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METAL HYDRIDE COOLING FOR SPACE APPLICATIONS

Hal J. Strumpf
Honeywell Aerospace, Torrance, U.S.A.

Abstract

Metal hydride systems have the potential to provide cooling or refrigeration for a variety of space applications. The cooling can often be accomplished at low electrical power requirements, always critical for space-based systems. Due to the high density of metal hydrides, the systems tend to be very compact, minimizing precious volume and envelope. However, the relatively low hydrogen capacity of metal hydrides tends to make the systems heavy. Thus, metal hydride applications are best suited for systems where power and volume are more critical than weight.

This paper presents descriptions of three metal hydride systems investigated by Honeywell Aerospace (formerly AlliedSignal Aerospace). These systems include a 10 K sorption cryocooler system for periodic cooling of a focal plane array for a low-earth orbit satellite, a batch-mode astronaut cooling system for extravehicular activity, and a continuous space habitation cabin cooling system to remove electrical and metabolic heat loads.

KEYWORDS

Metal Hydrides, Refrigeration, Space Applications, Cryocooler, Extravehicular Activity

INTRODUCTION

Metal hydride systems have the potential to provide cooling or refrigeration for a variety of space applications. The cooling can often be accomplished at low electrical power requirements, always critical for space-based systems. This is especially true if low grade sources of waste heat are available to be used to provide some or all of the pumping or compression power.

Due to the high density of metal hydrides, the systems tend to be very compact, minimizing precious volume and envelope. However, the relatively low hydrogen capacity of metal hydrides tends to make the systems heavy. Thus, metal hydride applications are best suited for systems where power and volume are more critical than weight.

A number of applications have been investigated by Honeywell Aerospace (formerly AlliedSignal Aerospace prior to the merger of AlliedSignal and Honeywell). These applications include personal astronaut cooling during extravehicular activity, food refrigeration and freezing, detector cooling for earth observation, extraordinary medical needs, and habitation cabin cooling. A number of these systems are described below. There are other applications for space use of metal hydrides as a hydrogen storage medium (rather than to provide cooling) that have been investigated by Honeywell Aerospace. These are not discussed in the present paper.

Certain metals react with hydrogen to form a metal/hydrogen compound called a metal hydride. Such reactions are often fully reversible, i.e.,

$M + H \Leftrightarrow MH$; where M is the reacting metal.

At a given temperature, the forward reaction (hydrogen absorption) and the reverse reaction (hydrogen desorption) occur at a relatively constant pressure over a wide range of compositions. This pressure, called the plateau pressure, may be different for the absorbing and desorbing isotherms, because of repeatable hysteresis effects. The absorption reaction is usually exothermic, while the desorption reaction is usually endothermic. The process can be repeated indefinitely as long as the reaction remains reversible, the material does not degrade, and the alloy does not undergo side reactions to form stable metal hydrides or nonreactive species.

In the cooling mode, a fully hydrided alloy would desorb hydrogen endothermically, while absorbing and consuming the heat load from the component or system to be cooled. In a sealed vessel, this process would lead to an increase in the hydrogen pressure to a value above the plateau pressure of the metal hydride at the desired temperature. To maintain constant pressure (and temperature), the hydrogen must be released to an unhydrided bed of a different alloy, where it can be absorbed. Since the absorption reaction is exothermic, the released heat of reaction would need to be removed by a heat sink, which can be at a higher temperature than the cooling load. This process would continue until all the hydrogen in the cooling bed is transferred to the absorbing bed. An alternative approach could allow for venting of the hydrogen to space, eliminating the need for the second bed and the heat sink, but requiring the consumption of hydrogen.

Successful application in practical systems requires particular properties of the hydrided alloys. Good alloy candidates must have high heats of reaction. This parameter dictates, along with the density of the alloy and the total uptake of hydrogen, the total energy density of the material. High energy densities allow for volume and/or weight minimization for a given cooling requirement. The plateau pressures must also be in the range of the operational constraints of the system.

Suitable alloys must also have reasonable kinetics of absorption and desorption. Rapid kinetics of desorption are required for operation during the cooling mode. If it is extremely difficult to recharge the alloy to its fully hydrided state due to unfavorable absorption kinetics, it may be impractical to regenerate the material after use.

PERIODIC 10 K METAL HYDRIDE SORPTION CRYOCOOLER SYSTEM

A study was performed to develop a metal hydride sorption cryocooler system capable of supplying periodic refrigeration at 10 K. The system is intended to cool a focal plane array for a low-earth orbit satellite. The refrigeration is effected by sublimating solid hydrogen at 10 K. The solid hydrogen is produced in a batch process by cooling, solidifying, and subcooling liquid hydrogen formed at 30 K by a Joule-Thomson (J-T) expansion.

The spent hydrogen from the sublimation and J-T expansion is absorbed by two metal hydride sorption bed assemblies. One bed operates at a low pressure corresponding to the hydrogen vapor pressure at 10 K, while the other bed operates at a higher pressure corresponding to the hydrogen vapor pressure at 30 K. The reversible properties of metal hydrides allow for hydrogen storage and retrieval and enable recycling of the hydrogen used to produce the refrigeration. After the periodic refrigeration intervals are complete, hydrogen is desorbed from the metal hydride beds by heating. The heating results in thermal compression of the hydrogen and allows a high-pressure hydrogen source to be refilled as required for the batch refrigeration process. The two bed assemblies are similar in configuration but are of different capacity and utilize different metal hydride materials (appropriate to the operating conditions).

System Requirements

The basic system requirements are summarized in Table 1.

Table 1. System Requirements

Parameter	Requirement
Focal plane temperature, K	10
Focal plane heat load, W	0.1
Focal plane cavity temperature, K	30
Cavity heat load, W	0.5
Upper stage temperature, K	65
Upper stage heat load, W	1.5
Cooldown time to 10 K, s	120
Cooling duration, h	0.25
Cycle time between cooldowns, h	1.5
Consecutive cooldowns before recharge	3
Total cycle time, h	24
Heat rejection temperature, K	250
Focal plane weight (beryllium), g	600
Operational life, yr	10

System Architecture

The overall system schematic shown in Figure 1 is a modified version of that of Bard, *et al.* [1] The system provides for cooling loads at three temperatures: 65 K, 30 K, and 10 K. The continuous 65-K load is provided by a mechanical cryocooler.

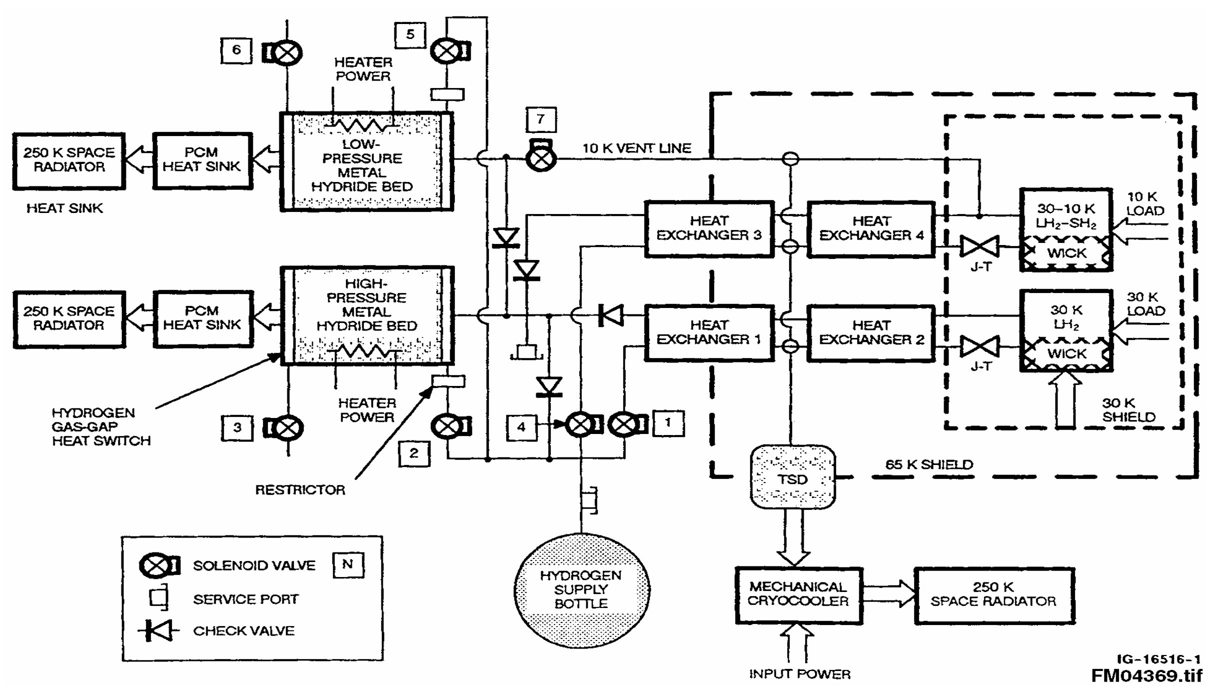

Fig. 1. Periodic 10 K Sorption Cryocooler

The cooling load at 30 K is intermittent. This cooling is accomplished by the J-T expansion of hydrogen, producing a mixture of hydrogen liquid and vapor. The liquid hydrogen is collected in a porous wick that interfaces with the heat load. Precooling for the J-T expansion (necessary because of the relatively low

J-T inversion temperature of hydrogen) is provided by a thermal storage device (TSD), cooled by the mechanical cryocooler. The TSD comprises hydrogen flow passages embedded in a thermal storage material (a high heat capacity metal, such as lithium or magnesium, operating in the 60-to 70-K range).

The hydrogen vapor remaining after the J-T expansion, as well as the hydrogen vaporized by the heat load, is absorbed by the high-pressure metal hydride sorption bed. The released heat of reaction is absorbed by a paraffin wax phase change material (PCM) heat of fusion heat sink, which enables constant-temperature operation of the sorption bed.

After the intermittent cooling period, the absorbed hydrogen is recycled using thermal compression. To effect this thermal compression, the metal hydride bed is heated to a relatively high temperature. This raises the equilibrium hydrogen pressure and enables the hydrogen to be transferred to a high-pressure storage bottle by bed desorption. During the recovery period, the TSD is cooled by the mechanical cryocooler, and the paraffin wax heat sink is regenerated by rejecting the heat of fusion to space using a radiator.

The cooling load at 10 K is also intermittent. The cooling is provided by hydrogen sublimation at 10 K. The 10 K is attained by cooling and solidifying the 30 K liquid produced by the J-T expansion by exposure to low pressure provided by the low-pressure metal hydride sorption bed. During regeneration, the hydrogen stored in the low-pressure bed is first transferred to the high-pressure bed by thermal compression and then to the hydrogen storage bottle by a second compression step.

Low-Pressure Metal Hydride Bed Assembly

The low-pressure metal hydride bed assembly is shown in Figures 2 and 3 [2]. The configuration is an integral assembly comprising a metal hydride bed containing metal hydride powder, a gas gap thermal switch, a PCM heat of fusion heat sink, and a space radiator.

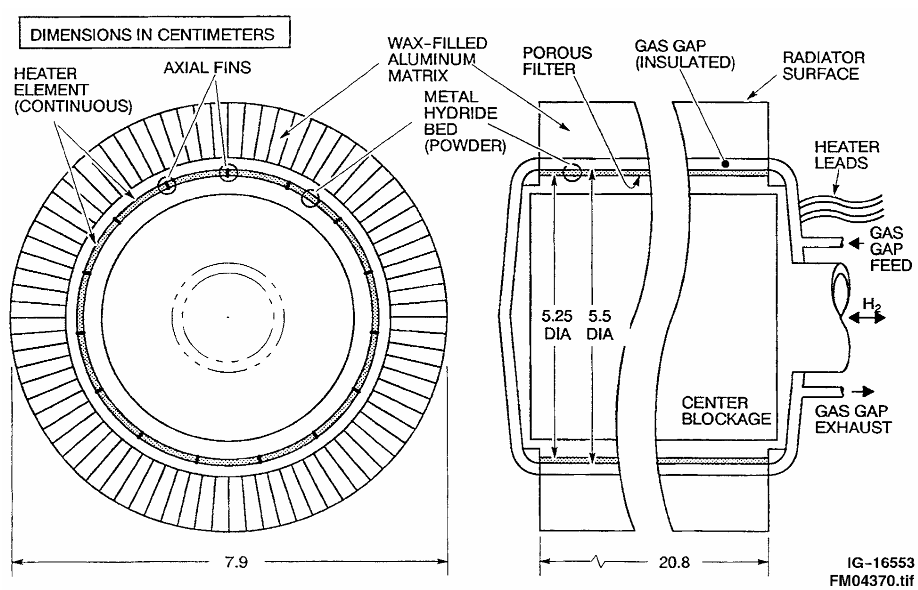

Fig. 2. Low-pressure Metal Hydride Bed Assembly

Hydrogen flows into or out of the bed via a duct with walls fabricated from a porous stainless-steel plate used to support a porous filter. The duct has a center blockage to reduce wasted volume. This arrangement allows for a uniform flow in the radial direction, thus minimizing pressure drop. The particles of metal hydride powder reside in an annular region between the porous filter and an outer stainless-steel tube, which contains the hydrogen pressure. Axial and radial stainless-steel fins attached to the porous plate promote effective heat transfer and compartmentalize the metal hydride particles. The outer tube fits over the fins, forming the metal hydride compartments. A continuous heater element is wound within the fin passages. This element provides the heat for hydrogen desorption.

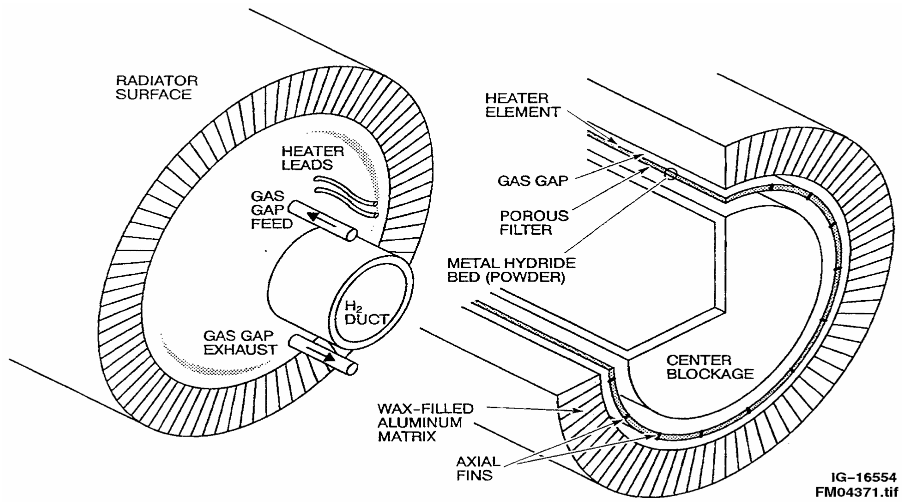

Fig. 3. Low-pressure Metal Hydride Bed, Isometric View

The metal hydride bed is surrounded by an annular gas gap. The gap is filled with aluminum multilayer insulation. The gas gap functions as a thermal switch, offering a conductive path when filled with hydrogen and acting as an insulator when evacuated.

Outside the gas gap is the heat-of-fusion heat sink, consisting of an aluminum structure containing the paraffin wax PCM. The structure is composed of inner and outer tubes with axial fins in the annular region. The PCM is contained and compartmentalized within the fin passages. The aluminum outer surface of the heat sink acts as the radiator, and is treated with an appropriate coating.

The metal hydride material selected for the low-pressure bed is zirconium nickel. This metal exhibits a reversible hydriding reaction between hydrides of nominal composition ZrNiH and $ZrNiH_3$. The ZrNiH composition represents the solubility limit. The selected PCM is n-docosane (n-$C_{22}H_{46}$), a normal paraffin wax with a congruent melting temperature of 317 K.

High-Pressure Metal Hydride Bed Assembly

The high-pressure bed assembly is similar in configuration to the low-pressure bed assembly. The high-pressure bed is much larger than the low-pressure bed, absorbing almost twenty times the mass of hydrogen. The high-pressure bed assembly is shown in Figures 4 and 5 [3].

The metal hydride material selected for the high-pressure bed is the modified lanthanum/nickel alloy, $LaNi_{4.8}Sn_{0.2}$. The selected PCM is n-tetradecane (n-$C_{14}H_{30}$), a normal paraffin wax with a congruent melting temperature of 279 K.

System Integration and Performance

The system integration concept is shown in Figure 6. This package provides for a compact cyrocooloer assembly utilizing appropriate shielding. The system performance meets the requirements listed in Table 1 at a power usage of 90 W.

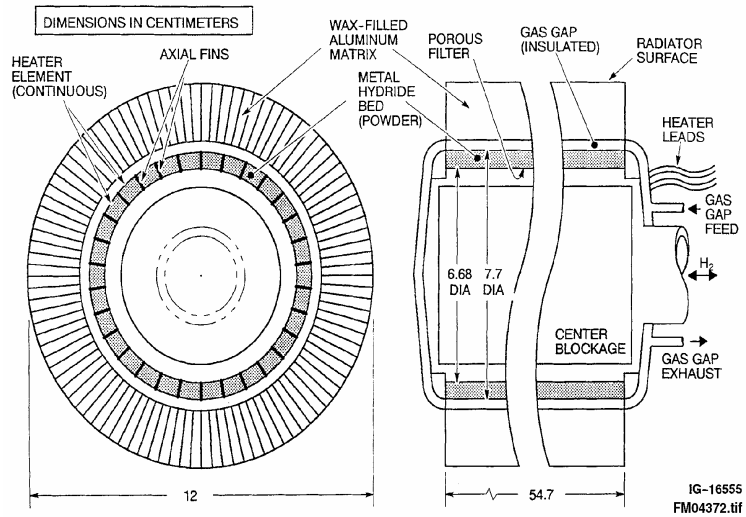

Fig. 4. High-pressure Metal Hydride Bed Assembly

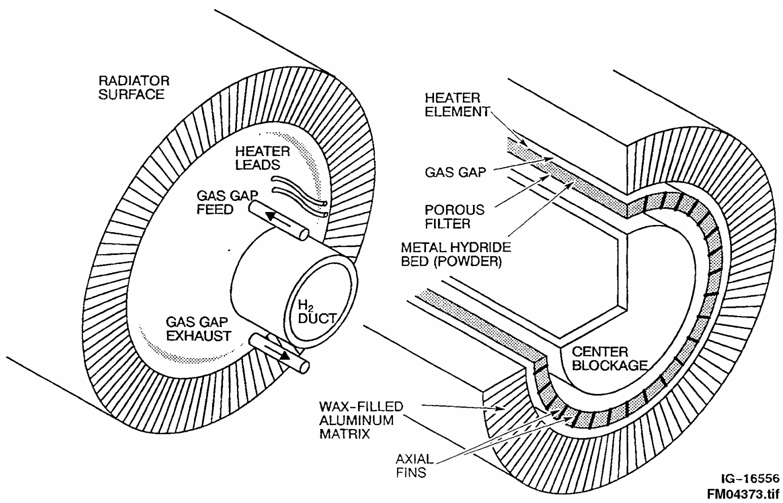

Fig. 5. High-pressure Metal Hydride Bed, Isometric View

METAL HYDRIDE ASTRONAUT COOLING SYSTEM

A metal hydride system has been designed to provide a heat sink for personal astronaut cooling during extravehicular activity (EVA). The metal hydride heat sink is a component of the coolant loop subassembly for an advanced space suit portable life support system extravehicular mobility unit (EMU) for space station or lunar applications. The heat sink absorbs and rejects metabolic and equipment heat loads generated during EVA. The heat loads are transported by water circulating through the coolant loop. To minimize mass, the heat sink vents hydrogen to space, operating in the desorbing mode only. The sink is regenerated after EVA in a habitation module by absorbing hydrogen.

A number of different types of heat sinks are under consideration for the advanced space suit, including waxes, ice, sublimators, and boilers, each in possible combination with a space radiator. The metal hydride heat sink offers a number of advantages compared to other approaches. Primary among these advantages is the high heat of hydrogen desorption per unit of metal volume. This results in considerably smaller component volume compared to wax or ice heat-of-fusion heat sinks. Volume is of critical importance in the size-limited EMU. Compared to water sublimators or boilers, the metal hydride heat sink offers an order of magnitude reduction in amount of vented material. In addition to the obvious resupply benefits, the nonpolar, radiation-transparent hydrogen is a more benign vent material than water. This is reflected in the two orders of magnitude reduction in allowable molecular column density in the vicinity of International Space Station for water as compared to hydrogen.

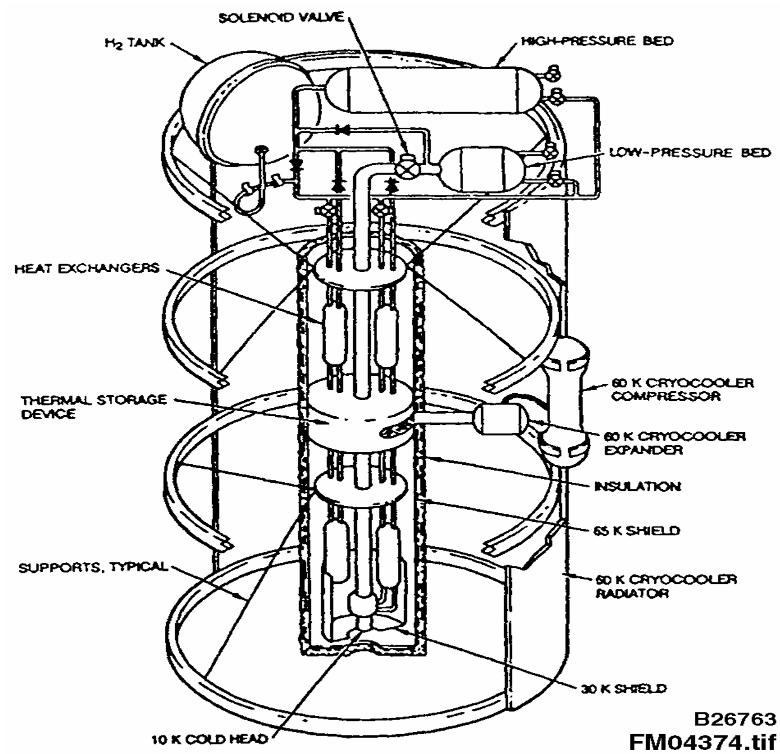

Fig. 6. System Integration

System Architecture and Operation

A simplified system schematic is shown in Figure 7. The coolant water is circulated through the coolant loop by a pump. The water picks up metabolic and environmental heat loads in the liquid-cooled ventilation garment (LCVG) and additional equipment heat loads downstream of the pump, including that from the metal oxide carbon dioxide and humidity remover (MOCHR). The water flows across the automatic cooling control unit (ACCU) to the heat rejection system (HRS), which removes the accumulated heat loads. Depending on the desired temperature at the LCVG inlet, the ACCU bypasses some of the coolant water around the HRS. The water exiting from the HRS combines with the bypassed water and flows through the trim cooler. This heat exchanger cools the vent loop breathing gas. The water exiting the trim cooler is supplied to the LCVG.

In the HRS, there is a radiator in series with the metal hydride heat exchanger. The radiator, which covers the outer surface of the astronaut's backpack, utilizes available direct heat rejection to space, minimizing the heat load on the metal hydride unit. The coolant water first flows through the radiator, rejecting heat to space at the highest system temperature. Heat rejection in the metal hydride cooler is regulated by a backpressure valve. When completely closed, the backpressure valve prevents any hydrogen desorption, resulting in a zero heat rejection rate. As the valve is opened, hydrogen is desorbed to space. The valve position regulates the hydrogen desorption rate, which is directly related to the heat rejection rate.

The maximum coolant water temperature exiting the HRS is set a few degrees below the minimum required comfort temperature—around 10 deg C. This is desirable for smooth system control, and enables the ACCU to always control the inlet LCVG temperature. If the radiator can cool the water below 10 deg C at the proper ACCU setting, the backpressure valve remains closed.

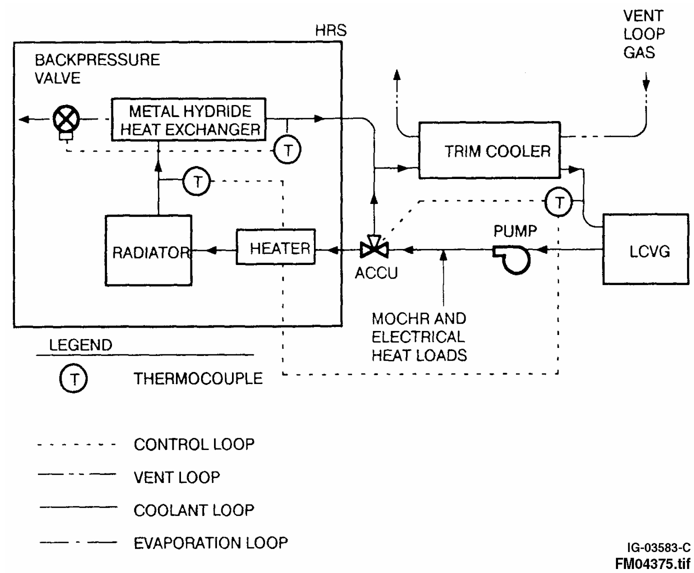

Fig. 7. Coolant Loop Operation

Total hydrogen usage for a typical eight-hour mission is 0.4 kg.

Metal Hydride Heat Exchanger Design

The metal hydride material is the vanadium alloy $(V_{0.89}Ti_{0.11})_{0.95}Fe_{0.0\ 5})$. This material has a high heat of reaction and good hydrogen capacity. The metal hydride heat exchanger is in the form of a stainless steel, plate-fin, cross-counterflow heat exchanger, multipassed on the water side. Alternating fin layers are for the coolant loop water and metal hydride sides. The metal hydride-side fins are packed with metal hydride powder. Both ends of the metal hydride-side passages are open to a hydrogen plenum; thus, the effective hydrogen flow length is one-half the heat exchanger passage length. The design is shown in Figure 8. As indicated, there are four water-side passes. The single-pass water flow length is 30.5 cm, the metal hydride-side flow length is 9.0 cm, and the stack height is 28.7 cm. There are 20 sets of flow passages. Total loaded weight is 16 kg.

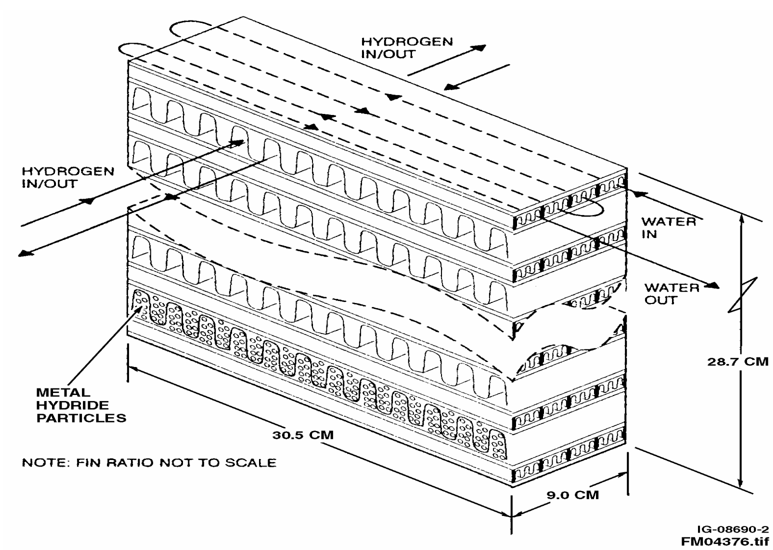

Fig. 8. Metal Hydride Heat Exchanger

An alternative to the series radiator—metal hydride heat exchanger design is an integral configuration. This approach spreads out the metal hydride to a thickness of one fin layer, covering the entire backpack inside radiator surface (approximately 1 m^2). A typical design is shown in Figure 9. The cooling water flows through a single-layer coldplate heat exchanger mechanically attached to the metal hydride passage. This configuration presents a useful packaging option.

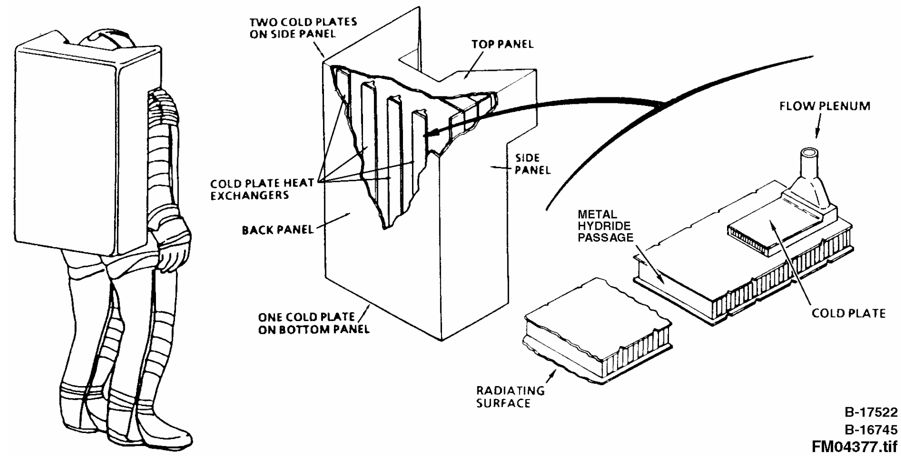

Fig. 9. Integral Metal Hydride/Radiator System

METAL HYDRIDE HABITATION CABIN COOLING SYSTEM

Continuous cooling can be provided for a space habitation cabin using a series of cycled metal hydride beds. The cabin heat loads, which are collected by a heat transport fluid, include both electronic and metabolic heat. Power for the cooling is provided primarily by waste heat. Small amounts of additional power are required for pumping and valve operation. Waste heat must be available at a moderately-high temperature, assumed to be around 150 deg C for the present system. In addition, an intermediate-temperature heat sink (at around 65 deg C) is required. This can be provided by a space radiator or process flow stream. Cooling is effected at 25 deg C.

A proposed system architecture is shown in Figure 10. Two sets of cooling and absorbing beds are required to provide continuous operation. While the first set of beds is providing the cooling function, the second set of beds is being regenerated. After regeneration, the beds are switched.

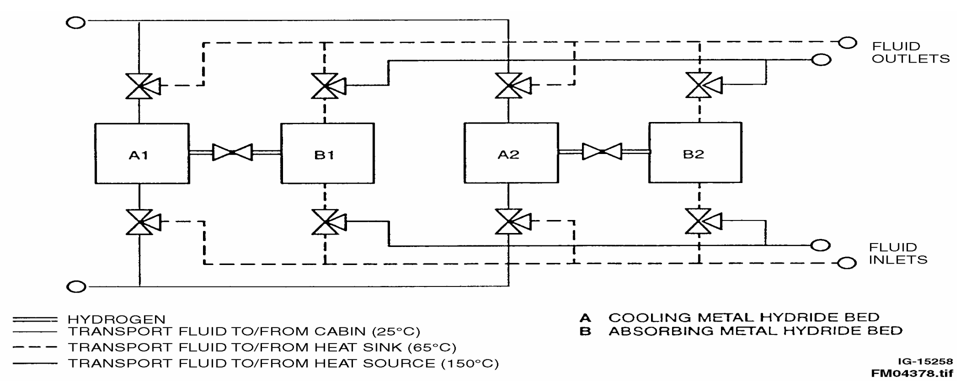

Fig. 10. Cooling System Architecture

The system requires three transport fluid lines: one connecting to the cabin heat load, another connecting to the heat sink, and the third to the heat source. The same transport fluid is used for all lines. Appropriate fluid heat exchangers are, of course, required. These devices are standard components and are not discussed here.

System operation occurs as follows. At the start of a cycle, bed A1 is partially loaded with hydrogen and is at 25 deg C. Bed B1 is desorbed of most of its hydrogen and is at 65 deg C. Bed A2 is desorbed of most of its hydrogen and is at 25 deg C. Bed B2 is partially loaded with hydrogen and is at 65 deg C. Transport fluid from the cabin flows through bed A1, which operates at 25 deg C. The transport fluid is cooled by the endothermic hydrogen desorption reaction. Hydrogen from bed A1 is released to bed B1, which operates at 65 deg C, being cooled by the transport fluid from the heat sink. Beds A1 and B1 operate in these modes for the complete half-cycle.

Bed B2 is heated to 150 deg C by the transport fluid from the heat source. This raises the temperature and pressure in the bed. Desorption continues at 150 deg C into bed A2, which is cooled by the transport fluid. The hydrogen transfer is completed prior to the end of the half-cycle. After hydrogen transfer, the hydrogen valve is closed. Transport fluid from the heat sink then flows through bed B2, cooling the bed to 65 deg C. At this time, the hydrogen valve is opened and some hydrogen is desorbred from bed A2 to bed B2. The desorption cools bed A2 to 25 deg C. At this time, the half-cycle is complete, and the beds are switched. Bed A2 now operates in the cooling mode and bed B2 operates in the absorbing mode. Beds A1 and B1 operate in the regeneration mode. Each metal hydride bed is similar in configuration to the bed shown in Figure 8—the sizes are different and the water is replaced with an appropriate high-temperature transport fluid.

Two separate metal hydrides bed designs and materials are required—one for the cooling beds (A1 and A2) and one for the absorbing beds (B1 and B2). A good candidate material for the cooling beds is the alloy $(V_{0.89}Ti_{0.11})_{0.95}Fe_{0.05}$. This alloy has an approximate desorbing pressure of 0.20 MPa at 25 deg C and an approximate absorbing pressure of 1.5 MPa at 65 deg C. For the absorbing beds, a good candidate material is another vanadium alloy, $(V_{0.9}Ti_{0.1})_{0.98}Fe_{0.02}$. This alloy has an absorbing plateau pressure of 0.16 MPa at 65 deg C .

References

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