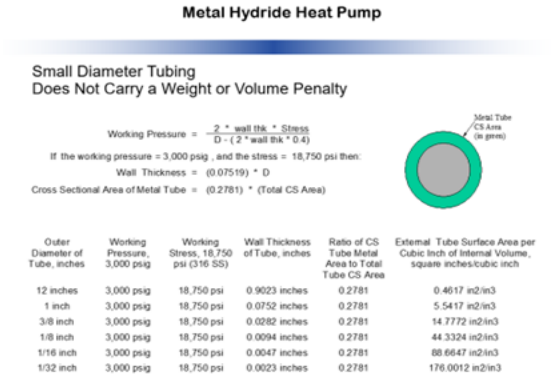


Fig. 5. ECC-MHHX Heat Pump Water Heater COP (heating COP) as a function of voltage for metal hydrides with different enthalpies.



Outer Diameter of Tube, inches	Working Pressure, 3,000 psig	Working Stress, 18,750 psi (316 SS)	Wall Thickness of Tube, inches	Ratio of CS Tube Metal Area to Total Tube CS Area	External Tube Surface Area per Cubic Inch of Internal Volume, square inches/cubic inch
12 inches	3,000 psig	18,750 psi	0.9023 inches	0.2781	0.4617 in2/in3
1 inch	3,000 psig	18,750 psi	0.0752 inches	0.2781	5.5417 in2/in3
3/8 inch	3,000 psig	18,750 psi	0.0282 inches	0.2781	14.7772 in2/in3
1/8 inch	3,000 psig	18,750 psi	0.0094 inches	0.2781	44.3324 in2/in3
1/16 inch	3,000 psig	18,750 psi	0.0047 inches	0.2781	88.6647 in2/in3
1/32 inch	3,000 psig	18,750 psi	0.0023 inches	0.2781	176.0012 in2/in3

Fig. 6. Working pressure and surface per internal volume of various diameters of metal hydride tubing

As seen in Figure 6, microtube heat exchangers provide practical benefits including: the ability to hold very high pressures within tubes, flexible tubes which can be coiled, and highly configurable tube patterns which allow precise thermal performance. Furthermore, microtubes take advantage of fundamental design principles as decreasing the diameter increases the surface area per unit volume. As the convective heat transfer rate (Q) is proportional to the surface area, per Equation 2, small diameter tubes increase the heat transfer rate as well.

$$Q = Time \times h \times External\ Surface\ Area \times \left(T_{surface} - T_{external}\right) \quad (2)$$

In most heat exchangers, the technical design limitation to tube diameter is pressure drop. However, the small molecular size and high velocity of hydrogen enables it to travel through very small diameter tubes with very little pressure loss. Microtubes tubes have allowed for over a 10X decrease in sorption time. In lab testing (Figure 7), 100% of the MHHX hydrogen capacity is absorbed in under 40 seconds, compared to 1600 seconds with the previous generation of MHHX.

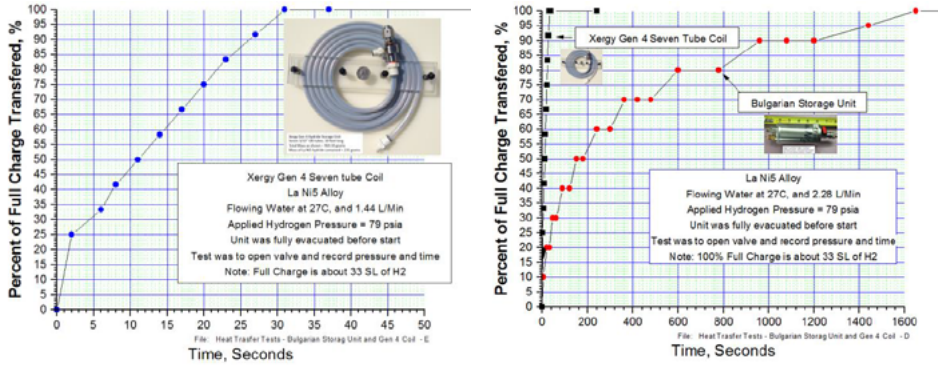


Fig. 7. Comparison of mass flow rate of hydrogen into metal hydride microtubes (left) and into a typical tank-type metal hydride cannister (right).

2. Environmental and Commercial Analysis of Room Air Conditioners Employing Metal Hydride Solid-State Refrigerant Technology

2.1. Introduction

Air conditioning solutions utilizing heat exchangers with metal hydride refrigerant show a very strong potential to provide a novel cooling solution with low energy consumption and zero GWP. Like a vapor compression air conditioner, a MHHX uses a compressor to generate its cooling power, however the cooling is generated via ionic sorption of hydrogen gas rather than through the incumbent vapor-compression refrigeration. The compression can be provided by a typical mechanical compressor or an electrochemical compressor (ECC) – like a proton exchange membrane (PEM) ECC or a nickel hydrogen (Ni-H) ECC. While a mechanical compressor's efficiency is thermodynamically limited to the Carnot cycle, an electrochemical compressor is electrochemically limited by the materials in the system.

The refrigeration efficiency of a metal hydride heat pump (MHHP) system using a PEM ECC, Ni-H ECC, or mechanical compression was explored. The energy use and economic viability of the systems was explored for the current technology with a target payback period of 3 years on the premium over an incumbent room air conditioner (RAC). As the energy use of such a system is very dependent on the climate conditions, this analysis uses climate data for a 90 m^2 apartment in New Delhi, India, a climate reflective of the median cooling requirements of the emerging middle class. The benchmark unit operates with a seasonal COP of 3.5 and a GWP of 17601 [3].

2.2. System Overview

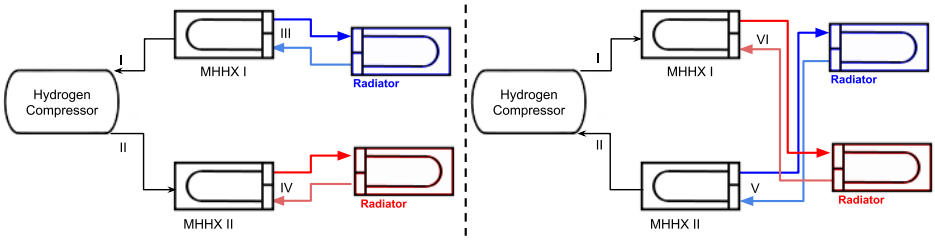


Fig. 8. MHHP RAC system half-cycles with H_2 flows (I, II) and heat transfer fluid flows (III-VI). Left: First half-cycle; Right: Second half-cycle.

Regardless of the hydrogen compressor in the system, a MHHP RAC system functions the same. During the first half of a cycle (Figure 8, left), high pressure hydrogen flows out of the compressor (II) and adsorbs onto MHHX II, while low pressure hydrogen is desorbed from MHHX I and flows into the compressor (I). The coil under low pressure adsorbs heat from the cooling fluid (III) to generate cooling power on the cold radiator, while the coil under high pressure releases heat in the waste heat exchange fluid (IV) to the hot radiator. During the second half of a cycle (Figure 8, right), the hydrogen flow is reversed. High pressure hydrogen flows out of the compressor (I) into MHHX I and low-pressure hydrogen flows out of the MHHX II and into the compressor (I). MHHX II now generates the cooling power (V) for the cold radiator and MHHX II (VI) now rejects waste heat to the hot radiator.

2.3. Benchtop Prototype PEM-ECC-MHHP System

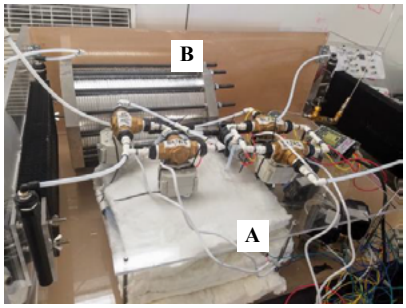


Fig. 9. Benchtop prototype air conditioner with a pair of MHHX in insulation (A) and PEM-ECC (B).

A benchtop prototype AC (Figure 9) was designed and built using 250 W PEM ECC and MHHX technology as a proof of concept. The initial run of the system (Figure 10) showed that the average temperature drop across a MHHP under low pressure is about 3.56 C and provided a 174 W cooling load (of the expected 250 W). After "breaking-in" the PEM ECC, a process that takes about 50 minutes, the PEM ECC performed as expected for about 20 minutes, until the humidifier ran out of water and the performance of the system dropped. During the time that the PEM ECC performed as expected, its average power consumption was 163 W. Although the COP of this run (~1) is less than that of the incumbent technology, the benchtop prototype provided a standard system design for the RAC systems.

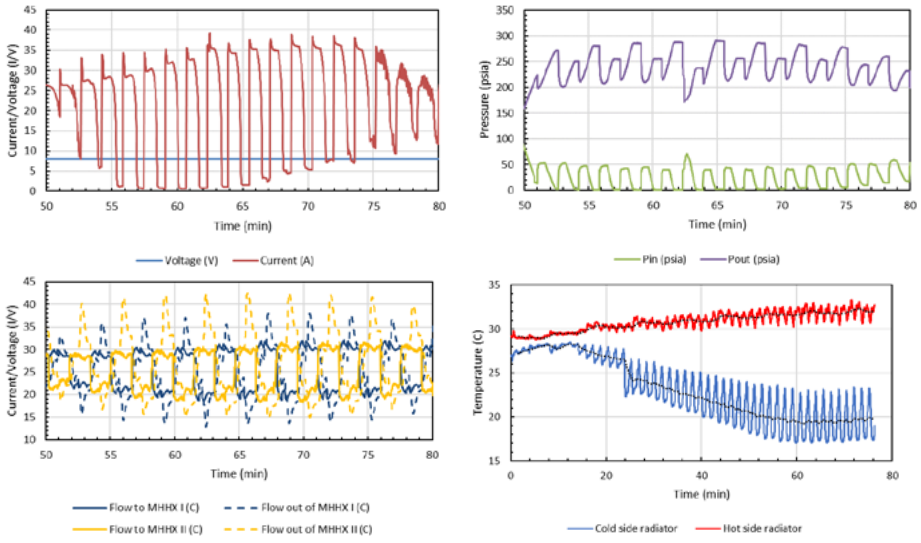


Fig. 10. (Clockwise, from top left) Compressor power, compressor pressure, and MHHX performance of benchtop prototype after first run start-up procedure, heat pump temperature throughout a run of the prototype

This analysis identified the first key engineering challenge in designing a MHHP RAC – reducing the required hydrogen flow rate. Substituting the R-2006, an AB_5 metal hydride, with R-2042, a Vanadium-BCC metal hydride, increased the hydrogen to sorption enthalpy ratio by 1.4, decreasing the required hydrogen flow by about 28%. The required hydrogen flow was further reduced by increasing the cycle time from 2 minutes to 4 minutes – reducing the required hydrogen flow by 50% but increasing the required metal hydride mass by a factor of 2.

With these modifications, the 250 W system was scaled up to a residential RAC system. An analysis of the cooling requirements of a New Delhi apartment showed that a MHHP system would require 2.5 kW of sensible cooling power to maintain a comfortable room temperature. Both PEM ECC-MHHP RAC and Ni-H ECC-MHHP systems were designed with an ILD subsystem to meet these conditions.

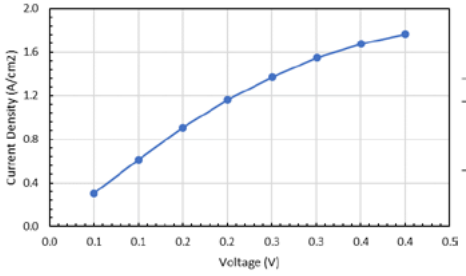
2.4. Overview of 2.5 kW MHHX Subsystem for Residential RAC

Regardless of the type of compressor used, every system has the same fundamental 2.5 kW MHHX subsystem design. The system requires 4 MHHX coils using R-2042X solid state refrigerant. Two coils make up each metal hydride heat exchanger (i.e. MHHX I and MHHX II seen in Figure 1) to provide a constant output of sensible cooling. The total subsystem material cost of the metal hydride heat exchangers is about $22.10, although this is largely due to the cost of the heat exchangers – the R-2042X solid state refrigerant would only cost an estimated $4.00. The refrigerant required for a comparable conventional air conditioner, using R-410A is about 6 lbs. Estimating from its cost on business-to-business (B2B) ecommerce sites, R-410A costs about $1.25 per pound, the total cost of conventional refrigerant is $7.50.

2.5. Residential RAC PEM-ECC-MHHP

A residential room air conditioner (RAC) with a metal hydride heat pump using a proton exchange membrane electrochemical compressor (PEM-ECC-MHHP) was designed to meet the cooling requirements of a typical New Delhi apartment. Given the modifications outlined in the previous section, the design requirements (Figure 11) of the ECC were calculated.

The key design variable in a PEM electrochemical compressor is the voltage applied to each cell. Changing the voltage applied to a cell changes the current density of the cell as dictated by the polarization curve, as seen in Figure 11. As the ECC requires a total 6,150 amps, the voltage determines both the number of cells the ECC requires as well as its power consumption and coefficient of performance.



Parameter	Requirement
Hydrogen Flow Rate (SLM)	42.9
Total Amperage (A)	6,150
Active Area (cm^2)	150

Fig.11. Polarization Curve of selected 25.4 μm PEM and design requirements of PEM-ECC for a 2.5 kW MHHP

As seen in Figure 14, the optimal COP design of the system is about 6.67. This system would require 57 cells with a voltage and current density of 0.12 V and 0.73 A/cm^2. With the current technology, the bill of materials (BOM) of the system totals to about $490.

The PEM-ECC was, again, identified as the cost critical component, equal to 62% of the total BOM. To achieve the target payback period of 3 years, the system must be improved. The membrane component of the system showed the strongest potential for improvement. The current density of a membrane can be improved at a given voltage by decreasing the thickness of the membrane. A general analysis of current membranes shows that at any given voltage the current density improves with the thickness by about 0.7-0.8 (A/cm2)/μm. As seen in Figure 12, the system requires about a 1.86X improvement to its current density to achieve a payback period of 3 years. This system would require membranes about 10μm thick and would operate at a voltage of 0.12 V with a current density of 1.36 A/cm2. The BOM of this system would be about $343. The system would have a 1.83X decrease in energy consumption and a 2.3X decrease on overall climate impact from the benchmark technology [3].

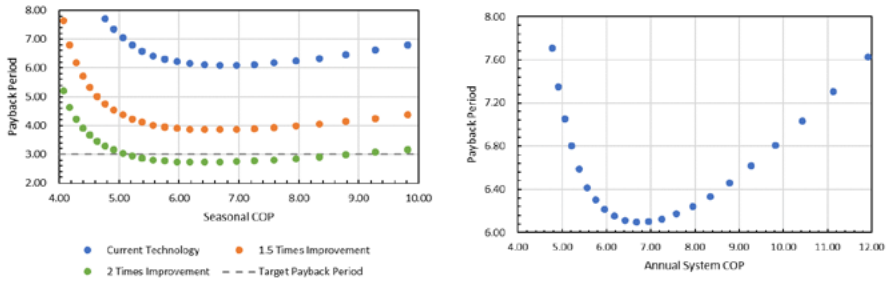


Fig. 12. Required improvement to current density of PEM ECC to achieve target payback period of 3 years (left) and payback period analysis of current PEM ECC to find optimum design COP (right)

2.6. Residential RAC Ni-H-ECC-MHHP

A Nickle Metal Hydride Electrochemical Compressor has the same design requirements as the PEM ECC. However, because the Ni-H ECC functions in a "batch" mode, compressing a batch of hydrogen to the appropriate pressure and then discharging it, two Ni-H ECC subsystems would be required to provide a continuous flow of hydrogen to the metal hydride coils. Like the PEM ECC, the key Ni-H ECC design variable is the cell voltage. However, for a Ni-H ECC, the relation between the cell voltage and the current density is considerably more linear and was assumed to be linear for the purpose of this investigation.

As seen in Figure 13, the optimum COP of the system is 5.25, achieving a payback period of 2.6 years. The given a 3-year restraint on the payback period the maximum COP of the system is 7.7. A system designed for a COP of 7.7 would require 0.044 volts per cell, resulting in a current density of 0.11 A/cm^2. The BOM of this system would be about $374 when produced at 100,000 units/year. This system would have a 2.21X reduction in power consumption from the benchmark unit and a 2.76X decrease in overall climate impact.

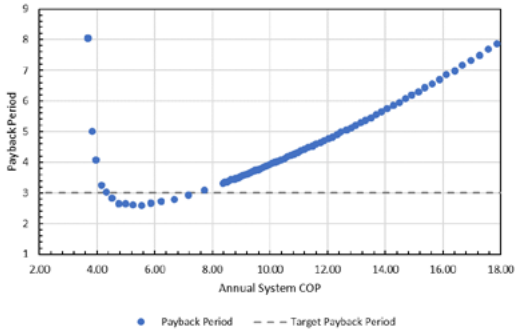


Fig. 13. Payback period analysis of Ni-H ECC to find Optimum Design COP

2.7. Residential RAC Using Rotary Compression MHHP with Integrated ILD System

While electrochemical compressors have the potential to greatly increase the COP of a MHHP RAC, conventional RAC rotary and scroll compressors can also provide the required hydrogen flow. A rotary mechanical compressor designed for a 6000 BTU/hr., R-22 RAC was substituted for the PEM-ECC in the R-2008 benchtop prototype. This mechanical compressor provided a hydrogen flow rate of 30 SLPM-H2 – 5X the required hydrogen flow for the 250 W unit. Therefore, the RAC providing 2.5 kW of sensible cooling would require 8,600 BTU/hr. mechanical compressor to provide ~42.9 SLPM-H2.

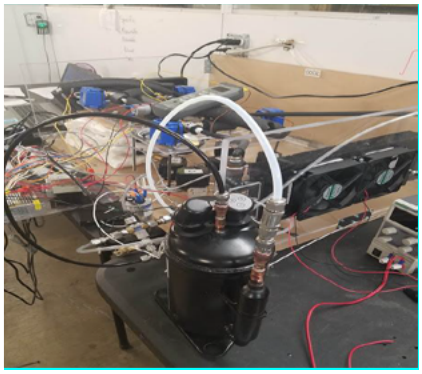


Fig. 14. Benchtop RAC prototype (250 W, R-2008) using a rotary compressor designed for a 6000 BTU/hr. (1758 W) RAC using R-22

An analysis of the compressors rotary and scroll compressor products product found that the average COP of these compressors, when using R-22 is 3.17 [4]. The average COP of these compressors in a R-2042 MHHP subsystem would be 4.52, with a power consumption of 550 W. While these systems were not designed nor optimized for hydrogen flow, they still show strong potential for a high efficiency cooling solution. The MHHX component costs of the RAC is comparable to the non-compressor components of a conventional RAC. Therefore, a RAC utilizing a conventional compressor shows strong potential for an early, low cost MHHP-RAC.

2.8. Comparative Cost Analysis

With the current technology, the Ni-H ECC was found to be a much more effective system than the PEM ECC. The main cost difference between the Ni-H ECC and PEM ECC is the cost of the electrochemical cells. As seen in Table 1, although the Ni-H ECC requires considerably more cells, the cost per cell is far lower. This is largely due to the decreased material cost of the Ni-H bipolar plates and electrode. The Ni-H uses 1% platinum carbon rather than the more costly pure platinum coating of the PEM cells. The PEM plates are over 10x thicker than the Ni-H plates, requiring much more material.

Table 1. Cost Comparison between the Ni-H ECC (0.068 V, 0.17 A/cm2) and PEM ECC (0.125 V, 0.761 A/cm2) Designed for a Minimum Payback Period Using Current Technology

Component	Ni-H Cost per Cell	PEM Cost per Cell
Electrode	$0.323	$2.833
Metal Support	$0.029	$0.05
Gasket & Sealing	$0.098	$0.756
Bipolar Plate	$0.049	$2.00
Total Cost per Cell	**$0.0490**	**$0.5639**
Optimal Number of Cells	296	54
Cost of Cells	$145.04	$304.51
Cost of other Components	$50.00	$58.28
Optimal COP	5.25	6.67
Minimum Payback Period (yrs.)	2.6	6.11

3. ULT Freezer Application

A ULT freezer is freezer that operates between -40 and -86°C. Modern ULT freezers typically use up to 20 times the energy footprint of household fridges. One approach to building these units involves employing hydrofluorocarbon R-508B. Alternatively, Dichlorodifluoromethane (R-12) and Chlorodifluoromethane (R-22) are also used for this application as a refrigerant, although recently their use has been banned under the

Montreal Protocol. These units are used for many sensitive applications (such as storage of medical samples) and operate 24-7 consuming significant energy; and operate with very poor efficiency (COP < 0.5).

One feature of solid-state refrigerant heat pump systems is their ability to provide significantly higher efficiencies at ultra-low temperatures. Changes of temperatures of almost -100°C are being demonstrated (Figure 15) with very small diameter tubing possessing extremely high surface areas per unit mass and unit volume.

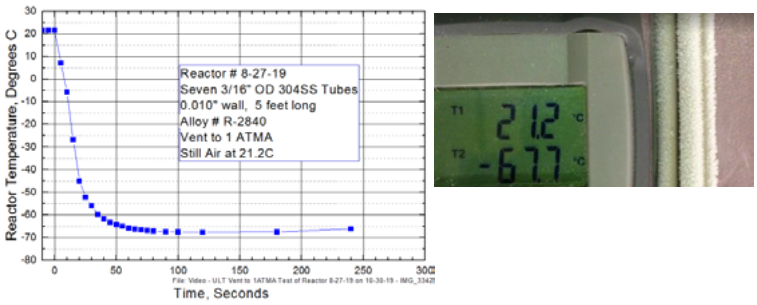


Fig. 15. Reactor temperature of ultra-low temperature (ULT) prototype run (left) and prototype reactor showing frost on surface (right)

An additional advantage of metal hydride air conditioners, refrigerators and ULT freezers is their ability to run on low grade thermal energy (such a solar thermal or geothermal energy). Even heat source temperatures as low as 70°C can be used for any application because the metal hydride alloys can be "staged" to produce any pressure needed to operate the metal hydride device.

Figure 16 below demonstrates this unique ability where only 70°C hot water can be used to compress Hydrogen gas from 21 psia up to over 5000 psig using only five stages of metal hydride alloys. This is possible because each hydride alloy will generate a threefold pressure rise (via the 70°C heat) during its compression stage, thus increasing the hydrogen outlet pressure to over three times the inlet pressure coming into the hydride stage. Each following hydride "stage" has been alloyed engineered to accept the "high pressure" hydrogen gas exiting the previous hydride stage as it's "low pressure' inlet hydrogen. Additionally, multi-staged metal hydrides can be applied beyond heat pump applications to high pressure hydrogen gas generation.

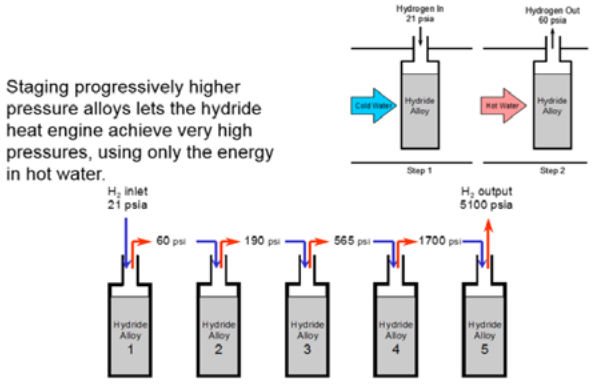


Fig. 16. Low-cost solar thermal energy can be used as the energy source to power (top right); Multi-staged MH Alloys to produce cooling, gas liquefaction and high-pressure hydrogen gas generation.

4. Conclusions & Further Applications

The comparably low cost of solid-state refrigerant per ton of cooling, as well as the removal of materials with global warming potential, is very promising for its use to reduce the carbon footprint of residential air

conditioners. Metal hydride technology utilizes the exceptional heat transfer ability of metal hydride alloys - housed in very small diameter tubes - to create extremely large external surface areas per unit volume, mass and cost. This new heat transfer technology is a new technology platform that represents a paradigm shift in the reduction of energy use, and the cost of, many of our cooling, heating and power generation products, and will greatly speed up our transition to a solar energy economy.

5. Nomenclature

Table 2. Acronyms and abbreviations, defined

Term	Definition	Term	Definition
AB2	Linear molecular geometry	MHHX	Metal hydride heat exchanger
AB5	Trigonal bipyramidal geometry	Mm	Mischmetal
B2B	Business-to-business	Ni-H	Nickel-hydrogen
BCC	Body-centered cubic	PCT	Pressure-concentration-temperature
BOM	Bill of materials	PEM	Proton exchange membrane
COP	Coefficient of performance	P_H	Pressure (high)
ECC	Electrochemical compressor	P_L	Pressure (low)
GWP	Global-warming potential	P_P	Pressure (plateau)
IMC	Intermetallic compound	RAC	Room air-conditioner
MH	Metal hydride	SR	Sorbent refrigerant
MHHP	Metal hydride heat pump (a system containing 2+ MHHX)	ULT	Ultra-low temperature

Acknowledgements

This work was supported by a research award DE-EE-0008218 funded by the U.S. Department of Energy, Building Technologies Office. The technologies outlined in this paper are protected by US Patents referenced [5].

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6. Appendix I: Proposed Nomenclature for Sorbent Refrigerants

6.1. Appendix I.A: Nomenclature for Metal Hydride Solid State Refrigerants

Below is the proposed nomenclature for metal hydride based, solid state refrigerants (the R-2000 series refrigerants). The R-2100 to R-2300 series refrigerants are Vanadium-BCC metal hydrides. The R-2400 to R-2600 series refrigerants are AB5-type intermetallics. The R-2700 series refrigerants are TiFe based, AB-type intermetallics. The R-2800 to R-2900 series refrigerants are AB2-type intermetallics. The R-20XX series refrigerants have been left as a place holder for miscellaneous, novel, and proprietary metal hydride refrigerants.

Table 3. Metal Hydride Solid State Refrigerants

Metal Hydride Solid State Refrigerant	**Metal Hydride Class**	**SR Designation**
V(75)Ti(17.5)Zr(7.5)	V-BCC	R-2120

V(75)Ti(10)Zr(7.5)Cr(7.5)	V-BCC	R-2300
V(0.85)Ti(0.1)Fe(0.05)	V-BCC	R-2310
V(92.5)Zr(7.5)	V-BCC	R-2220
MmNi(4.8)Al(0.2)	AB_5	R-2410A
LaNi(4.7)Sn(0.3)	AB_5	R-2560A
LaNi(4.8)Sn(0.2)	AB_5	R-2560B
LaNi(4.8)Sn(0.2)	AB_5	R-2560C
Mm(0.5)La(0.5)Ni(4.7)Sn(0.3)	AB_5	R-2660
LaNi(4.8)Al(0.2)	AB_5	R-2510
LaNi(5)	AB_5	R-2500
MmNi(4.7)Fe(0.3)	AB_5	R-2440A
La(0.85)Ce(0.15)Ni(5)	AB_5	R-2570
MmNi(4.7)Al(0.3)	AB_5	R-2410B
La(0.2)Y(0.8)Ni(4.6)Mn(0.4)	AB_5	R-2535
MmNi(4.15)Fe(0.85)	AB_5	R-2440B
La(0.4)Ce(0.4)Ca(0.2)Ni(5)	AB_5	R-2527
Mm(1-x)Ca(x)Ni(5-y)Al(y)	AB_5	R-2412
Ca(0.2)Mm(0.8)Ni(5)	AB_5	R-2420
TiFe(0.9)Mn(0.1)	AB	R-2700
Zr(0.7)Ti(0.3)Mn(2)	AB_2	R-2860
Ti(0.9)Zr(0.1)Mn(1.4)Cr(0.35)V(0.2)Fe(0.05)	AB_2	R-2871
Ti(0.8)Zr(0.2)CrMn	AB_2	R-2870A
Zr(0.8)Ti(0.2)FeNi(0.8)V(0.2)	AB_2	R-2832
Ti(0.77)Zr(0.3)Cr(0.85)Fe(0.7)Mn(0.25)Ni(0.2)Cu(0.03)	AB_2	R-2875
TiCr(1.9)Mo(0.01)	AB_2	R-2816B
TiCr(1.9)	AB_2	R-2810
ZrFe(1.8)Cr(0.2)	AB_2	R-2913
[Ti(0.97)Zr(0.03)](1.1)Cr(1.6)Mn(0.4)	AB_2	R-2870B
TiCr(1.5)Mn(0.25)Fe(0.25)	AB_2	R-2843A
TiCr(1.5)Mn(0.2)Fe(0.3)	AB_2	R-2843B
TiCrMn	AB_2	R-2840
ZrFe(1.8)Ni(0.2)	AB_2	R-2904
Ti(0.86)Mo(0.14)Cr(1.9)	AB_2	R-2816A
Xergy ULT Refrigerant	AB_2	R-2028X
Xergy A/C Refrigerant	AB_5	R-2006X
Xergy A/C Refrigerant	V-BCC	R-2042X

6.2. Appendix I.B: Nomenclature for other Sorbent Refrigerants

Other sorbent refrigerants include Metal Organic Framework (MOF) solid state refrigerants (R-3000s) and liquid desiccant (LD) sorbent liquid refrigerants (R-4000s). The proposed general nomenclature for these refrigerants can be found in the table below.

Table 2. Metal Organic Framework Solid State Refrigerants

Metal Organic Framework Classification	Dimension of Organic/Inorganic	SR Series
Molecular Complexes	0/0	R-30XX

Chain Coordination Polymers	1/0	R-31XX
Layered Coordination Polymer	2/0	R-32XX
3-D Coordination Polymer	3/0	R-33XX
Hybrid Inorganic Chains	0/1	R-34XX
Mixed Inorganic-Organic Layers	1/1	R-35XX
Mixed Inorganic-Organic 3-D Framework	2/1	R-36XX
Hybrid Inorganic Layers	0/2	R-37XX
Mixed Inorganic-Organic 3-D Framework	1/2	R-38XX
3-D Inorganic Hybrids	0/3	R-39XX

Table 3. Liquid Desiccant Sorbent Liquid Refrigerants

Liquid Desiccant Classification	**SR Series**
Room Temperature Ionic Liquid Desiccant	R-41XX
Alkali Metal Liquid Desiccant	R-42XX
Alkali Earth Metal Liquid Desiccant	R-43XX
Organic Liquid Desiccant	R-44XX