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Golben

(54) METAL HYDRIDE BASED VEHICULAR EXHAUST COOLER

(75) Inventor: **Peter Mark Golben**, Florida, NY (US)

Correspondence Address:
HAYNES AND BOONE, LLP
901 MAIN STREET, SUITE 3100
DALLAS, TX 75202 (US)

(73) Assignee: **HERA USA Inc.**, Ringwood, NJ

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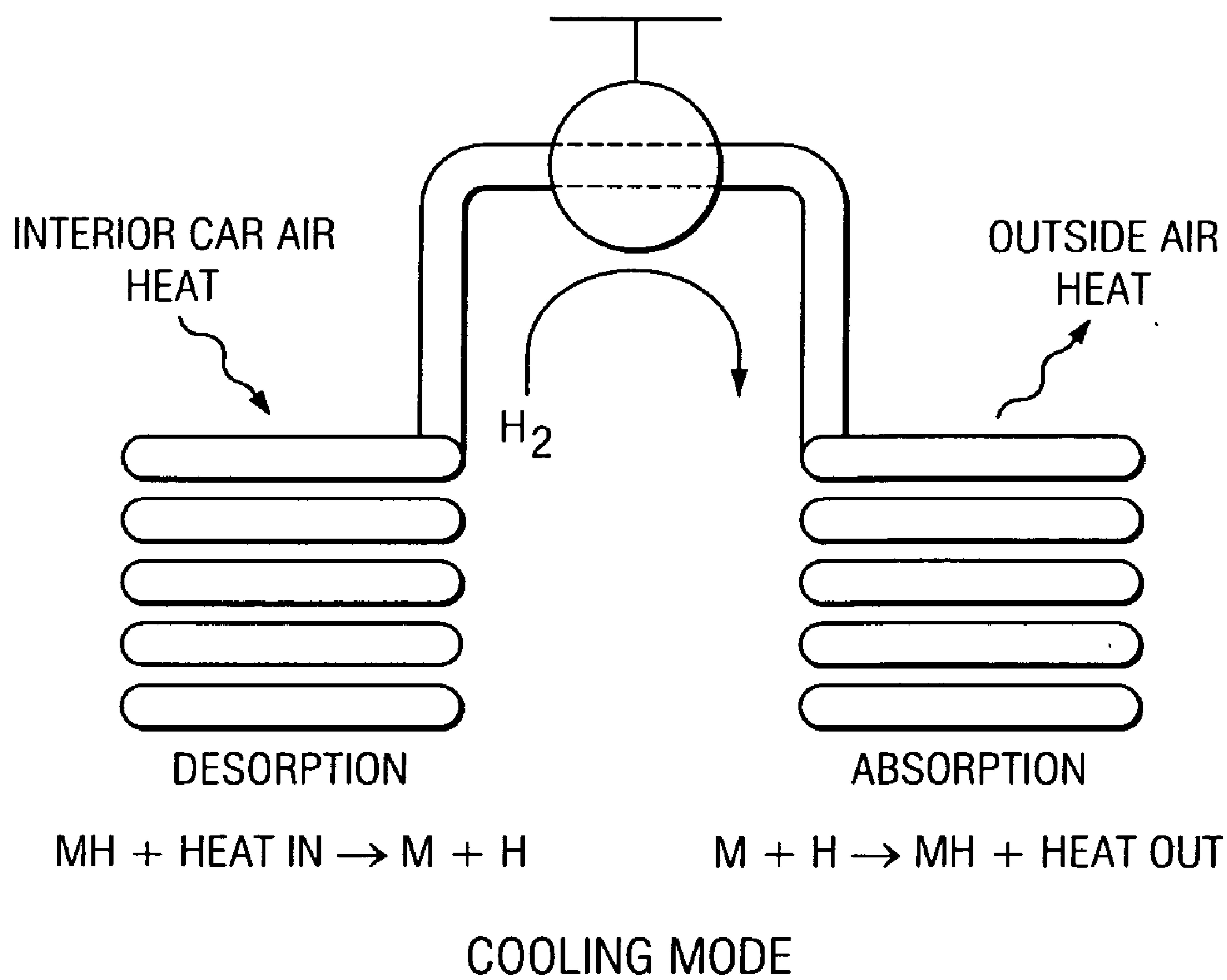
(52) **U.S. Cl.** **165/104.12**

(57) **ABSTRACT**

A metal hydride heat pump comprising a first compartment, including a first fluid inlet and a first fluid outlet, wherein the first fluid inlet is configured for fluid communication with the first fluid outlet; a second compartment, including a second fluid inlet and a second fluid outlet, wherein the first fluid inlet is configured for fluid communication with the second fluid outlet; and a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within each of the first and second compartments, and each of the vessels containing at least a hydrided form of a low temperature metal hydride material, a hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein the hydridable form of a high temperature metal hydride material is in fluid communication with the hydrided form of a low temperature metal hydride material, such that heat can be transferred from (a) fluid flowing through the first compartment to (b) the hydrided form of a low temperature metal hydride material, so as to effect desorption of hydrogen from the hydrided form of a low temperature metal hydride material, and such that the hydridable form of a high temperature metal hydride material is configured to absorb the desorbed hydrogen and generate heat upon the absorption such that the generated heat can be transferred to fluid flowing through the second compartment; wherein each of the vessels has an external surface area, and defines an internal volume for containing at least the hydrided form of a low temperature metal hydride material, the hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in^2 per cubic inch.



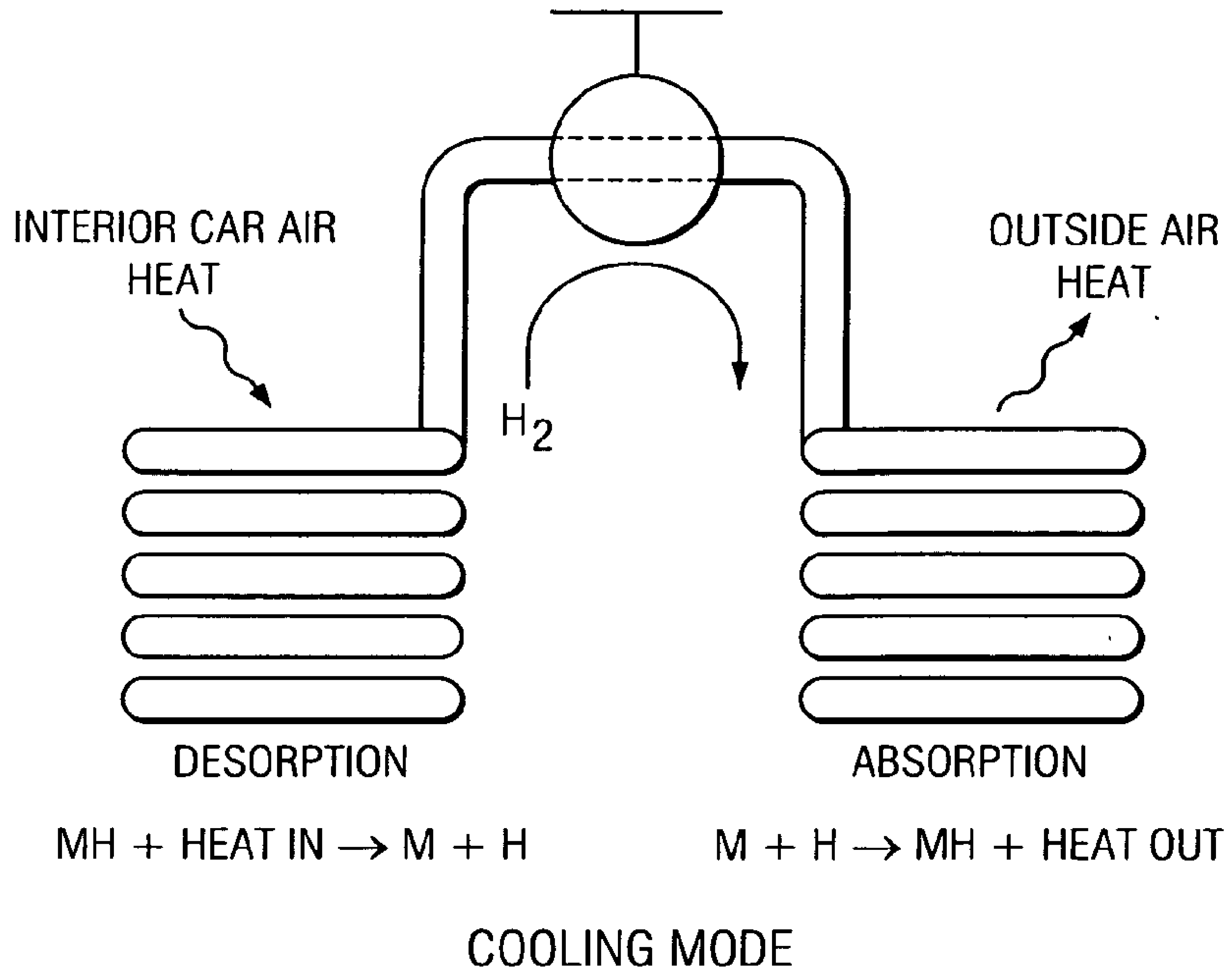

INTERIOR CAR AIR
HEAT
OUTSIDE AIR
HEAT
H2
DESORPTION
ABSORPTION
MH + HEAT IN → M + H
M + H → MH + HEAT OUT
COOLING MODE

FIG. 1

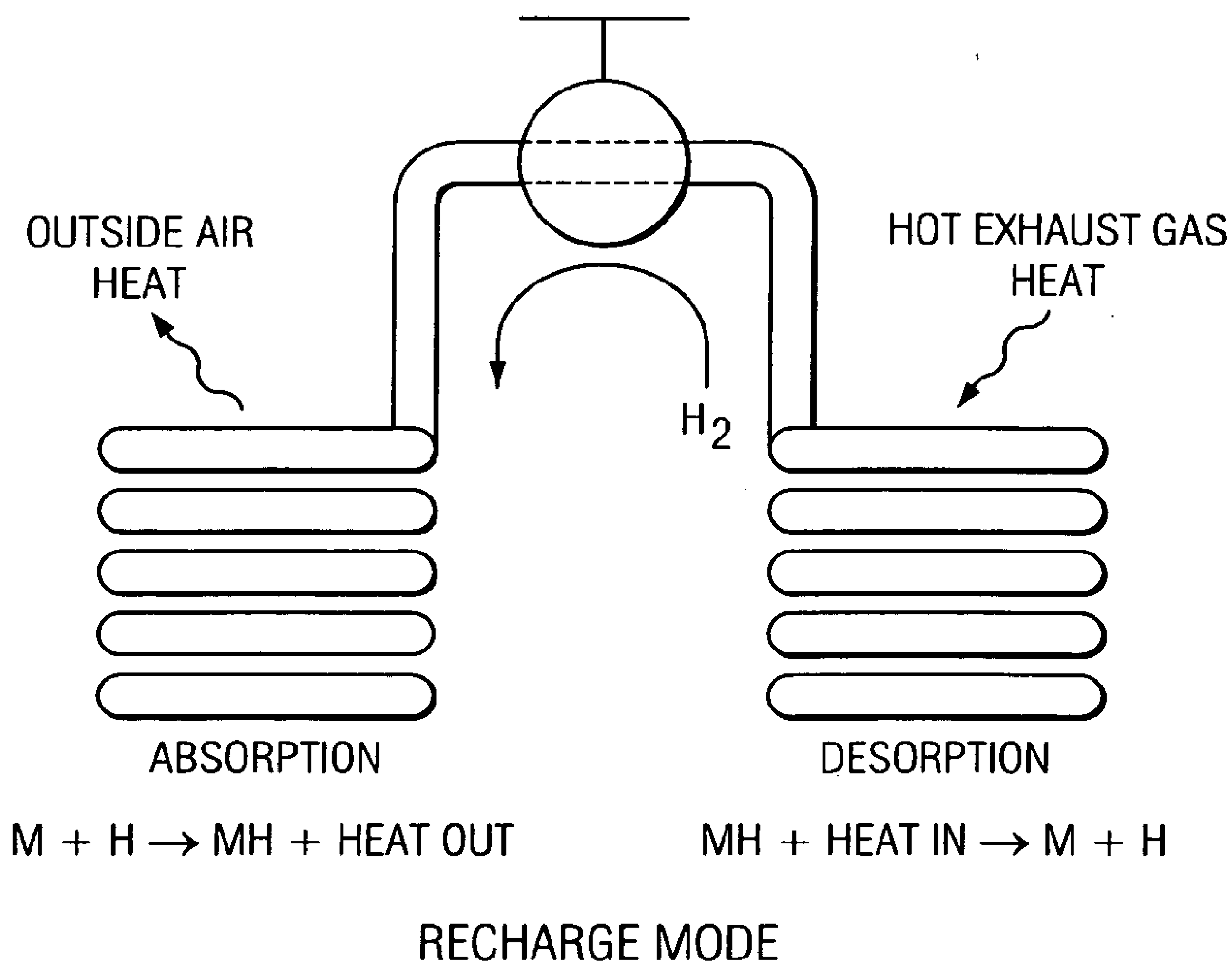

OUTSIDE AIR
HEAT
HOT EXHAUST GAS
HEAT
H2
ABSORPTION
DESORPTION
M + H → MH + HEAT OUT
MH + HEAT IN → M + H
RECHARGE MODE

FIG. 2

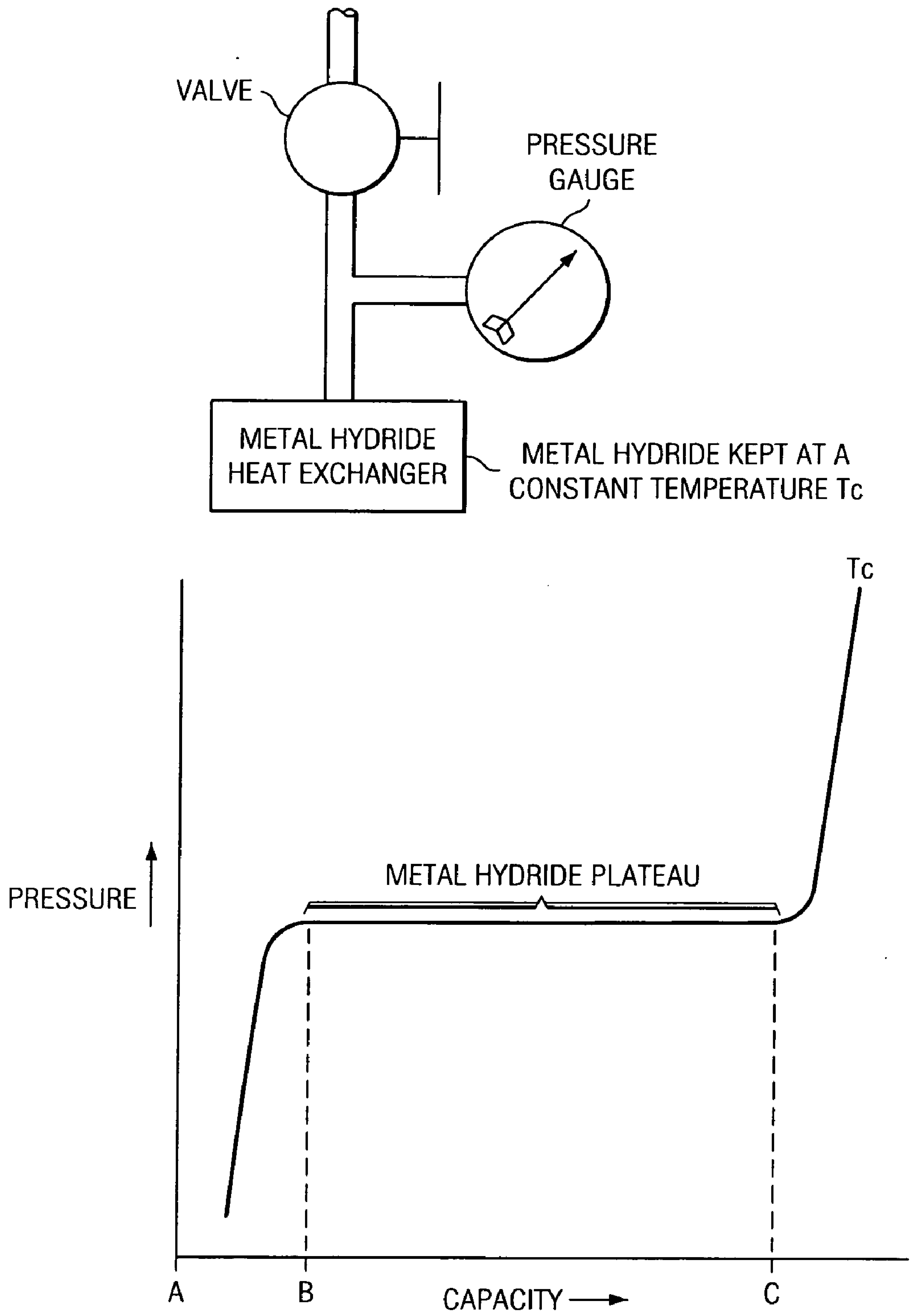
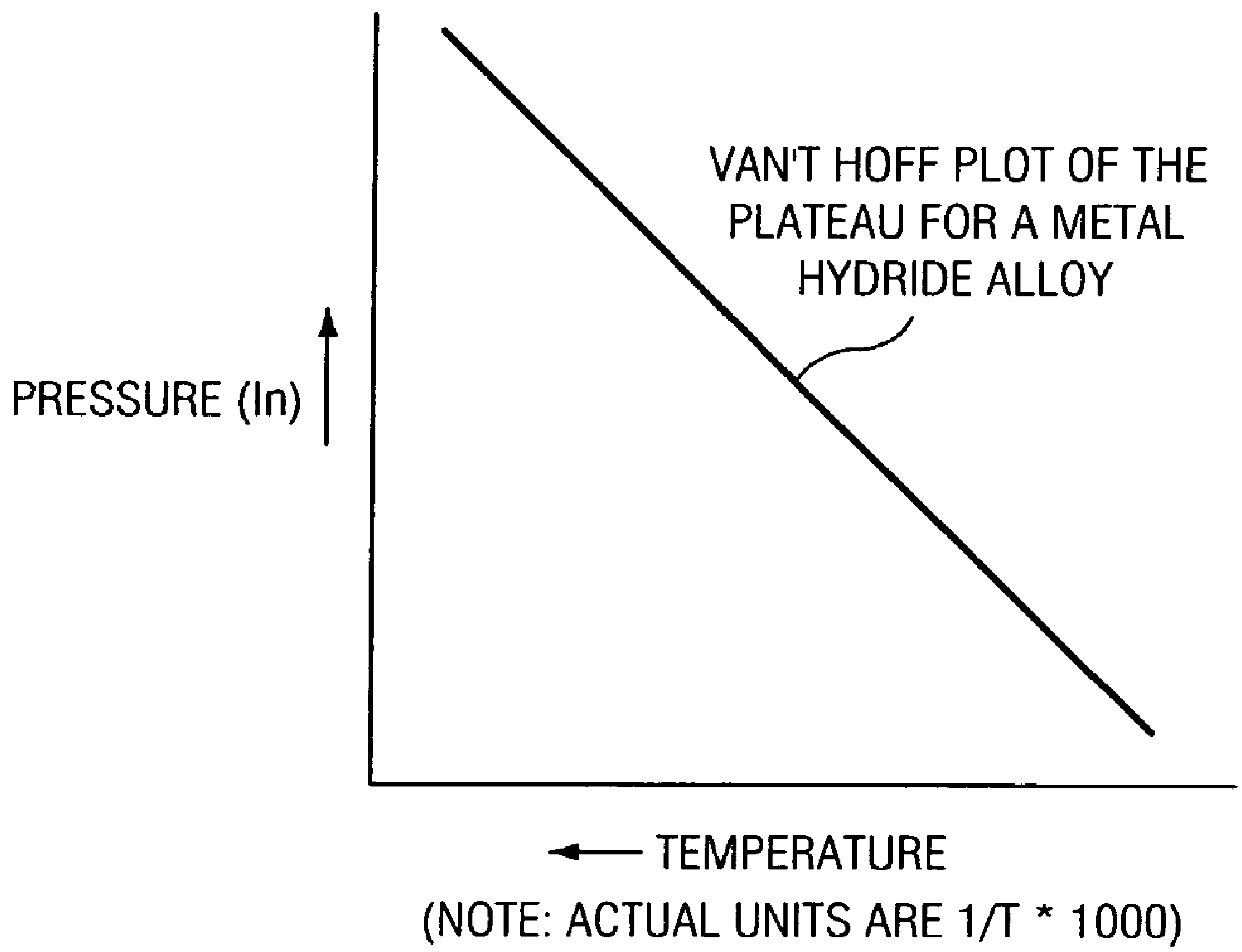


FIG. 3

PCT TEST APPARATUS AND PLOT

FIG. 4

SAMPLE METAL HYDRIDE VAN'T HOFF PLOT



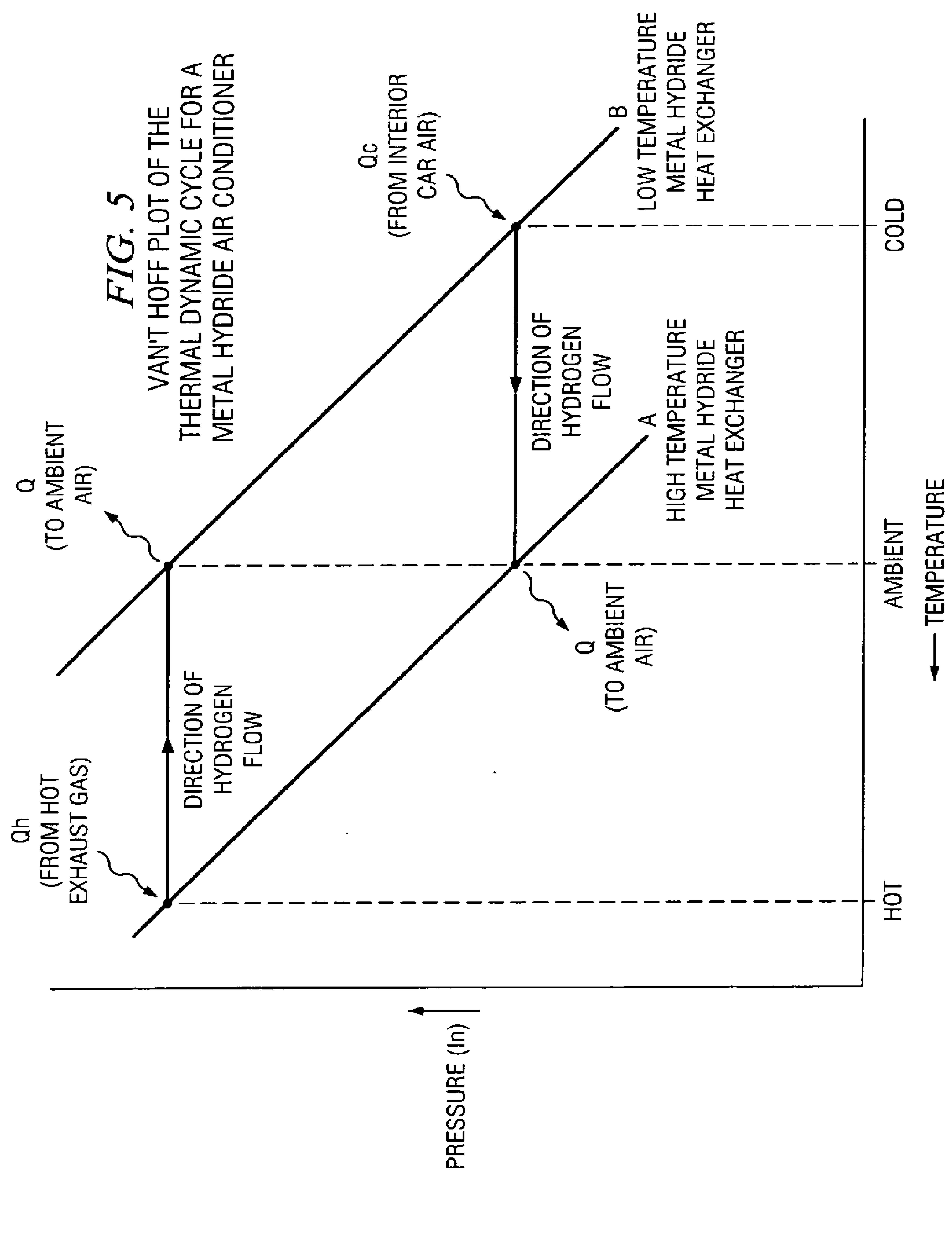


FIG. 5

VAN'T HOFF PLOT OF THE THERMAL DYNAMIC CYCLE FOR A METAL HYDRIDE AIR CONDITIONER

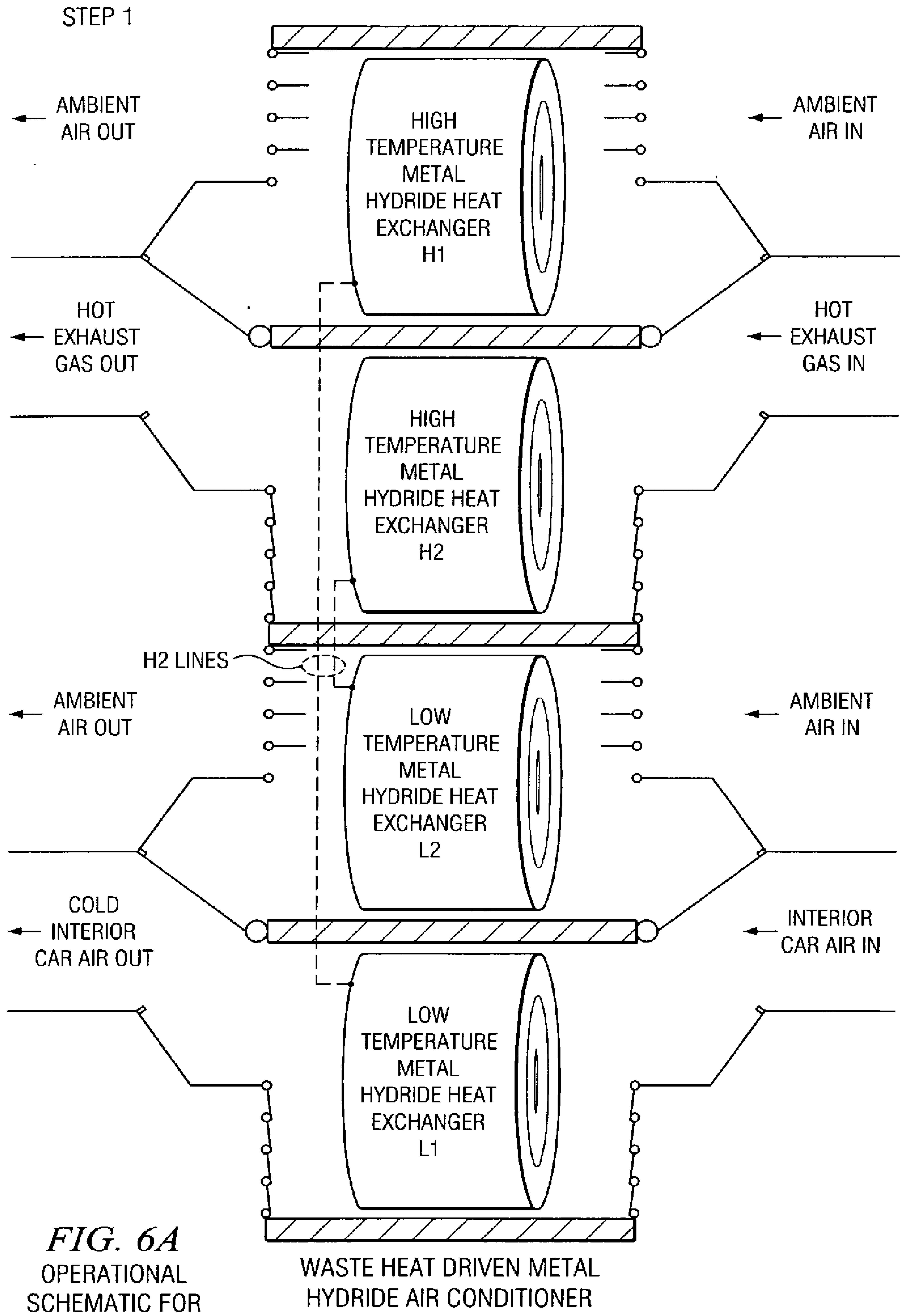


FIG. 6A
OPERATIONAL SCHEMATIC FOR PROCESS STEP #1

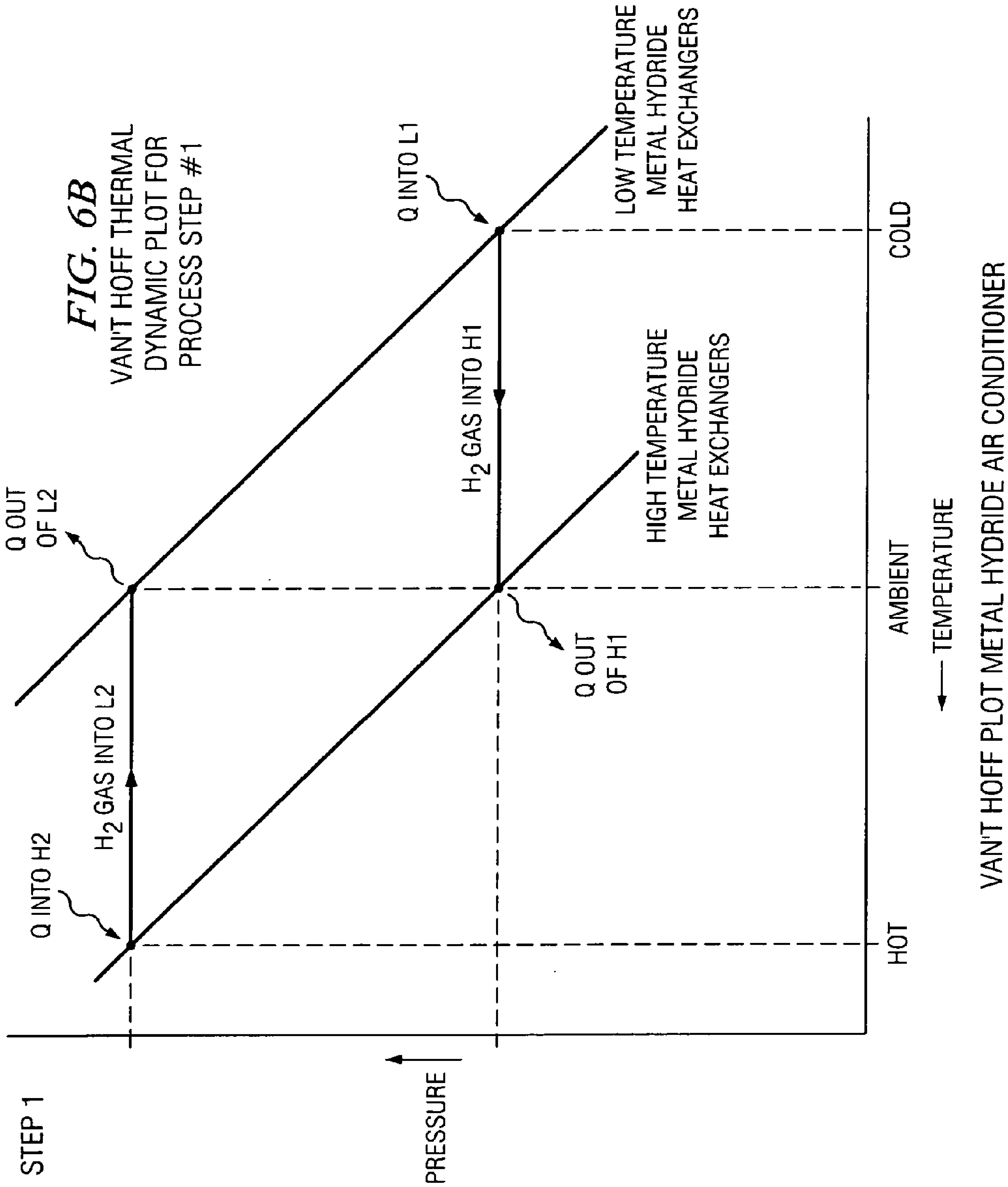


FIG. 6B
VAN'T HOFF THERMAL DYNAMIC PLOT FOR PROCESS STEP #1

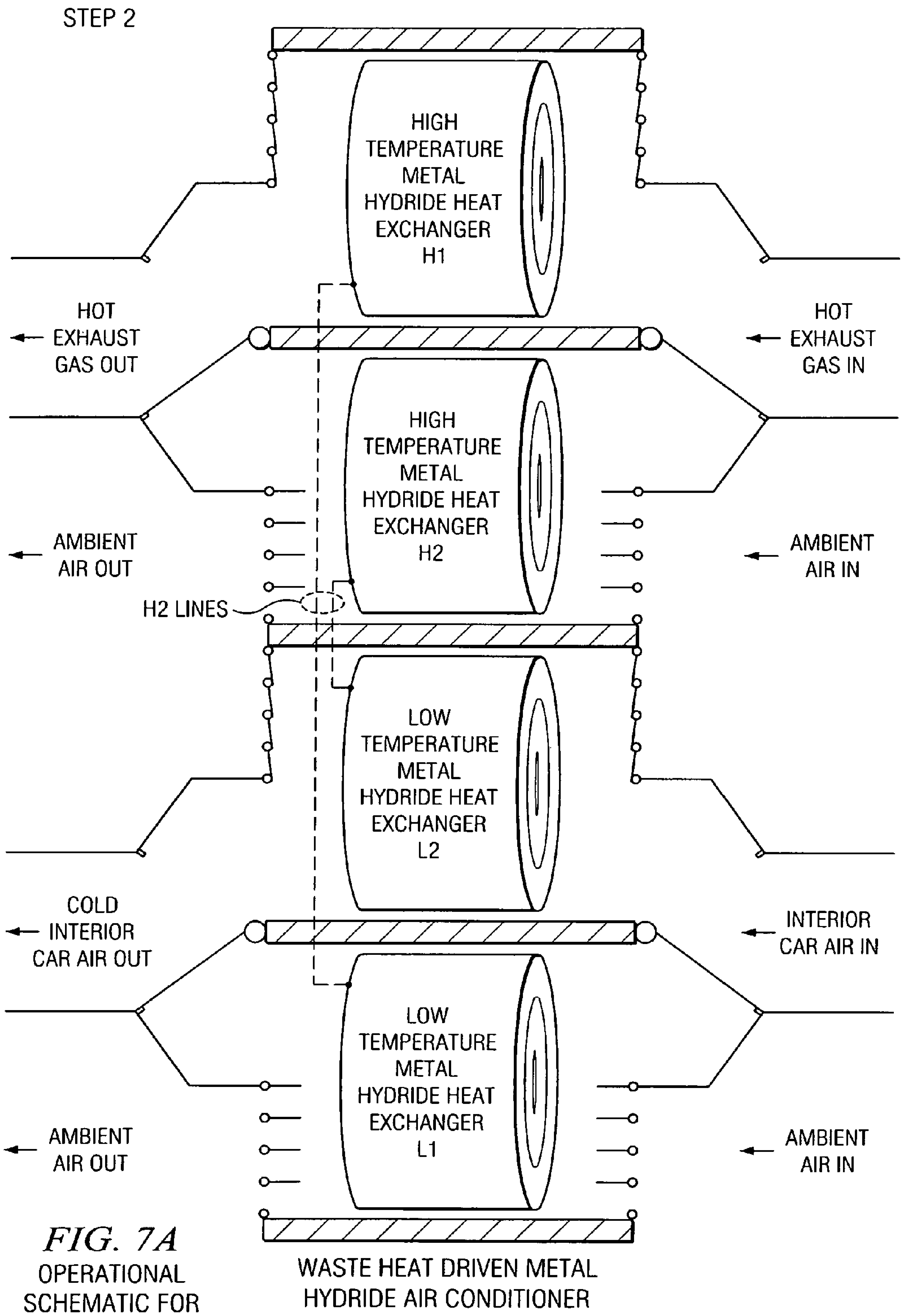


FIG. 7A
OPERATIONAL SCHEMATIC FOR PROCESS STEP #2

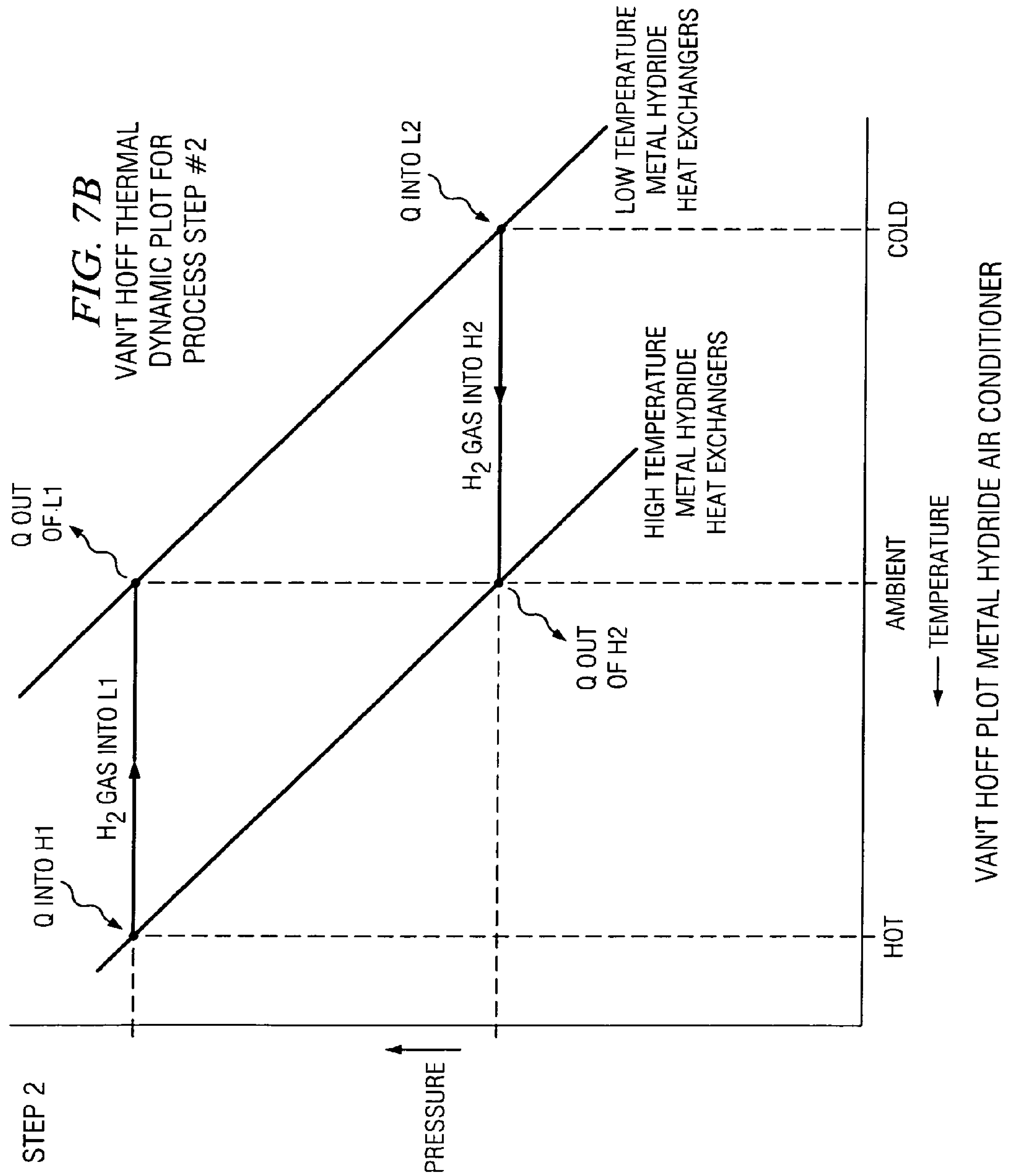


FIG. 7B
VAN'T HOFF THERMAL DYNAMIC PLOT FOR PROCESS STEP #2

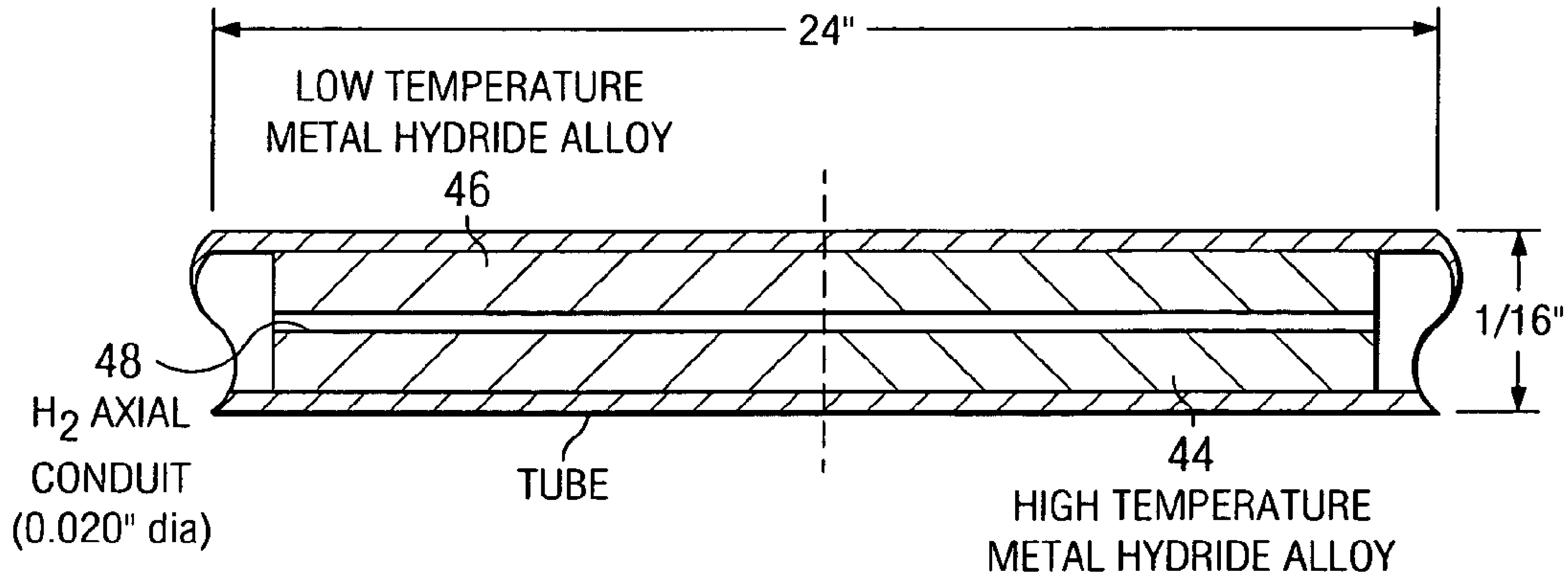


FIG. 8
SECTIONAL VIEW OF SINGLE METAL HYDRIDE HEAT EXCHANGER, SHOWING MAJOR COMPONENTS

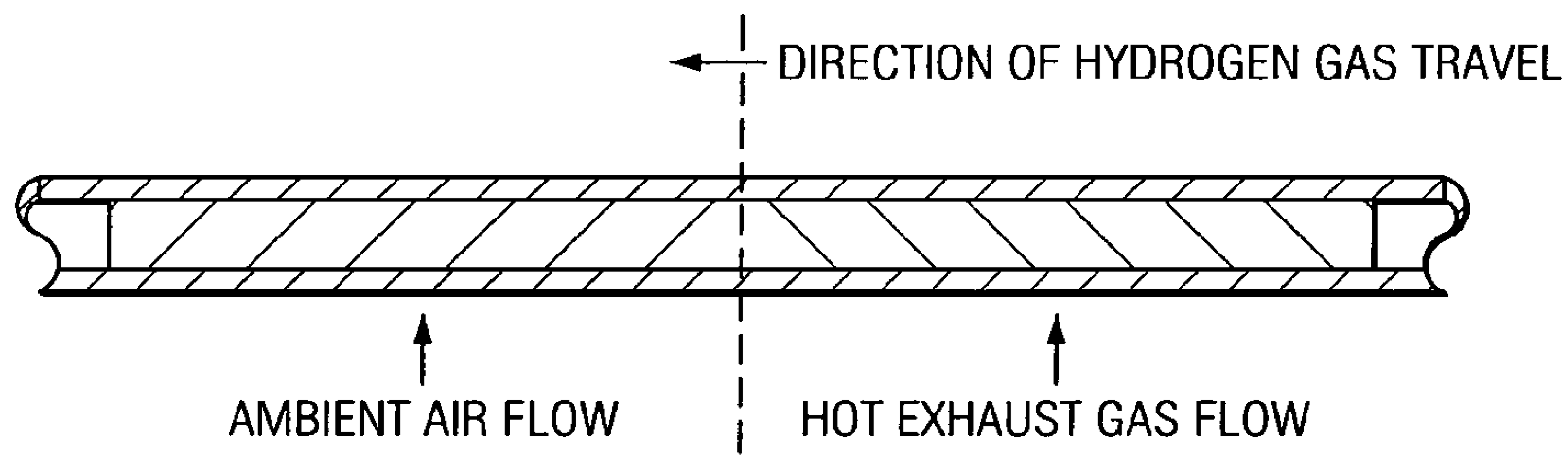


FIG. 9A
SINGLE METAL HYDRIDE TUBE IN RECHARGE MODE

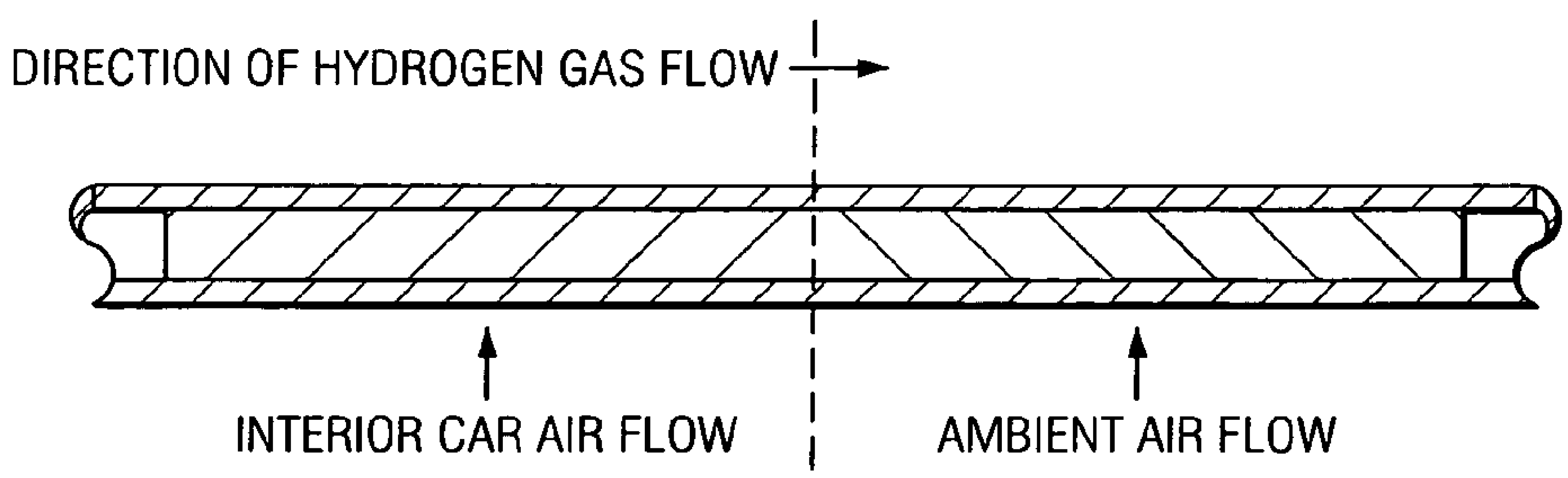


FIG. 9B
SINGLE METAL HYDRIDE TUBE IN COOLING MODE

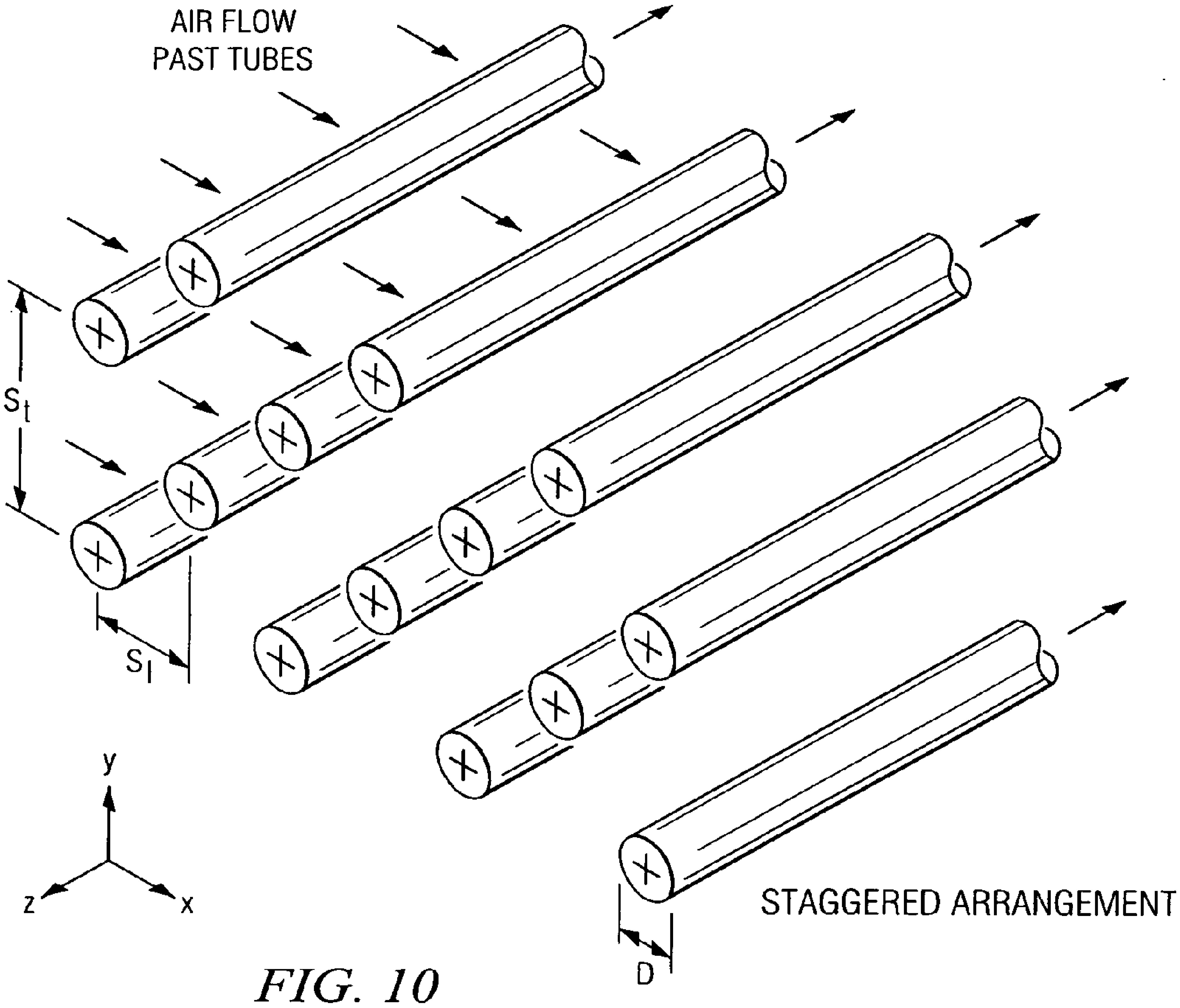


FIG. 10

METAL HYDRIDE TUBE PLACEMENT
IN THE BENCH TOP MHAC

FIG. 11

VIEW OF THE TWO BED, METAL HYDRIDE HEAT EXCHANGERS

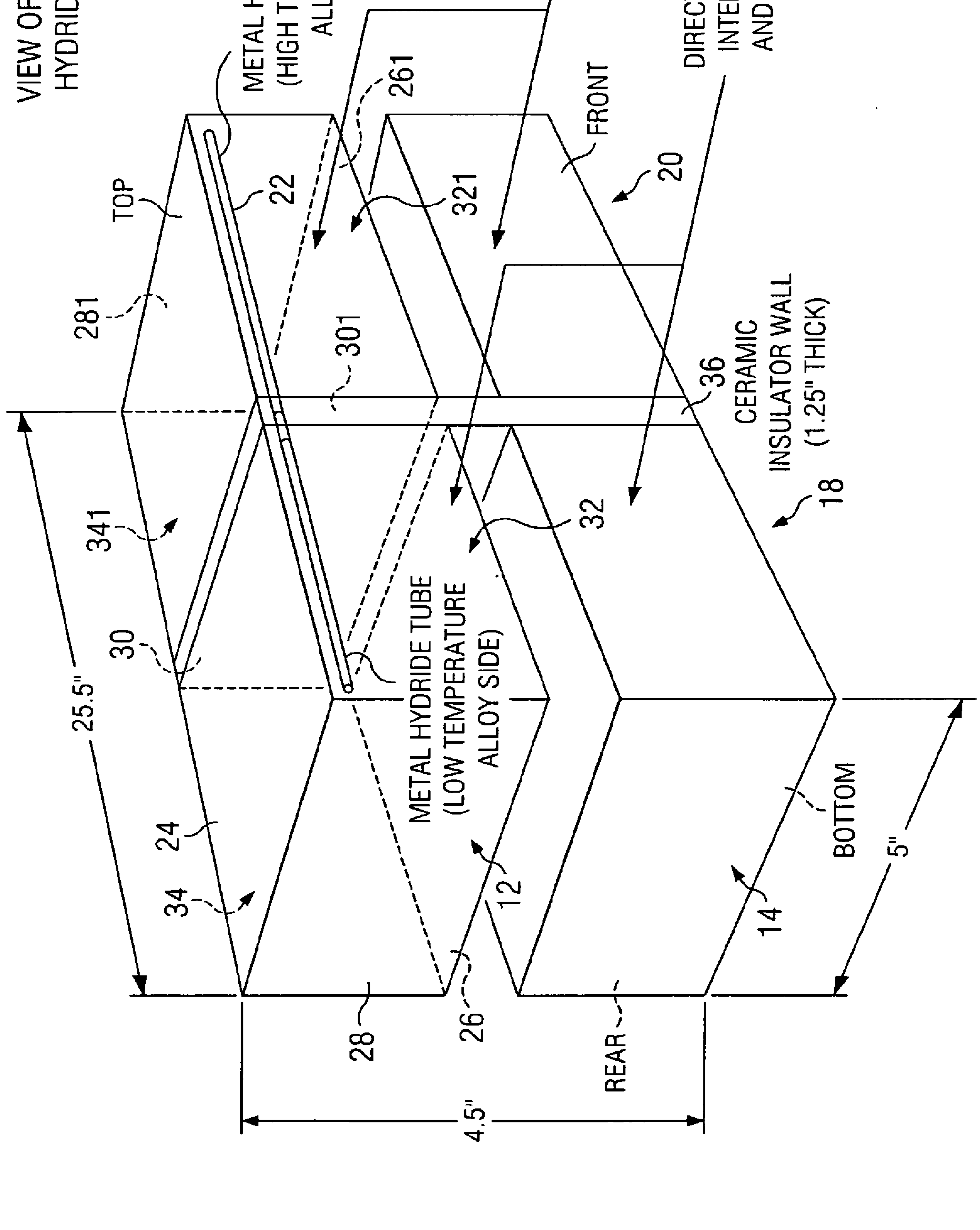


FIG. 12

TOP VIEW SCHEMATIC OF THE TOP MH BED IN THE MHAC

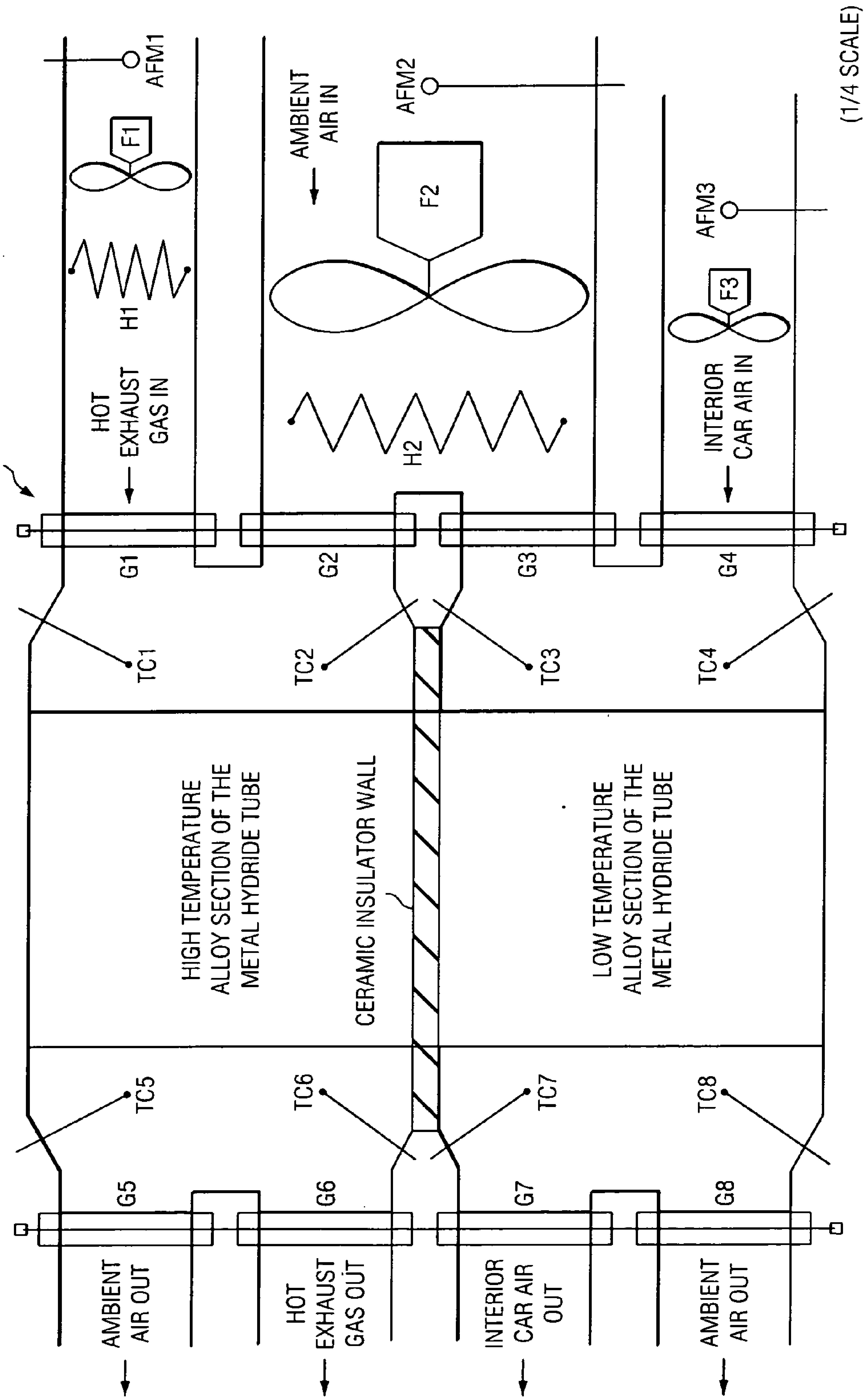
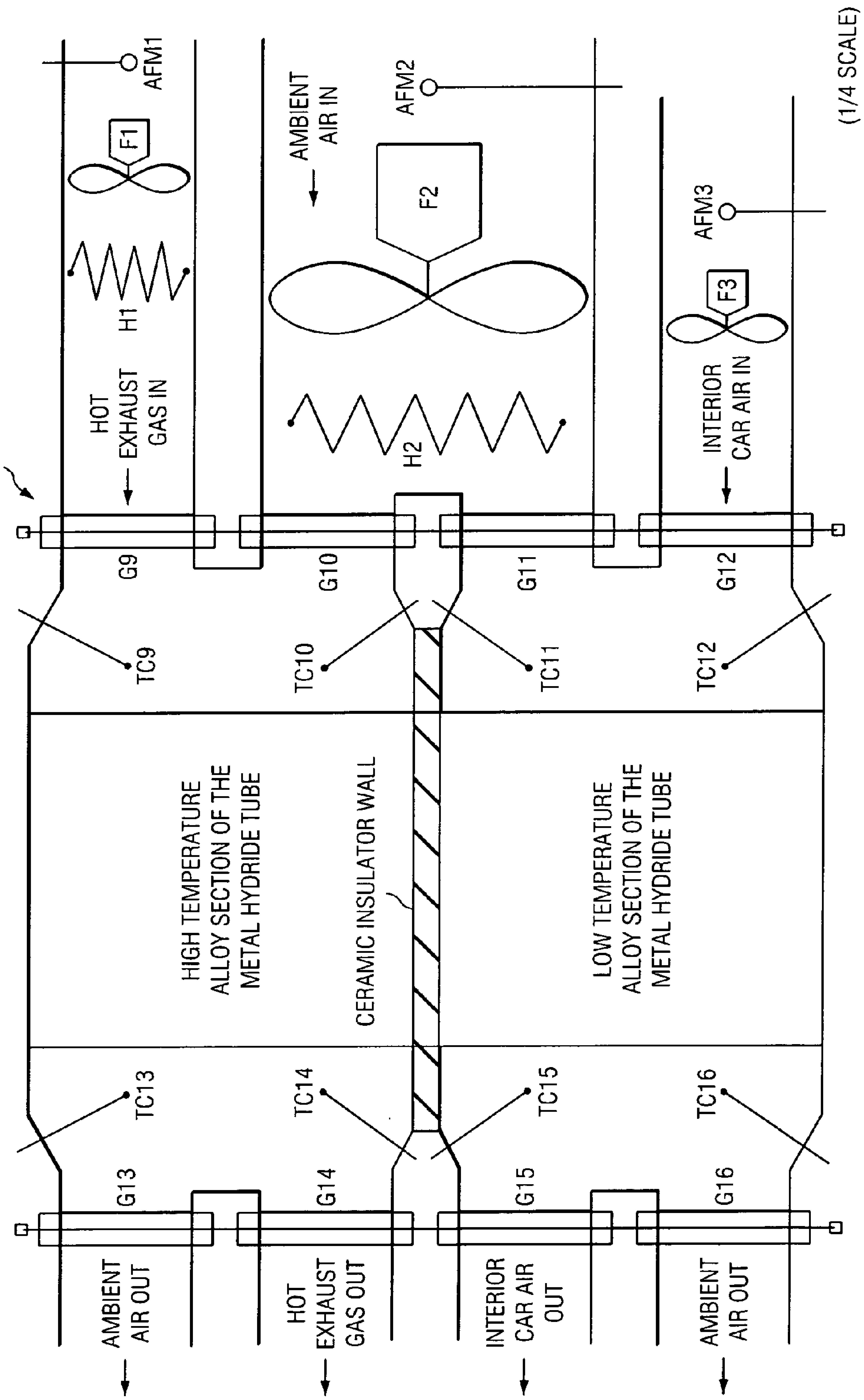


FIG. 13

TOP VIEW SCHEMATIC OF THE BOTTOM MH BED IN THE MHAC



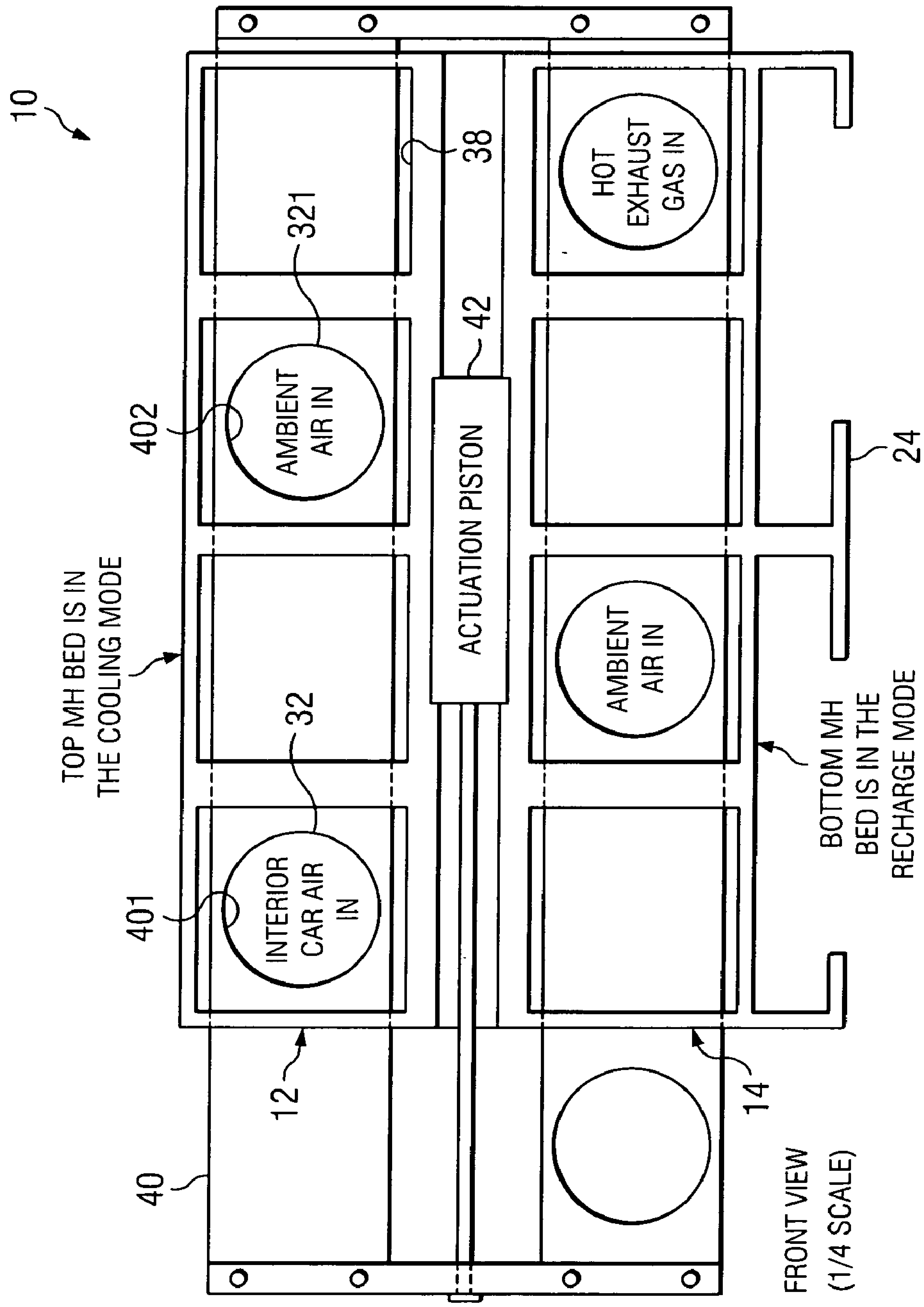


FIG. 14
GATE VALVE OPERATION FOR THE AIR INLET SIDE OF THE MHAC UNIT - POSITION 1

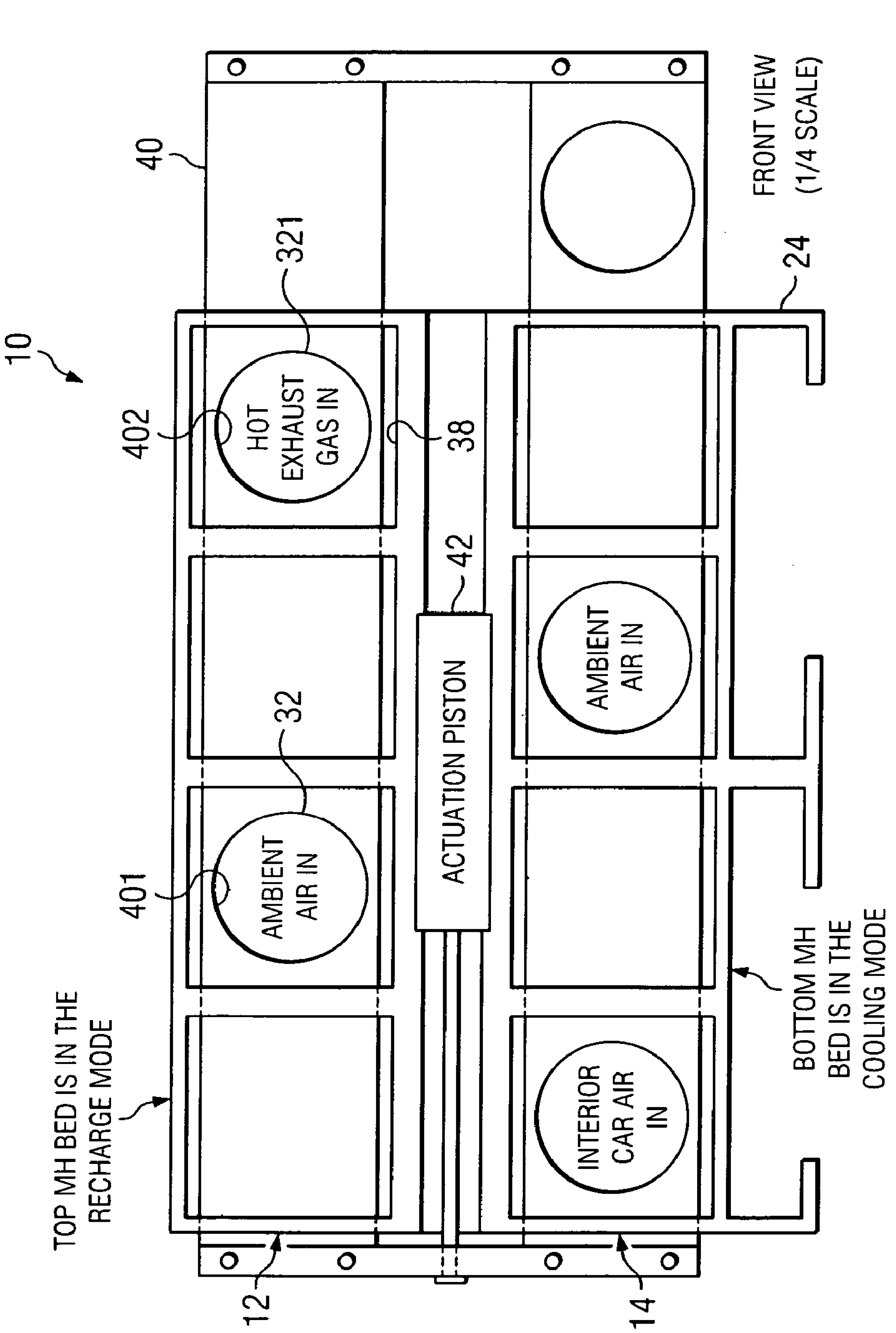


FIG. 15

GATE VALVE OPERATION FOR THE INLET SIDE OF THE MHAC UNIT - POSITION 2

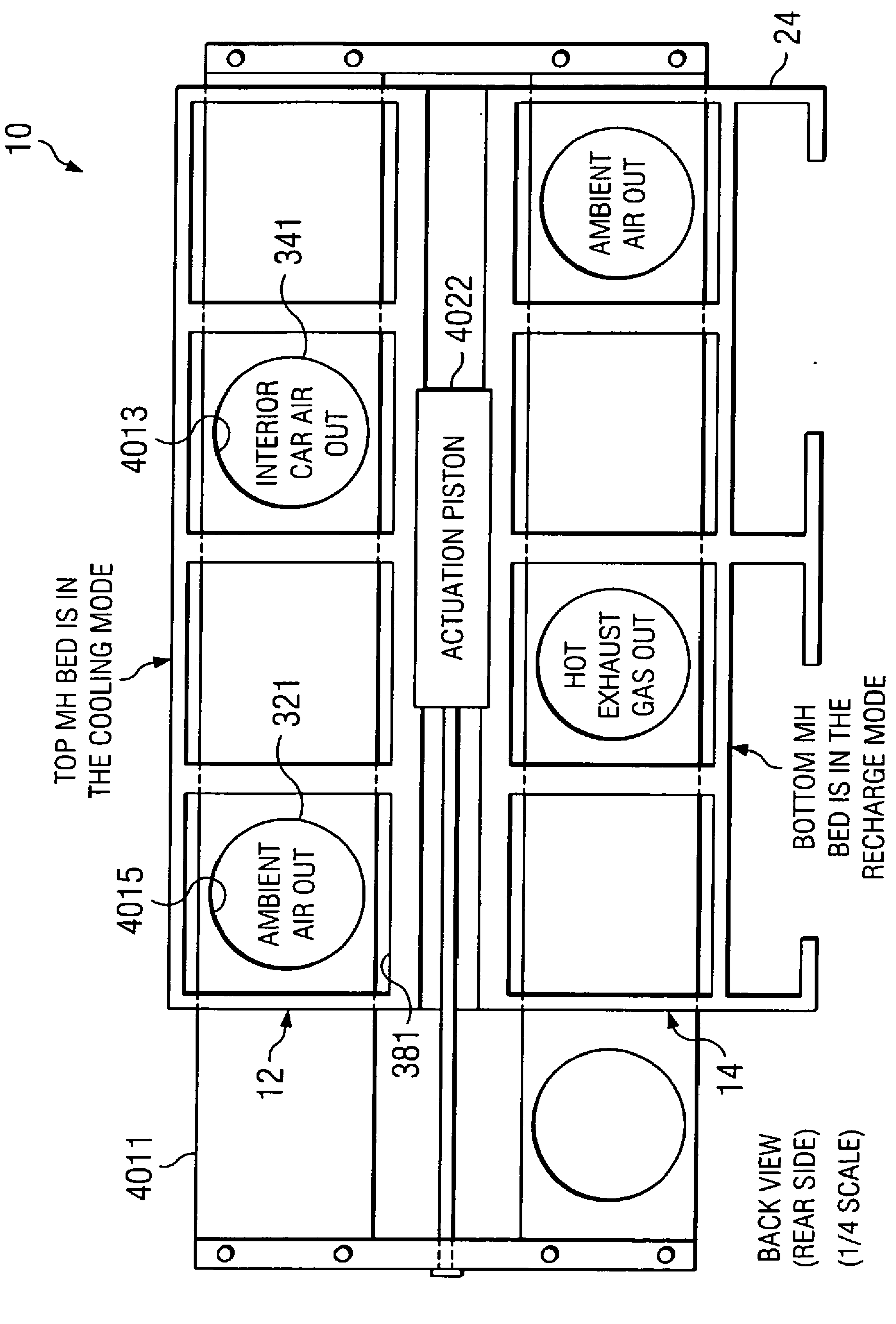


FIG. 16

GATE VALVE OPERATION FOR THE AIR OULET SIDE OF THE MHAC UNIT - POSITION 1

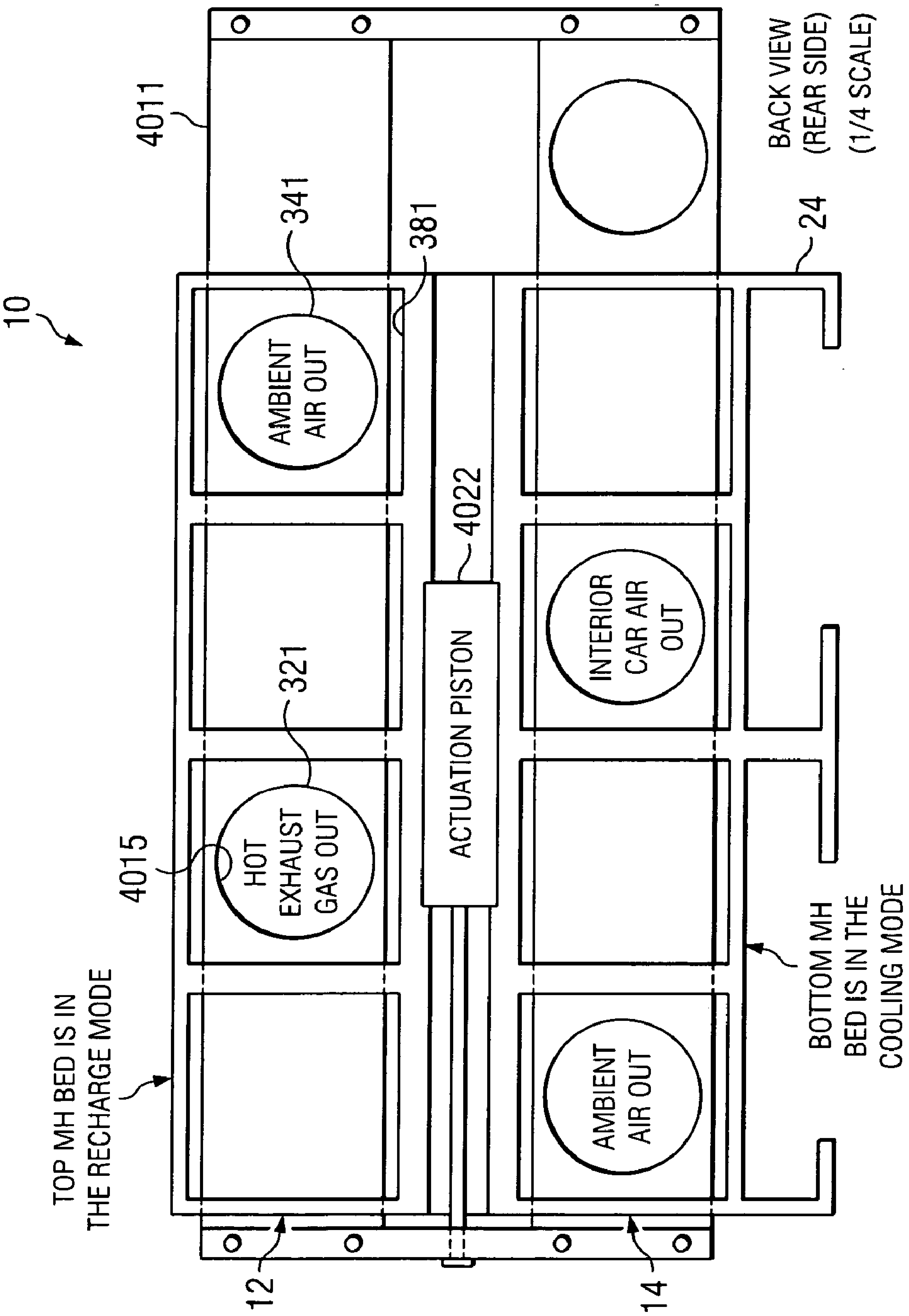


FIG. 17

GATE VALVE OPERATION FOR THE OUTLET SIDE OF THE MHAC UNIT - POSITION 2

METAL HYDRIDE BASED VEHICULAR EXHAUST COOLER

FIELD OF THE INVENTION

[0001] This invention relates to the field of metal hydride-based heat pumps and, in particular, metal hydride based heat pumps used for air conditioning.

BACKGROUND OF THE INVENTION

[0002] A metal hydride based heat pump has been developed for vehicular applications, and particularly for passenger compartment air conditioning using energy from the hot exhaust gas of a vehicle, such as an automobile. Although the invention is described in relation to an automobile, it is understood that the present invention can find application in any type of vehicle which produces a hot exhaust gas.

[0003] There are a number of other heating and cooling applications that might be satisfied by this metal hydride heat pump technology including:

[0004] near instant passenger compartment heating for cold winter days;

[0005] preheating the catalytic converter upon cold engine start up to reduce air pollution emissions;

[0006] cooling for electronic components and batteries;

[0007] cooling engine inlet air to improve performance and efficiency.

[0008] The source of energy for these heat pump applications could be the hot exhaust gas, engine exhaust manifold or engine coolant.

[0009] Existing automotive air conditioners use the conventional freon refrigeration cycle. The freon air conditioner takes its power directly from the engine via a belt driven compressor. When the air conditioner operates, it consumes engine power that would otherwise be available for propulsion. There is a corresponding reduction in power available for acceleration and a reduction in vehicle gasoline mileage.

[0010] There is sufficient energy in a usable temperature range in the exhaust gas stream of an automotive internal combustion engine to provide 100% of the air conditioning power requirement of a Metal Hydride Automobile Air Conditioner (MHAC) system. The major benefit of this power source is the elimination of the freon compressor, belts and pulleys from the engine and the electric compressor clutch. Without the compressor's drag on the engine, more engine power is available for propulsion, thus increasing acceleration, overall efficiency and gas mileage.

[0011] Another major benefit of the MHAC system is that it does not use freon and is environmentally sound. Freon has been identified as the major contributor to atmospheric ozone depletion. Fifty percent (50%) of the world's freon is associated with air conditioning and refrigeration equipment including automobile air conditioners. New refrigerant formulations are claimed to cause only 10% of the environmental damage of today's freon, but even this rate is unacceptably high. The MHAC uses a sealed, low pressure system containing non-polluting hydrogen gas as the safe and effective working fluid. These attributes make the MHAC an excellent candidate for the next generation of automotive air conditioning technology.

SUMMARY OF THE INVENTION

[0012] In one aspect the present invention provides a metal hydride heat pump comprising a first compartment, including a first fluid inlet and a first fluid outlet, wherein the first fluid inlet is configured for fluid communication with the first fluid outlet; a second compartment, including a second fluid inlet and a second fluid outlet, wherein the first fluid inlet is configured for fluid communication with the second fluid outlet; and a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within each of the first and second compartments, and each of the vessels containing at least a hydrided form of a low temperature metal hydride material, a hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein the hydridable form of a high temperature metal hydride material is in fluid communication with the hydrided form of a low temperature metal hydride material, such that heat can be transferred from (a) fluid flowing through the first compartment to (b) the hydrided form of a low temperature metal hydride material, so as to effect desorption of hydrogen from the hydrided form of a low temperature metal hydride material, and such that the hydridable form of a high temperature metal hydride material is configured to absorb the desorbed hydrogen and generate heat upon the absorption such that the generated heat can be transferred to fluid flowing through the second compartment; wherein each of the vessels has an external surface area, and defines an internal volume for containing at least the hydrided form of a low temperature metal hydride material, the hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in2 per cubic inch.

[0013] In another aspect the present invention provides a metal hydride heat pump comprising a compartment, including a first gas inlet and a first gas outlet, wherein the first gas inlet is configured for fluid communication with the first gas outlet; and a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within the compartment, and each of the vessels containing at least a metal hydride material; wherein the material of construction of each of the vessels is a stainless steel alloy comprising less than 3 weight percent of carbon based on the total weight of the stainless steel alloy.

[0014] In a further aspect the present invention provides a metal hydride heat pump comprising a compartment, including a first gas inlet and a first gas outlet, wherein the first gas inlet is configured for fluid communication with the first gas outlet; and a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within the compartment, and each of the vessels containing at least a metal hydride material and gaseous hydrogen; wherein each of the vessels has an external surface area, and defines an internal volume for containing at least the metal hydride material and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in2 per cubic inch.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The invention will be better understood by reference to the following detailed description of the invention in conjunction with the following drawings in which:

[0016] **FIG. 1** is a schematic illustration of a metal hydride-based air conditioner in a cooling mode;

[0017] **FIG. 2** is a schematic illustration of a metal hydride-based air conditioner in a recharge mode;

[0018] **FIG. 3** shows the test apparatus and plot;

[0019] **FIG. 4** shows the sample metal hydride Van't Hoff plot;

[0020] **FIG. 5** shows the Van't Hoff Plot of the thermal dynamic cycle for a metal hydride air conditioner;

[0021] **FIG. 6A** shows the operational schematic for process Step **1**;

[0022] **FIG. 6B** shows the Van't Hoff thermal dynamic plot for process Step **1**;

[0023] **FIG. 7A** shows the operational schematic for process Step **2**;

[0024] **FIG. 7B** shows the Van't Hoff thermal dynamic plot for process Step **2**;

[0025] **FIG. 8** is a sectional view of the single metal hydride heat exchanger, showing major components;

[0026] **FIG. 9A** shows the single metal hydride tube in recharge mode;

[0027] **FIG. 9B** shows the single metal hydride tube in cooling mode;

[0028] **FIG. 10** shows the metal hydride tube placement in the bench top MHAC;

[0029] **FIG. 11** is a view of the two beds, metal hydride heat exchangers;

[0030] **FIG. 12** is a top view schematic of the top MH bed in the MHAC;

[0031] **FIG. 13** is a top view schematic of the bottom MH bed in the MHAC;

[0032] **FIG. 14** shows the gate valve operation for the inlet side of the MHAC unit—Position **1**;

[0033] **FIG. 15** shows the gate valve operation for the inlet side of the MHAC unit—Position **2**.

[0034] **FIG. 16** shows the gate valve operation for the outlet side of the MHAC Unit—Position **1**; and

[0035] **FIG. 17** shows the gate valve operation for the outlet side of the MHAC Unit—Position **2**.

DETAILED DESCRIPTION

[0036] There are a number of metals that possess the remarkable ability to absorb large quantities of hydrogen gas. Absorption occurs under specific temperature and pressure conditions. The hydrogen is released (desorbed) when the alloy temperature is elevated or the pressure is reduced. The absorption/desorption phenomenon is a "reversible" reaction and the metals that absorb hydrogen are called reversible metal hydride materials.

[0037] When a reversible metal hydride material absorbs hydrogen gas, heat is given off; the reaction is exothermic. In order to desorb hydrogen from the metal hydride material, heat is required; the reaction is endothermic. If the desorbing material takes its heat from ambient temperature air, the air temperature decreases, thus producing the refrigeration associated with air conditioning.

[0038] The reversible metal hydride reaction can be expressed in the simplified chemical equation:

$$M+H \leftrightharpoons MH$$

[0039] where M is a metal or metal alloy and H is hydrogen. The top arrow in the equation signifies the absorption cycle:

$$M+H \rightarrow M+heat$$

[0040] The lower arrow shows the reversibility of the reaction and signifies the desorption cycle:

$$M+H \leftrightharpoons MH+heat\ in$$

[0041] The reversibility of the metal hydrogen reaction and the heat associated with it provide the basis for hydride heat pumps. The heat pump is a closed unit in which hydrogen serves as an energy carrier between two or more hydride beds. By selecting appropriate hydriding materials, heat sources, and heat sinks, heat can be pumped over wide temperature differentials. Elements of the process are illustrated in **FIGS. 1 and 2**.

[0042] **FIG. 1** illustrates an air conditioner in the cooling mode. Hydrogen which has been stored as a solid metal hydride in the left hand bed is desorbed or released. The hydrogen flows into the right hand bed (mechanical pumping is not required). The heat necessary for desorption is taken from passenger compartment air, causing cooling of the passenger compartment.

[0043] When all of the hydrogen has been desorbed from the left hand hydride bed (and subsequently absorbed by the right hand bed), it must be recharged into the left hand bed to become available for additional cooling. **FIG. 2** illustrates the recharge mode. Here, the right hand bed is heated by exhaust gas causing it to release its hydrogen which then returns to the left hand bed.

[0044] The MHAC consists of a minimum of two (paired) 2-bed systems. One pair of beds operates in the cooling mode while the other pair is in the recharge mode. In this way, continuous cooling is available for passenger compartment air conditioning.

[0045] **FIG. 3** shows a simple test set up along with a sample PCT (Pressure/Composition/Temperature isotherm) curve which describes the hydriding reaction in more detail. In this test procedure, a sample of metal hydride is placed inside a container which has a pressure gauge and valve. Initially, this container is fully evacuated so that the hydride pressure and capacity (the amount of hydrogen "inside" the container) is zero. This condition corresponds to point A in **FIG. 3**. Slowly the valve on the container is opened and hydrogen gas is allowed to enter into the container. When this happens, the pressure in the container immediately rises until point B is reached. This is the point where hydrogen begins to enter into the metal hydride material. Between point B and C in **FIG. 3**, hydrogen continues to enter into the container but no pressure rise is observed. Therefore, all of this hydrogen has gone into the metal hydride material. After the material is "fully charged" with hydrogen, the pressure in the container will resume its pressure rise as more hydrogen enters the container. This test has now generated the alloy's PCT curve that shows where the "plateau" (between points B and C) lies. This PCT test is done at a constant temperature and, therefore, determines the pressure the alloy "generates" at a given temperature. Remember, during the absorption of hydrogen into the metal, heat is generated and must be "transferred" out of the metal hydride. Correspondingly, when hydrogen leaves the metal hydride (i.e: desorption), heat must be transferred into the metal hydride.

[0046] It has been found that this plateau pressure changes exponentially with temperature. If the plateau pressure is plotted using the logarithm scale of pressure as the abscissa and the inverse of absolute temperature as the ordinate, then a straight line plot of the plateau pressure change vs. the temperature results. **FIG. 4** shows a sample plot of such a curve, which is called the "Van't Hoff plot" for this particular metal hydride material.

[0047] The key to a successful metal hydride air conditioner is the selection of the "right" metal hydride materials and heat exchangers in which to use them. **FIG. 5** is a plot of such a pair of metal hydride materials, material A on this graph is the "high temperature" metal hydride material and material B is the "low temperature" metal hydride material. Looking at **FIG. 5**, the thermodynamic process of a metal hydride air conditioner can be followed:

[0048] Process A—Hydrogen gas, coming from the low temperature metal hydride material, flows into the high temperature material. In order for this process to occur, heat must be provided to the low temperature material B, simultaneously an equal amount of heat must be removed from the high temperature material A. The interior car air provides this heat for material B and thus gets cold. Outside ambient air removes material A's heat of absorption.

[0049] Process B—The high temperature material A has been heated up to the exhaust gas temperature which now enables the hydrogen gas to flow from material A back into material B. The heat that is needed to remove the hydrogen from material A is provided by the hot exhaust gas. The corresponding heat that is generated in material B as hydrogen gas enters it is dissipated to the heat sink, which is the ambient air.

[0050] From **FIG. 5**, the coefficient of performance (COP) of the air conditioner can be determined. The COP of a heat pump type air conditioner is defined as:

$$COP = \frac{\text{Amount of heat you put in}}{\text{Amount of heat (i.e. cooling) you produce}} = \frac{QH}{QC}$$

[0051] Therefore, the theoretical best COP would be equal to 1, meaning that you are producing an equivalent amount of cooling as to the heat you must supply.

[0052] Since the production of cooling in a metal hydride air conditioner is a "batch" type process, two pairs of metal hydride heat exchangers must be employed to produce continuous cooling. Therefore, while one pair is cooling, the other pair is being regenerated with the hot exhaust heat. **FIGS. 6A and 6B** (Step **1**) and **FIGS. 7A and 7B** (Step **2**) demonstrate this batch process.

[0053] **FIG. 6A** shows the schematic layout and ducting of the two pairs of metal hydride heat exchangers when the air conditioner is in the "Step **1**" mode. Here metal hydride heat exchanger pair H_1 and L_1 are producing cooling while heat exchanger pair H_2 and L_2 are being regenerated. **FIG. 6B** shows the Van't Hoff plot conditions for each alloy in Step **1**. Notice that the control of air flow through the air conditioner is accomplished with the use of simple louvers. Physically, in Step **1** (**FIG. 6A**), the following heat transfer processes are occurring:

[0054] a) Interior car air is passing through metal hydride heat exchanger L_1. Since L_1 is in the desorbing mode, heat is being removed from the interior car air stream.

[0055] b) At the same time, ambient air is passing through metal hydride heat exchanger L_2. Since hydrogen is being absorbed by this material, heat is being generated which is dissipated to the outside ambient air stream.

[0056] c) Hot exhaust gas is passing through metal hydride heat exchanger H_2. Heat from this exhaust gas stream is used to "release" the hydrogen in this heat exchanger.

[0057] d) Ambient air is passing through metal hydride heat exchanger H_1. Since H_1 is absorbing hydrogen gas, this heat of absorption is dissipated to the outside ambient air.

[0058] After the Step **1** process is complete, the air flow control louvers will switch and redirect the air flow so that Step **2** can start. In Step **2**, metal hydride heat exchanger pairs H_2 and L_2 now produce the cooling and pair H_1 and L_1 are being regenerated. **FIG. 7A** shows the operational schematics for this process with **FIG. 7B** showing the corresponding Van't Hoff thermodynamic plots. The physical Step **2** processes occurring (shown in **FIGS. 7A and 7B**) are:

[0059] a) Ambient air is now passing through heat exchanger L_1, thus removing its heat of formation.

[0060] b) Interior car air is passing through heat exchanger L_2. Since exchanger L_2 is in the desorption mode, heat is being removed from the interior car air.

[0061] c) Ambient air is passing through heat exchanger H_2 and removing the heat that is being generated in H_2.

[0062] d) Hot exhaust gas is passing through heat exchanger H_1 and supplying the heat needed to release the hydrogen gas in exchanger H_1.

[0063] Metal hydride air conditioners are based on the principle of transporting hydrogen gas back and forth between two heat exchangers containing metal hydride material.

[0064] Cooling is generated when the hydrogen gas "leaves" the metal hydride material. Conversely, heat is generated when the hydrogen gas "enters" the metal hydride material.

[0065] In one embodiment, about 40% of the total mass of a metal hydride heat exchanger is non-metal hydride material. Therefore, the remaining 60% of mass is metal hydride material.

[0066] Twenty-five percent (25%) of the total envelope of the metal hydride heat exchanger is containment vessel volume, therefore, 75% of the envelope volume is available for air flow.

[0067] The percent volume of metal hydride material in the containment vessel volume is about 33%. Therefore, about 8% of the total envelope volume of the metal hydride heat exchanger is metal hydride material.

[0068] The metal hydride air conditioner (MHAC), or heat pump, is of a "multi-tube" design.

[0069] Referring to FIGS. **8** to **15**, the metal hydride heat pump **10** is a shell and tube heat exchanger comprised of two (in this case "top" and "bottom") hydride tube beds, each disposed in separate housings **12**, **14**. The heat pump **10** has 356 straight hydride tubes per bed (712 tubes total). The hydride tube pattern is rectangular. A tubesheet **16** partitions each bed into a hot exhaust section and a cooling section, and also partitions each housing into first and second compartments **18**, **20**. The tubesheet **16** is perforated (i.e. includes apertures) for receiving the hydride tubes and thereby providing support for the hydride tubes **22**. The heat pump is insulated internally.

[0070] Each of the first and second housings **12**, **14** is mounted to a common frame **24**. In this embodiment, the first housing **12** is mounted above the second housing **14**. The first housing **12** includes a first compartment **18** and a second compartment **20**. The first compartment **18** of the first housing **12** is a "tubular" structure, defined by top and bottom walls **24**, **26**, and first and second sidewalls **28**, **30**. Each of the top and bottom walls **24**, **26** is joined to each of the sidewalls **28**, **30**. Each of the top and bottom walls **24**, **26**, and sidewalls **30** are manufactured from stainless steel. Opposing gas inlet **32** and gas outlet **34** openings are provided and are configured to effect flow of gas through the first compartment. The second sidewall **30** is perforated (i.e. includes apertures) to permit insertion of the metal hydride tubes **32** of the hydride tube beds therethrough, thereby effecting at least partial support of the metal hydride tubes **22** (i.e. the mounting of the metal hydride tubes to the first compartment).

[0071] The second compartment **20** is substantially the same as the first compartment **18**, and includes top and bottom walls **24**, **26**, first and second sidewalls **28**, **30**, and gas inlet **32**, and gas outlet **34**, openings. The second sidewall is also perforated (i.e. includes apertures) to permit insertion of the metal hydride tubes of the first of the two hydride tube beds, thereby effecting at least partial support of the metal hydride tubes (i.e. the mounting of the metal hydride tubes to the second compartment).

[0072] Each of the walls of the first and second compartments is thermally insulated. In this respect, the inside surface of each wall is covered with ¼ of an inch of high temperature ceramic fiber insulation.

[0073] A ceramic insulator **36** is provided between the second sidewalls **30**, **301** of the respective first and second compartments **18**, **20**. The ceramic insulator **36** is also perforated (i.e. apertures are provided). Each of the second sidewalls **30** and the insulator are coupled to one another with appropriate fasteners, causing the ceramic insulator to be pressed between the second sidewalls **30**, **301**. When coupled together, the perforations in the second sidewalls **30**, **301** and the insulator **36** are in alignment to permit insertion of the metal hydride tubes **22** therethrough so that the metal hydride tubes **22** become disposed with each of the first and second compartments **18**, **20**. In this respect, the coupled second sidewalls and the insulator functions as the tubesheet **16**.

[0074] The first housing **12** includes a first channel **38** extending peripherally from the bottom wall of the front side of the first housing, and also includes a second channel **381** extending peripherally from the bottom wall of the rear side of the housing **12**. The first and second channels are provided to support and facilitate sliding movement of inlet and outlet sliding gates **40**, **4011**, respectively.

[0075] The inlet sliding gate **40** opens and closes the gas inlets **32**, **321**. In this respect, the inlet sliding gate includes a first opening **401** which is configured to simultaneously register with the gas inlet of the first compartment and one of (i) a first conduit, for effecting fluid communication between the gas inlet and the first conduit and thereby providing passenger compartment air flow to the first compartment **18**, and (ii) a second conduit, for effecting fluid communication between the gas inlet and the second conduit and thereby providing ambient air flow to the first compartment **18**. The inlet sliding gate also includes a second opening **402** which is configured to simultaneously register with the gas inlet of the second compartment and one of (i) the second conduit, for effecting fluid communication between the gas inlet and the second conduit and thereby providing ambient air flow to the second compartment **20**, and (ii) a third conduit, for effecting fluid communication between the gas inlet and the third conduit and thereby providing exhaust gas flow to the second compartment **20**.

[0076] The inlet gate **40** is slideably moveable, so that in a first inlet gate position, the first opening simultaneously registers with the gas inlet of the first compartment **18** and the first conduit, and the second opening simultaneously registers with the gas inlet of the second compartment **20** and the second conduit. The inlet gate is also slideably moveable to a second inlet gate position, wherein the first opening simultaneously registers with the gas inlet of the first compartment **18** and the second conduit, and the second opening simultaneously registers with the gas inlet of the second compartment **20** and the third conduit.

[0077] The outlet sliding gate **4011** opens and closes the gas outlets **34**, **341**. In this respect, the outlet sliding gate **4011** includes a first opening **4013** which is configured to simultaneously register with the gas outlet of the first compartment and one of (i) a fourth conduit, for effecting fluid communication between the gas outlet and the fourth conduit and thereby returning the cooled interior air to the passenger compartment from the first compartment, and (ii) a fifth conduit, for effecting fluid communication between the gas outlet and the fifth conduit and thereby exhausting the heated ambient air from the first compartment. The outlet sliding gate 4011 also includes a second opening **4015** which is configured to simultaneously register with the gas outlet of the second compartment and (i) the fifth conduit, for effecting fluid communication between the gas outlet and the sixth conduit and thereby exhausting the heated ambient air from the second compartment, or (ii) a sixth conduit, for exhausting the cooled exhaust from the second compartment.

[0078] The outlet gate is slideably moveable, so that in a first outlet gate position, the first opening simultaneously registers with the gas outlet of the first compartment and the fourth conduit, and the second opening simultaneously registers with the gas outlet of the second compartment and the fifth conduit. The outlet gate is also slideably moveable to a second outlet gate position, wherein the first opening simultaneously registers with the gas outlet of the first compartment and the fifth conduit, and the second opening simultaneously registers with the gas outlet of the second compartment and the sixth conduit.

[0079] Sliding movement of each of the inlet and outlet gates **40**, **4011** is actuated by respective, separate extendible/retractable pistons **42**, **4022**. Each piston is coupled to a respective one of the inlet and outlet gates **40**, **4011**. Each piston is mounted to the frame of the heat pump **10**.

[0080] In one embodiment, the two pistons are configured to actuate the respective inlet and outlet gates so that the outlet gate is in the first outlet gate position when the inlet gate is in the first inlet gate position (cooling mode). Also, the two pistons are configured to actuate the respective inlet and outlet gates so that the outlet gate is in the second outlet gate position when the inlet gate is in the second inlet gate position (i.e. regeneration mode).

[0081] The second housing **12** is configured to be substantially the same as the first housing **10**. The inlet sliding gate of the second housing is coupled to the same actuating piston used to actuate the inlet sliding gate of the first housing. Similarly, the outlet sliding gate of the second housing is coupled to the same actuating piston used to actuate the outlet sliding gate of the first housing.

[0082] The hydride tubes **22** function as vessels defining an internal volume. Each of the vessels contains at least metal hydride material and gaseous hydrogen within the internal volume. The tubes are made of low carbon **316** seamless stainless steel. Preferably, the stainless steel alloy comprises less than 3 wt % carbon based on total weight of the alloy. The use of low carbon stainless steel reduces the amount of CH_4 that could be generated in the tubes at high temperatures. The tubes are rated for 3000 psi pressure.

[0083] In one embodiment, the ratio of the external surface area of the vessel to the internal volume of the vessel is greater than 45 in^2/in^3. Preferably, the ratio is greater than 89 in^2/in^3. Even more preferably, the ratio is greater than 176 in^2/in^3.

[0084] In another embodiment, when the vessel is in the form of an elongated tube sealed at both ends, the tube has an outside diameter less than ⅛ (0.125) of an inch. Preferably, the outside diameter is less than 1/16 (0.0625) of an inch (with a wall thickness of 0.005 inches). More preferably, the outside diameter is less than 1/32 (0.03125) of an inch (with a wall thickness of 0.0025 inches).

[0085] In one embodiment, the metal hydride heat pump **10** has two hydride tube beds; one bed provides cooling while the other is being recharged. The cycle time for each bed is split into two "half cycles" for regeneration. The hydride tube beds are operated 180° out of phase in order to provide continuous cooling of passenger compartment air.

[0086] Each hydride bed contains 356—1/16 of an inch diameter outside by 24 inches long straight low carbon stainless steel tubes. **FIG. 8** shows a simple cutaway view of a single metal hydride tube element **22**. This element consists of a 24 inch long, 0.0625 (1/16) inch in outer diameter, stainless steel tube. Inside this small tube are two different metal hydride materials. The "high temperature" material **44** is shown to occupy the right hand section of the tube (as shown in **FIG. 8**) and the low temperature material **46** is shown to occupy the left hand section. A hydrogen conduit **48** is axially disposed along the length of the tube to facilitate flow of hydrogen gas between the two materials. A disposition of a hydrogen conduit in a tube of an embodiment of the present invention is described in U.S. Pat. No. 4,396,114, which is incorporated herein by reference.

[0087] In one embodiment, the high temperature metal hydride material (hydridable form) is characterized by the formula:

$$Hf_A\,Zr_B\,Ti_C\,Ni_D\,Mm_E,$$

[0088] wherein

[0089] A=0.20 to 1.50

[0090] B=0 to 0.50

[0091] C=0 to 1.00

[0092] D=0.10 to 1.50, and

[0093] E=0 to 0.20

[0094] In one embodiment, the low temperature metal hydride material (hydridable form) is characterized by the formula:

$$Ti_F\,Zr_G\,Hf_H\,Mn_j\,V_K\,Fe_L\,Cr_M\,Ni_N$$

[0095] wherein

[0096] F=0.20 to 1.00

[0097] G=0 to 0.80

[0098] H=0 to 0.80

[0099] J=0.50 to 2.00

[0100] K=0 to 1.50

[0101] L=0 to 0.50

[0102] M=0 to 0.50, and

[0103] N=0 to 0.50

[0104] In one embodiment, the high temperature metal hydride material (the hydridable form) is $Hf_{1.0}\,Ni_{0.98}\,Mm_{0.02}$, and the low temperature metal hydride material (the hydridable form) is $Ti_{0.932}\,Zr_{0.052}\,Mn_{1.498}\,V_{0.464}\,Fe_{0.091}\,Cr_{0.001}\,Ni_{0.005}$.

[0105] Mm denotes mischmetal, a mixture of "rare earth" (lanthanum type) elements.

[0106] The term "hydrided form" refers to a form of the metal hydride material wherein hydrogen is associated with the material. The term "hydridable form" refers to a form of the metal hydride material wherein the material is capable of becoming associated with hydrogen.

[0107] The low temperature metal hydride material is metal hydride material characterized by an absorption plateau pressure (PA_L) and a desorption plateau pressure (PD_L). The high temperature metal hydride material is metal hydride material characterized by an absorption plateau pressure (PA_H) and a desorption plateau pressure (PD_H). At a given temperature within the operational range of the heat pump **10**, PA_L is greater than PA_H. Also, at a given temperature within the operational range of the heat pump **10**, PD_L is greater than PD_H. Each of the low temperature metal hydride material and the high temperature metal hydride material includes a hydrided form and a hydridable form. In the hydrided form, hydrogen is associated with the metal hydride material for example, by way of dissolution, ionic bonding, covalent bonding, or by way of being present in a complex material (e.g. sodium alanate). In the hydridable form, the metal hydrdide material is capable of becoming associated with hydrogen.

[0108] It is understood that "low temperature metal hydride material" can include a homogeneous or an inhomogeneous combination of more than one distinct substance, and that such distinct substance can be any of a hydrided or hydridable metal, an alloy of a hydrided or hydridable metal, a compound of hydrided or hydridable metal, or a hydrided or hydridable form of a complex metal hydride. Also, it is understood that "high temperature metal hydride material" can include more than one distinct substance, and that such distinct substance can be any of a hydrided or hydridable metal, an alloy of a hydrided or hydridable metal, a compound of a hydrided or hydridable metal, or a hydrided or hydridable form of a complex metal hydride. In these cases each of the substances of the low temperature metal hydride material must have PA_L greater than PA_H for each susbstance of the high temperature metal hydride material, and must also have PD_L greater than PD_H for each substance of the high temperature metal hydride material. Similarly, each of the substances of the high temperature metal hydride material must have PA_H less than PA_L for each substance of the low temperature metal hydride material, and also must have PD_H less than PD_L for each substance of the low temperature metal hydride material.

[0109] It is preferable that excess low temperature metal hydride material is used, relative to the high temperature metal hydride material. Hydrogen pressure at high temperatures such as 1000 degrees F. can become excessive, and it is generally desirable to maintain hydrogen pressure at about 700 psig. This can be maintained by using slightly more low temperature metal hydride material in the tube than is normally needed. This improves the likelihood that, during the recharge cycle, all of the hydrogen desorbed by the high temperature metal hydride material will have sufficient low temperature metal hydride material available for absorption. Preferably, the maximum storage capacity of the total amount of low temperature metal hydride material in the tube (vessel) is 1% to 10% greater than the maximum storage capacity of the total amount of high temperature metal hydride material in the tube (vessel). More preferably, it is 3% to 10% greater. Even more preferably, it is 5% to 10% greater.

[0110] **FIG. 9A** (MHAC recharging mode) shows that when the high temperature metal hydride material (right hand side of tube) is heated with hot exhaust heat, hydrogen is driven out of the high temperature metal hydride material and flows through the tube to the low temperature metal hydride material located in the left hand section of the tube. As the hydrogen enters the low temperature metal hydride material, heat is generated. This generated heat is removed by the ambient air flowing past the outside of the tube.

[0111] **FIG. 9B** shows the MHAC cooling mode. Here, ambient air is now flowing past the high temperature metal hydride material section (right side). This cools down the material which allows the hydrogen gas to flow back from the low temperature metal hydride material. As this hydrogen leaves the low temperature metal hydride material, cooling is generated. The heat removed from the low temperature metal hydride material is supplied by the car's interior air stream that is flowing past this left hand section of the tube.

[0112] The air conditioner will house 712 of these individual small tubes. These 712 tubes are split into two equal "beds" of about 356 tubes each. **FIG. 10** shows the basic staggered tube pattern for each bed. The split tube beds allow one bed to be recharged while the other bed is producing cooling, therefore, continuous cooling is generated by the MHAC.

[0113] **FIG. 11** shows the basic 2 bed metal hydride heat exchanger layout for this multi-tube design for the bench top prototype. The top metal hydride bed is separated from the bottom bed by about a 0.5 inch clearance. The metal hydride tubes are held in place at substantially the midpoint by the ss/ceramic wall.

[0114] **FIG. 12** is the component layout as viewed from the top half of the MHAC. This figure shows the conceptual placement of all components of the top half of the MHAC.

[0115] **FIG. 13** is an almost identical drawing for the bottom half of the MHAC.

[0116] In this respect, in one embodiment, there is provided a metal hydride heat pump **10** comprising a first compartment and a second compartment. The first compartment includes a first gas inlet configured for fluid communication with a first gas outlet. The second compartment includes a second gas inlet configured for fluid communication with a second gas outlet.

[0117] For the metal hydride heat pump **10**, a plurality of metal hydride vessels is provided, wherein each of the vessels is mounted to and disposed within each of the first and second compartments.

[0118] Each of the vessels contains at least a hydrided form of a low temperature metal hydride material, a hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein the hydridable form of a high temperature metal hydride material is in fluid communication with the hydrided form of the low temperature metal hydride material such that heat can be transferred from (a) gas flowing through the first compartment to (b) the hydrided form of a low temperature metal hydride material, so as to effect desorption of hydrogen from the hydrided form of a low temperature metal hydride material. The hydridable form of a high temperature metal hydride material is configured to absorb the desorbed hydrogen and generate heat upon the absorption such that the generated heat can be transferred to gas flowing through the second compartment. Each of the vessels has an external surface area, and defines an internal volume for containing at least the hydrided form of a low temperature metal hydride material, the hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in^2 per cubic inch.

[0119] In one embodiment, each of the vessels extends between the first and second compartments, and also extends into each of the first and second compartments. The low temperature metal hydride material is contained in a portion of the internal volume of each vessel disposed in the first compartment, and the high temperature metal hydride material is contained in a portion of the internal volume of each vessel disposed in the second compartment.

[0120] In one embodiment, the internal volume of the vessel contains an amount of metal hydride material consisting essentially of (i) an amount of a hydrided and/or a hydridable form of a low temperature metal hydride material, and (ii) an amount of a hydrided and/or a hydridable form of a high temperature metal hydride material, and wherein the amount of a hydrided and/or a hydridable form of a low temperature metal hydride material is substantially disposed in a portion of the internal volume of the vessel disposed in the first compartment, and wherein the amount of a hydrided and/or a hydridable form of a high temperature metal hydride material is substantially disposed in a portion of the internal volume of the vessel disposed in the second compartment.

[0121] In this context, "consisting essentially of" means that other materials may or may not be present in the internal volume. If present, these other materials may be present as impurities introduced as by-products during processing or from raw materials. These other materials are present in amounts which are not sufficiently significant to effect the desired properties of the respective metal hydride materials imparted to the heat pump during operation (cooling, regeneration) of the heat pump **10** incorporating these metal hydride materials.

[0122] The term "substantially disposed" means that small, insignificant amounts of the hydrogen storage materials may be present outside of the respective internal volume portions described above, so long as heat pump **10** operation (cooling, regeneration) is not significantly detrimentally affected.

[0123] The amount of a hydrided and/or a hydridable form of a low temperature metal hydride material has a first maximum hydrogen storage capacity (the maximum amount of hydrogen which can be absorbed by the amount of the low temperature metal hydride material), and wherein the amount of a hydrided and/or a hydridable form of a high temperature metal hydride material has a second maximum hydrogen storage capacity (which is the maximum amount of hydrogen which can be absorbed by the amount of the high temperature hydrogen storage material), such that the first maximum hydrogen storage capacity is 1% to 10% greater than the second maximum hydrogen storage capacity. Preferably, the first maximum hydrogen storage capacity is 3% to 10% greater than the second maximum hydrogen storage capacity. Even more preferably, the first maximum hydrogen storage capacity is 5% to 10% greater than the second maximum hydrogen storage capacity.

[0124] The following is a list of all of these components needed for the operation and instrumentation of the unit.

[0125] Exhaust Gas Simulation & Instrumentation Components

[0126] Item F**1** Exhaust gas simulation fan/blower. This fan will be variac controlled and is ducted for use in both top and bottom metal hydride (MH) beds.

[0127] Item H**1** Electrical resistance heating element, variac controlled to provide the required waste heat simulation.

[0128] Item G**1** Hot exhaust inlet gate valve to the high temperature metal hydride material in the top MH bed.

[0129] Item G**9** Hot exhaust inlet gate valve to the high temperature metal hydride material in the bottom MH bed.

[0130] Item G**6** Hot exhaust outlet gate valve from the high temperature metal hydride material section of the top MH bed.

[0131] Item G**14** Hot exhaust outlet gate valve from the high temperature metal hydride material section of the bottom MH bed.

[0132] Item AFM**1**"Exhaust Gas" air flow meter located upstream of the exhaust gas heating element. Analog output read by a computer data acquisition system using "Labtech NOTEBOOK" software.

[0133] Item TC**1** Fast response chromal/aluma thermocouple for measuring the exhaust gas temperatures flowing into the high temperature metal hydride material section of the top MH bed (analog signal fed into the computer/NOTEBOOK system).

[0134] Item TC**9** Thermocouple, hot exhaust gas inlet to the high temperature metal hydride material section of the bottom MH bed.

[0135] Item TC**6** Thermocouple, hot exhaust gas outlet from the high temperature metal hydride material section of the top MH bed.

[0136] Item TC**14** Thermocouple, hot exhaust gas outlet from the high temperature metal hydride material section of the bottom MH bed.

[0137] Ambient Cooling System

[0138] Item F**2** Ambient fan/blower, variac controlled, ducted to provide ambient air flow to the four needed regions.

[0139] Item H**2** Electrical resistance heating element, variac controlled, to provide heating of ambient air up to 110° F., for simulation of a hot summer day.

[0140] Item G**2** Ambient air inlet gate valve to the high temperature metal hydride material in the top bed.

[0141] Item G**3** Ambient air inlet gate valve to the low temperature alloy in the top bed.

[0142] Item G**5** Ambient air outlet gate valve from the high temperature metal hydride material in the top bed.

[0143] Item G**8** Ambient air outlet gate valve from the low temperature metal hydride material in the top bed.

[0144] Item G**10** Ambient air inlet gate valve into the high temperature metal hydride material tubes in the bottom MH bed.

[0145] Item G11 Ambient air inlet gate valve into the low temperature metal hydride material tubes in the bottom MH bed.

[0146] Item G13 Ambient air outlet gate valve from the high temperature metal hydride material tubes in the bottom MH bed.

[0147] Item G16 Ambient air outlet gate valve from the low temperature alloy tubes on the bottom MH bed.

[0148] Item AFM2 Air flow meter located before the fan in the ambient air inlet duct. Analog output into computer/NOTEBOOK data system.

[0149] Item TC2 Thermocouple, ambient air inlet to high temperature tubes on top bed.

[0150] Item TC3 Thermocouple, ambient air inlet to low temperature tubes on top bed.

[0151] Item TC5 Thermocouple, ambient air outlet from high temperature tubes on top bed.

[0152] Item TC8 Thermocouple, ambient air outlet from low temperature tubes on top bed.

[0153] Item TC10 Thermocouple, ambient air inlet to high temperature tubes on bottom bed.

[0154] Item TC11 Thermocouple, ambient air inlet to low temperature tubes on the bottom bed.

[0155] Item TC13 Thermocouple, ambient air outlet to high temperature tubes on bottom bed.

[0156] Item TC16 Thermocouple, ambient air outlet to low temperature tubes on bottom bed.

[0157] Interior Car Air System

[0158] Item F3 Interior car air fan/blower, variac controlled, ducted to provide air flow to either the top or bottom MH beds.

[0159] Item G4 Interior car air gate valve that lets air flow into the low temperature metal hydride material tubes in the top MH bed.

[0160] Item G7 Interior car air gate valve that lets air flow out of the low temperature metal hydride material tube section of the top MH bed.

[0161] Item G12 Interior car air gate valve that lets air flow into the low temperature metal hydride material tubes in the bottom MH bed.

[0162] Item G15 Interior car air gate valve that lets air flow out of the low temperature metal hydride material tube section of the bottom MH bed.

[0163] Item AFM3 Air flow meter measuring the air flow into the interior car inlet air flow duct.

[0164] Item TC4 Thermocouple, interior car air into the low temperature metal hydride material tubes in the top MH bed.

[0165] Item TC7 Thermocouple, interior car air leaving the low temperature metal hydride material tube section of the top MH bed.

[0166] Item TC12 Thermocouple, interior car air entering the low temperature metal hydride material tube section of the bottom MH bed.

[0167] Item TC15 Thermocouple, interior car air leaving the low temperature metal hydride material section of the bottom MH bed.

[0168] NOTE: All air flow meter and thermocouple data will be recorded via computer/"Labtech" NOTEBOOK software or equivalent.

[0169] Gate Valve Control

[0170] **FIGS. 14 and 15** show how operation and control of all of the inlet gate valves (G1, G2, G3, G4, G9, G10, G11, G12) will be accomplished with one actuation mechanism, a single acting pneumatic piston. In **FIG. 14**, the gate valves are positioned such that the top MH bed is in the cooling mode while the bottom MH bed is in the regeneration mode. After the time for a ½ cycle times out, the piston is energized and the gates will shift to the position shown in **FIG. 15**. In this new position, the bottom MH bed will be producing cooling while the top MH bed is being regenerated.

[0171] In a like manner, all of the gate valves (G5, G6, G7, G8, G13, G14, G15, G16) controlling the outlet air flow will be controlled by a single pneumatic piston. This configuration will provide the delayed switching of the outlet air flow paths needed to provide sensible heat recovery.

[0172] In one embodiment, the heat pump **10** is designed to produce 6000 BTU per hour of cooling at a temperature of at least 47 F using a hot air source (e.g. exhaust) at 1000 F following at 1 lbm/min air flow, with an ambient temperature of 120 F or less (with 3% relative humidity).

[0173] Although the disclosure describes and illustrates preferred embodiments of the invention, it is to be understood that the invention is not limited to these particular embodiments. Many variations and modifications may occur to those skilled in the art within the scope of the invention. For definition of the invention, reference is to be made to the appended claims.

What is claimed is:

1. A metal hydride heat pump comprising:

a first compartment, including a first fluid inlet and a first fluid outlet, wherein the first fluid inlet is configured for fluid communication with the first fluid outlet;

a second compartment, including a second fluid inlet and a second fluid outlet, wherein the first fluid inlet is configured for fluid communication with the second fluid outlet; and

a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within each of the first and second compartments, and each of the vessels containing at least a hydrided form of a low temperature metal hydride material, a hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein the hydridable form of a high temperature metal hydride material is in fluid communication with the hydrided form of a low temperature metal hydride material, such that heat can be transferred from (a) fluid flowing through the first compartment to (b) the hydrided form of a low temperature metal hydride material, so as to effect desorption of hydrogen from the hydrided form of a low temperature metal hydride material, and such that the hydridable form of a high temperature metal hydride material is configured to absorb the desorbed hydrogen and generate heat upon the absorption such that the generated heat can be transferred to fluid flowing through the second compartment;

wherein each of the vessels has an external surface area, and defines an internal volume for containing at least the hydrided form of a low temperature metal hydride material, the hydridable form of a high temperature metal hydride material, and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in2 per cubic inch.

2. The metal hydride heat pump as claimed in claim 1, wherein each of the vessels extends between the first and second compartments, and also extends into each of the first and second compartments.

3. The metal hydride heat pump as claimed in claim 2, wherein the low temperature metal hydride material is contained in a portion of the internal volume of the vessel disposed in the first compartment, and the high temperature metal hydride material is contained in a portion of the internal volume of the vessel disposed in the second compartment.

4. The metal hydride heat pump as claimed in claim 2, wherein the internal volume of the vessel contains an amount of metal hydride material consisting essentially of (i) an amount of a hydrided and/or a hydridable form of a low temperature metal hydride material, and (ii) an amount of a hydrided and/or a hydridable form of a high temperature metal hydride material, and wherein the amount of a hydrided and/or a hydridable form of a low temperature metal hydride material is substantially disposed in a portion of the internal volume of the vessel disposed in the first compartment, and wherein the amount of a hydrided and/or a hydridable form of a high temperature metal hydride material is substantially disposed in a portion of the internal volume of the vessel disposed in the second compartment.

5. The metal hydride heat pump as claimed in claim 4, wherein the amount of a hydrided and/or a hydridable form of a low temperature metal hydride material has a first maximum hydrogen storage capacity, and wherein the amount of a hydrided and/or a hydridable form of a high temperature metal hydride material has a second maximum hydrogen storage capacity, such that the first maximum hydrogen storage capacity is 1% to 10% greater than the second maximum hydrogen storage capacity.

6. The metal hydride heat pump as claimed in claim 5, wherein the first maximum hydrogen storage capacity is 3% to 10% greater than the second maximum hydrogen storage capacity.

7. The metal hydride heat pump as claimed in claim 6, wherein the first maximum hydrogen storage capacity is 5% to 10% greater than the second maximum hydrogen storage capacity.

8. The metal hydride heat pump as claimed in claim 3, wherein the low temperature metal hydride material is $Ti_F Zr_G Hf_H Mn_J V_K Fe_L Cr_M Ni_N$, and wherein the high temperature metal hydride material is $Hf_A Zr_B Ti_C Ni_D Mm_E$.

9. The metal hydride heat pump as claimed in claim 1, wherein the ratio is greater than 89.

10. The metal hydride heat pump as claimed in claim 1, wherein the ratio is greater than 176.

11. The metal hydride heat pump as claimed in claim 1, wherein the fluids flowing through each of the first and second compartments is gaseous.

12. The metal hydride heat pump as claimed in claim 1, wherein each of the vessels is in the form of an elongated tube sealed at both ends.

13. The metal hydride heat pump as claimed in claim 1, wherein the material of construction of each of the vessels is a stainless steel alloy comprising less than 3 weight percent of carbon based on the total weight of the stainless steel alloy.

14. A metal hydride heat pump comprising:

a compartment, including a first gas inlet and a first gas outlet, wherein the first gas inlet is configured for fluid communication with the first gas outlet; and

a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within the compartment, and each of the vessels containing at least a metal hydride material;

wherein the material of construction of each of the vessels is a stainless steel alloy comprising less than 3 weight percent of carbon based on the total weight of the stainless steel alloy.

15. A metal hydride heat pump comprising:

a compartment, including a first gas inlet and a first gas outlet, wherein the first gas inlet is configured for fluid communication with the first gas outlet; and

a plurality of metal hydride vessels, each of the vessels being mounted to and disposed within the compartment, and each of the vessels containing at least a metal hydride material and gaseous hydrogen;

wherein each of the vessels has an external surface area, and defines an internal volume for containing at least the metal hydride material and gaseous hydrogen, wherein a ratio of the external surface area to the internal volume is greater than 45 in^2 per cubic inch.

16. The metal hydride heat pump as claimed in claim 14, wherein the ratio is greater than 89.

17. The metal hydride heat pump as claimed in claim 14, wherein the ratio is greater than 176.

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