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(54) **SOLID STATE CRYOCOOLER**

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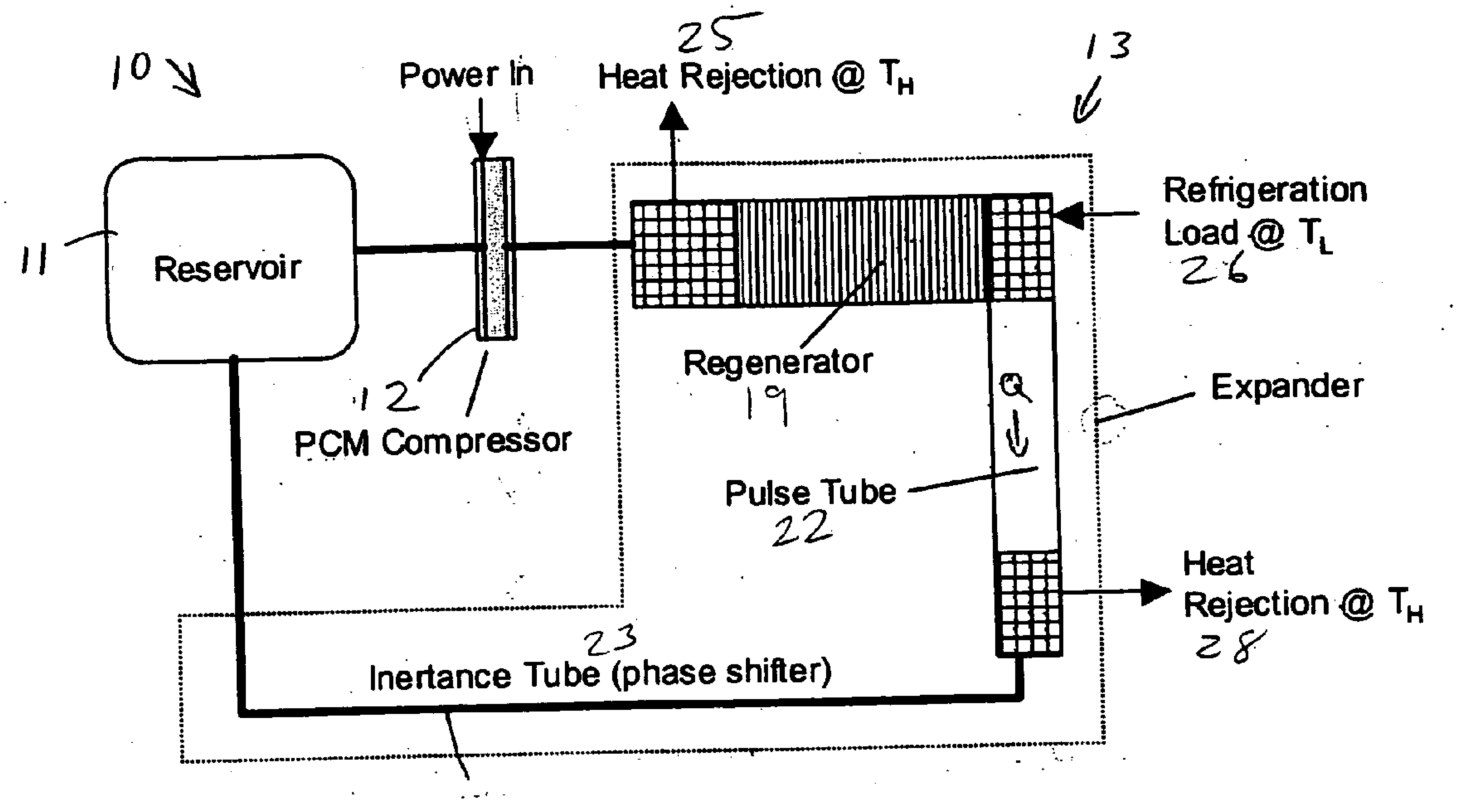
(57) **ABSTRACT**

A cryocooler is disclosed which includes a reservoir (**11**), an electrochemical cell or proton conductive membrane (PCM) compressor (**12**) coupled to a source of AC current, and a gas expander in the form of a pulse tube expander module (**13**). The compressor (**12**) includes a proton conductive membrane (**17**) positioned between a pair of electrically conductive electrodes (**18**) and (**19**). The pulse tube expander module **13** includes a regenerator (**21**), a pulse tube (**22**), and in inertance tube (**23**). The regenerator (**21**) has a heat rejection part or aftercooler (**25**) and a cooling part or cold heat exchanger (**26**). The pulse tube (**22**) includes a heat rejection portion or hot heat exchanger (**27**).



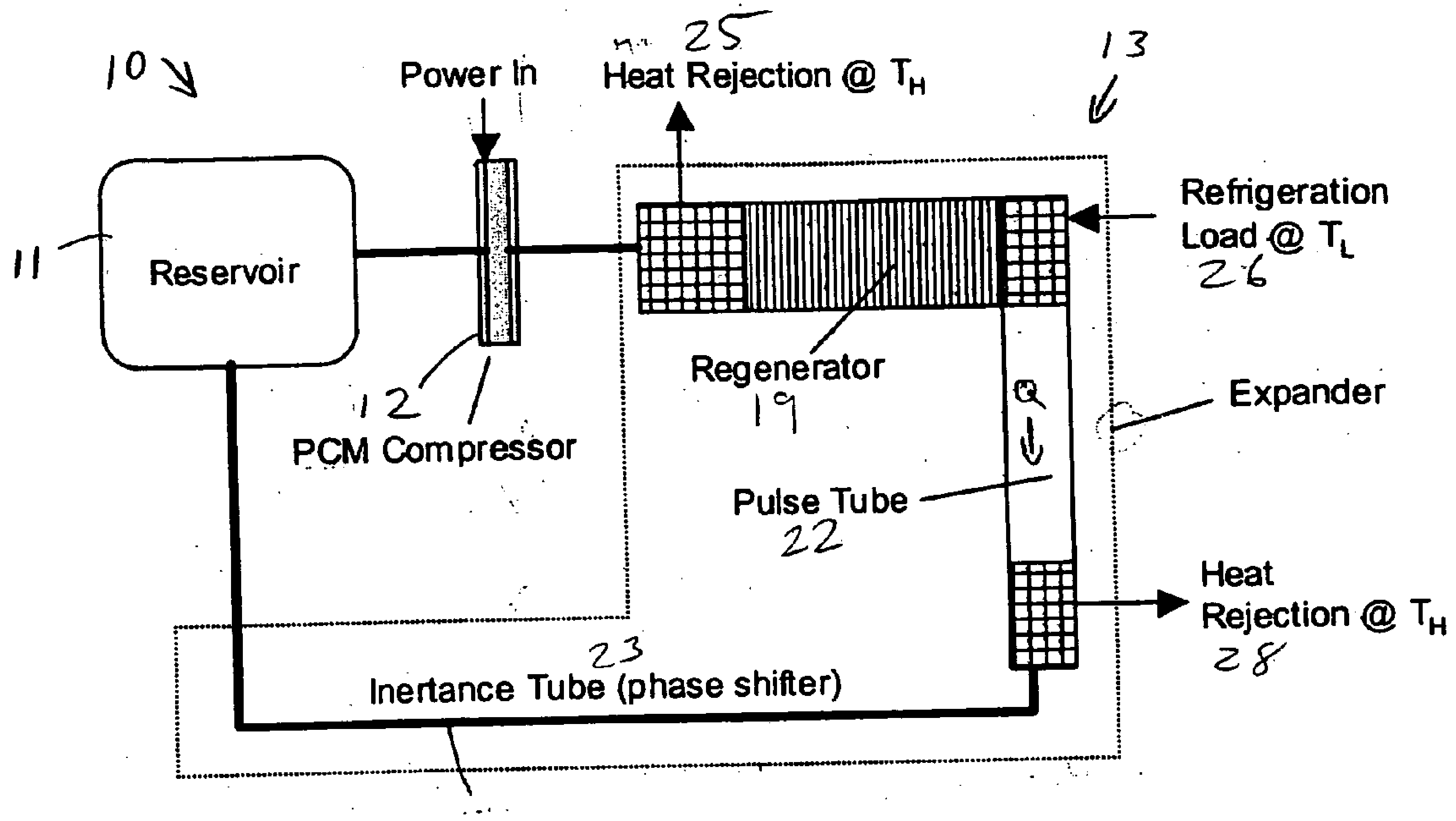

10
Power In
25
Heat Rejection @ T_H
13
11
Reservoir
Refrigeration Load @ T_L
26
12
PCM Compressor
Regenerator
19
Q
Expander
Pulse Tube
22
Heat Rejection @ T_H
28
23
Inertance Tube (phase shifter)

FIG 1

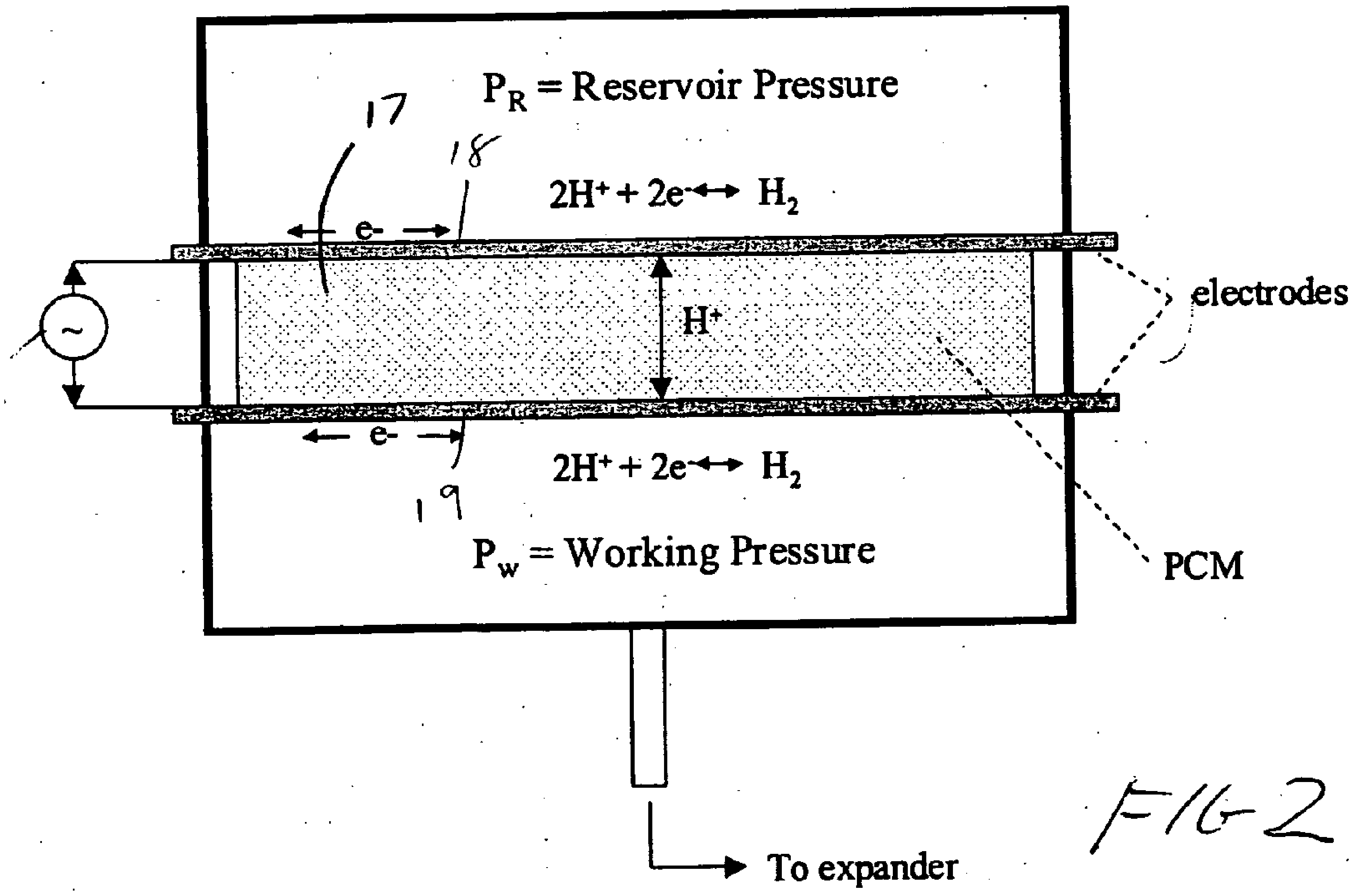

P_R = Reservoir Pressure
17
18
$2H^+ + 2e^- \leftrightarrow H_2$
e-
electrodes
H^+
~
e-
$2H^+ + 2e^- \leftrightarrow H_2$
19
P_w = Working Pressure
PCM
To expander

FIG 2

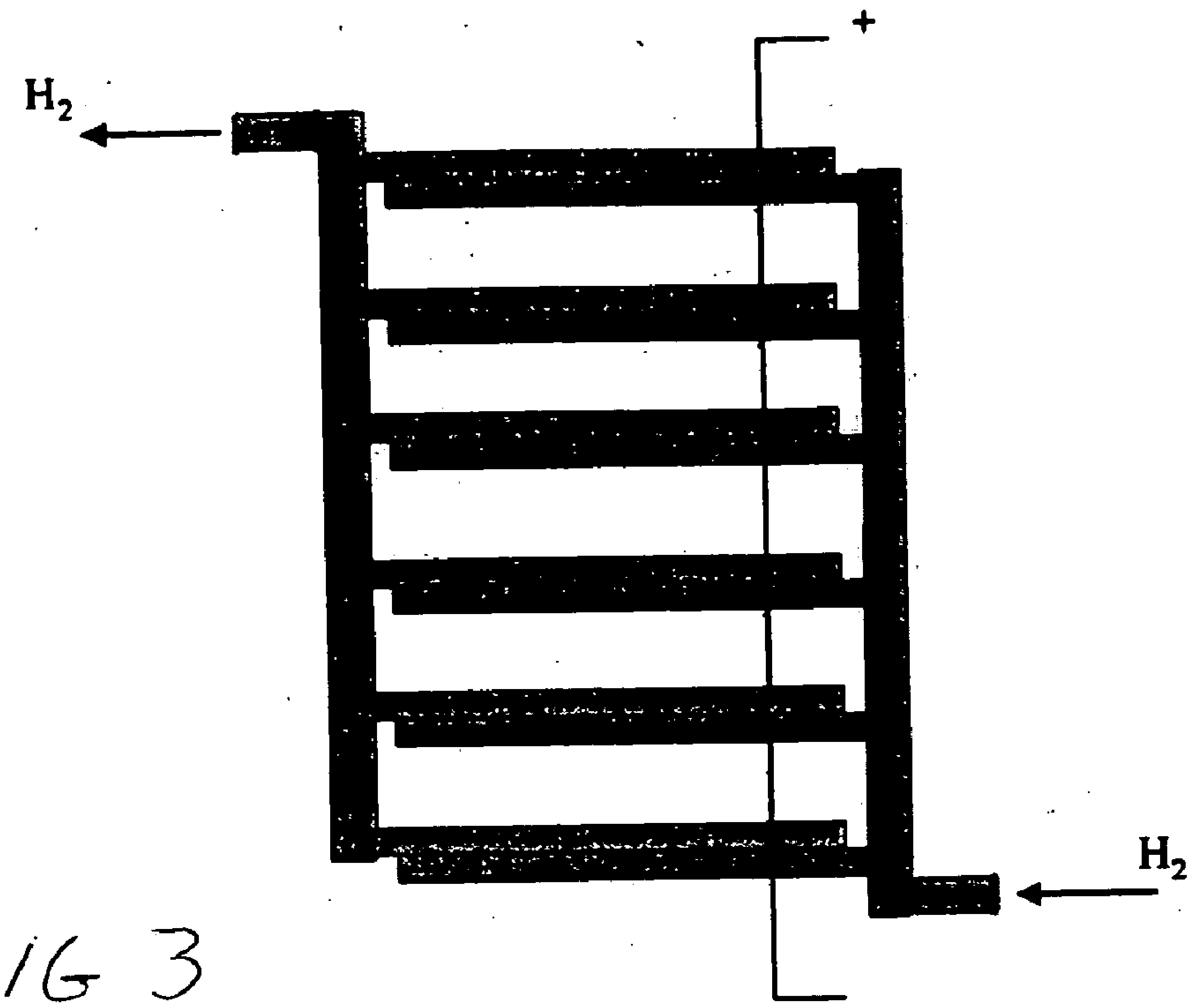

H_2
+
H_2

FIG 3

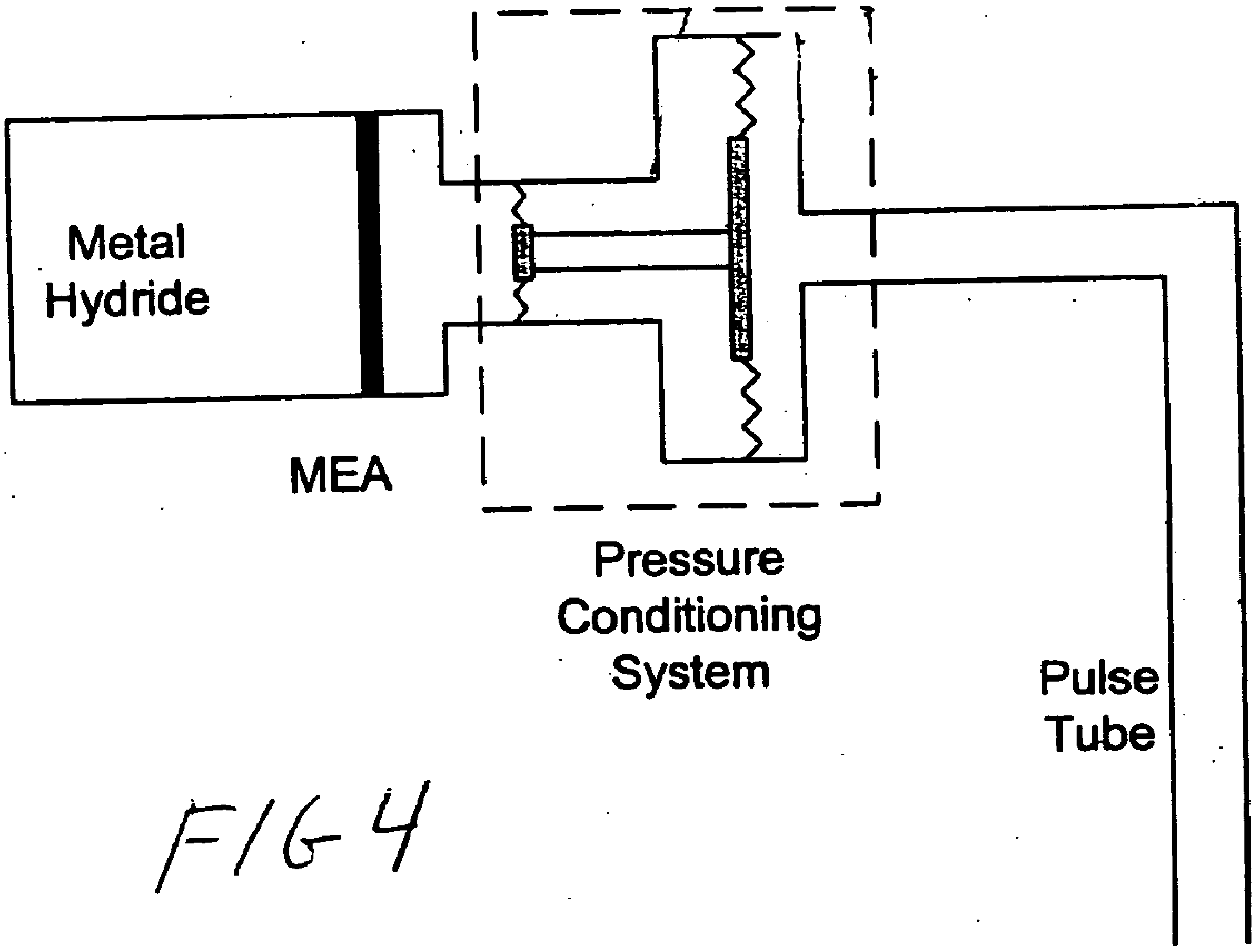

Metal Hydride
MEA
Pressure Conditioning System
Pulse Tube

FIG 4

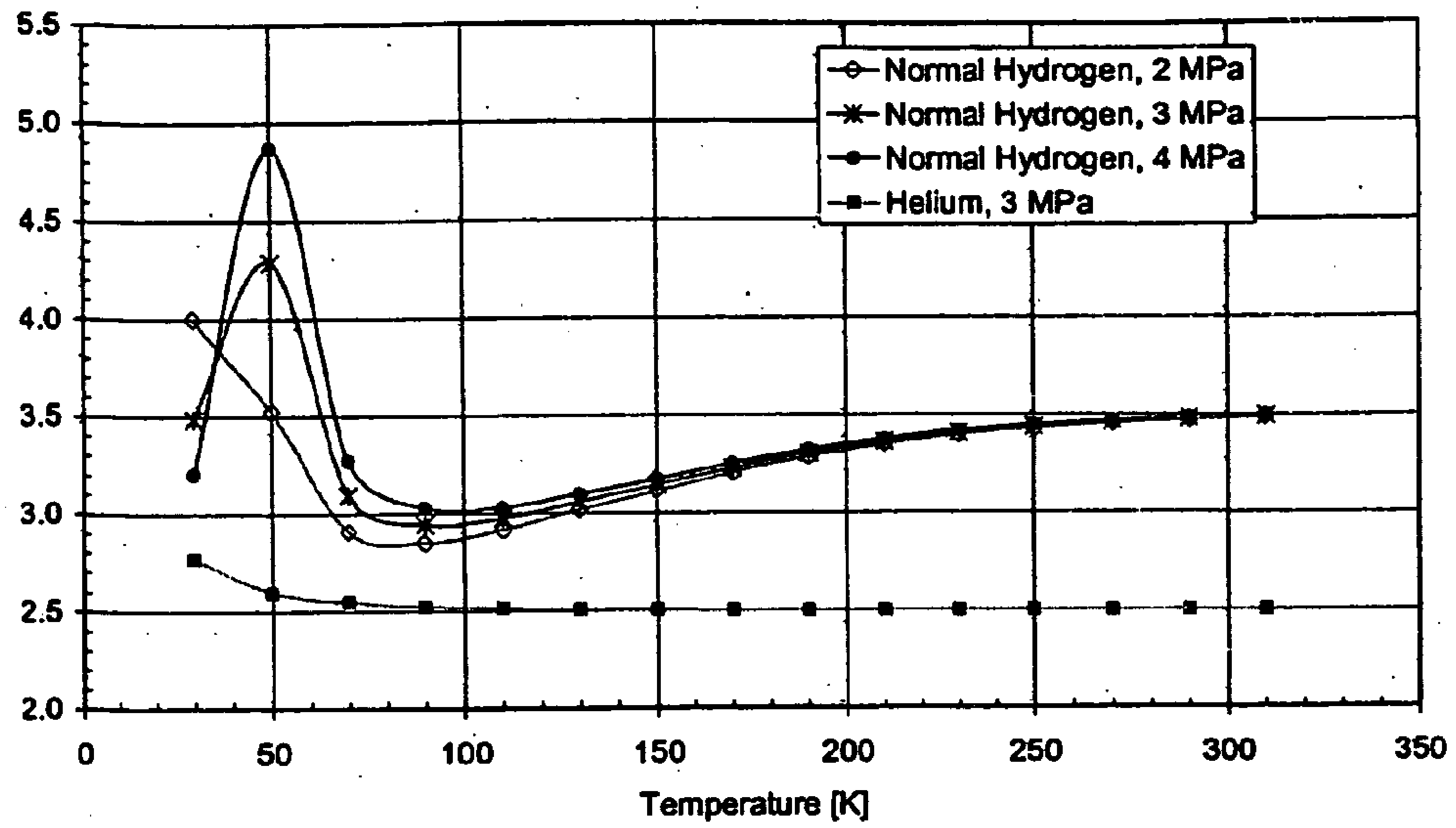

5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
50
100
150
200
250
300
350
Temperature [K]
Normal Hydrogen, 2 MPa
Normal Hydrogen, 3 MPa
Normal Hydrogen, 4 MPa
Helium, 3 MPa

FIG 5

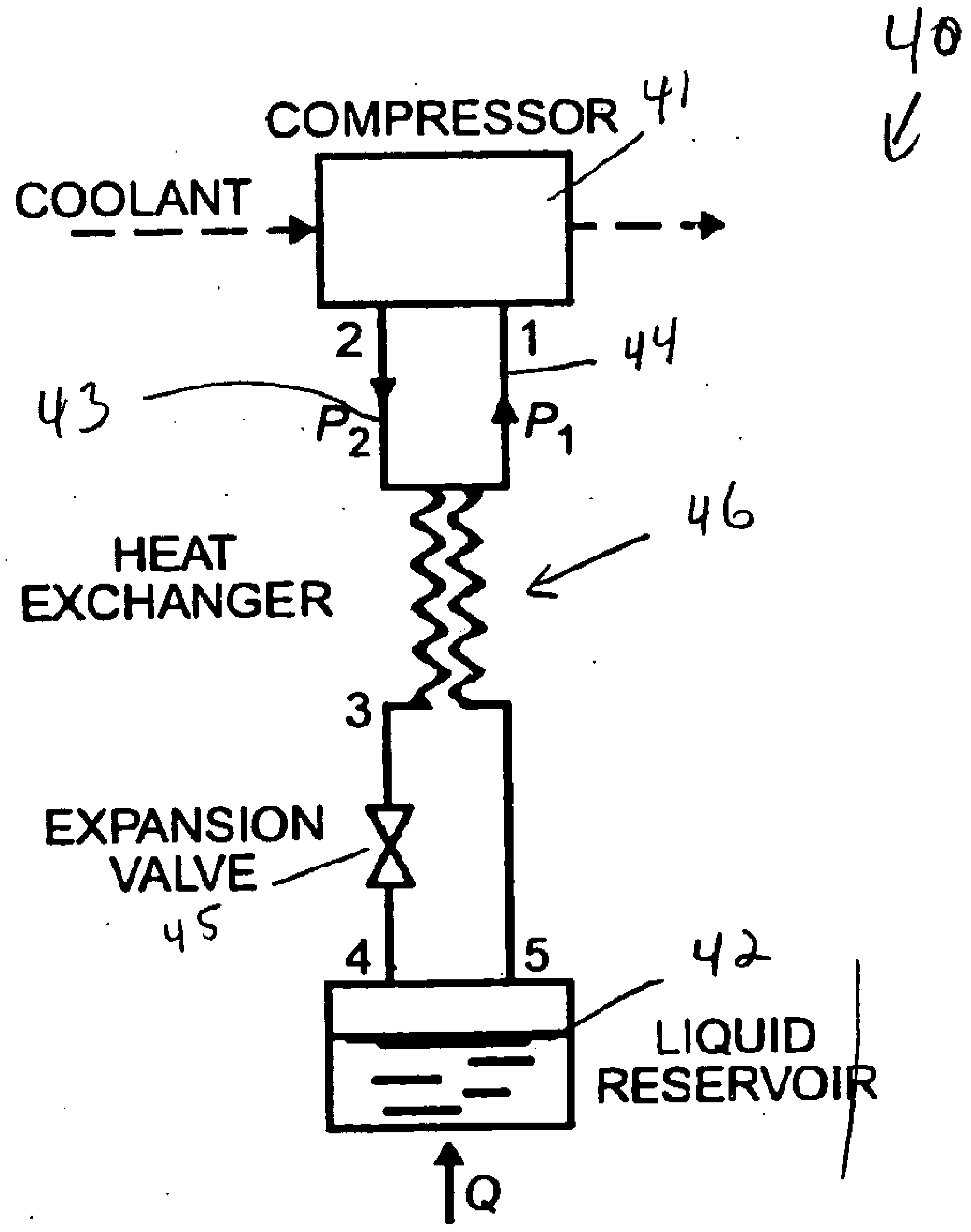

40
COMPRESSOR
41
COOLANT
2
1
44
43
P_2
P_1
46
HEAT EXCHANGER
3
EXPANSION VALVE
45
4
5
42
LIQUID RESERVOIR
Q

FIG 6

SOLID STATE CRYOCOOLER

TECHNICAL FIELD

[0001] This invention relates generally to cryocoolers, and more particularly to a solid state cryocooler.

BACKGROUND OF THE INVENTION

[0002] Since a cryocooler using a Stirling cycle can obtain cryogenic temperatures by repeatedly compressing and expanding a working gas, it has become widely used in cooling operations, such as for cooling of superconducting elements, refining and separation of gases, infrared ray sensors, or the like.

[0003] The operation principle of a Stirling cryocooler, using this Stirling cycle, relates to the rising and falling of a compression piston and a displacer in accordance with a refrigeration cycle.

[0004] A Stirling cryocooler typically includes a compressor having a compression piston, a regenerator having a regenerating agent, a displacer forming an expansion chamber and a compression chamber, a cooling part formed between the expansion chamber and the regenerator, and a heat rejection part formed around the compression chamber. A working gas is sealed under high pressure in a hermetically sealed flow passage constituted by these members, and the compression piston, of the compressor, and the displacer are reciprocated with a phase difference therebetween.

[0005] In the Stirling cryocooler, the compression piston is displaced by mechanical power, so that the pressure of the working gas in the sealed space is changed. The working gas in the expansion chamber is expanded, to cool, using the displacer moving in synchronization with the periodic change of this pressure. Therefore, a high heat efficiency can usually be achieved.

[0006] Another type of cryocoolers is known as a pulse tube cryocooler. Pulse tube cryocooler typically include a compressor to repetitively feed and suction a working gas, a regenerator, coupled to the compressor through a heat rejection part and having a regenerating agent, a pulse tube, coupled to the regenerator through a cooling part, and a buffer tank coupled to this pulse tube through a heat rejection part and an inertance tube.

[0007] A working gas such as helium, nitrogen or hydrogen can be sealed under high pressure in a hermetically sealed space of this pulse tube cryocooler. Then, similarly to the foregoing Stirling cryocooler, expansion and compression of the working gas is repeated by the compressor to form a pressure amplitude.

[0008] In the pulse tube cryocooler the working gas in the pulse tube oscillates in the flow passage, such that it functions as the displacer in the foregoing Stirling cryocooler example. Accordingly, the working gas can be made to work by controlling the phase of the displacement of the oscillating working gas and the pressure wave. Heat is rejected from the heat rejection parts, and heat is absorbed in the cooling part which becomes a cold head of the cryocooler, such that a cryogenic temperature state is formed. The inertance tube and the buffer serve to control the phases of the displacement of the oscillating working gas relative to the pressure wave created by the compressor.

[0009] Here, the displacer installed in the Stirling cryocooler is not necessary, and instead of the displacer, the high pressure gas is oscillated so that the working gas can be compressed and expanded. Therefore, there are no movable parts in the low temperature portion. Thus, since mechanical oscillation does not exist at a cooling head, an equipment structure becomes simple, resulting in high efficiency and reliability.

[0010] The output (cryocooler output) in the above pulse tube cryocooler is determined by a difference between an output (hereinafter referred to as an indicated cryocooler output) in proportion to the product of a pressure amplitude and a flow amplitude in the inner area of the pulse tube, and various heat losses generated inside the cryocooler. This is represented by the following relation.

(refrigeration output)=(indicated refrigeration output)−(heat loss)

[0011] A full explanation of these two types of cryocoolers as well as a detailed explanation of the their respective entropies is shown in U.S. Pat. No. 6,691,520, which is specifically incorporated herein by reference with regard to both the prior art and the present invention.

[0012] However, with both these types of cryocoolers the expander is driven by a compressor with flexure or coil spring suspended mechanical pistons driven by electromagnetic motor assemblies. The stressing lifetime and reliability requirements result in tight tolerances, labor intensive assembly procedures, and costly materials. The vibration output requirement also contributes to the design complexity of the cryocooler and necessitates expensive control electronics that mitigate the vibration output through closed-loop control of the input current waveform. All of these measures are costly to implement. Furthermore, even with the progress made to date on vibration control, jitter can still be an issue for sensor designers. In short, generation of the pressure wave through a mechanical piston introduces practical limits with respect to vibration output, reliability, lifetime, and packaging, and the industry is collectively approaching those limits.

[0013] Accordingly, it is seen that a need remains for a cryocooler that can be operated without creating vibrations and which is reliable for an extended period of time. It is to the provision of such therefore that the present invention is primarily directed.

SUMMARY OF THE INVENTION

[0014] In a preferred form of the invention a cryocooler comprises a gas expander, a gas reservoir in fluid communication with the gas expander, and a gas compressor in fluid communication with and between the reservoir and the gas expander. The gas compressor is an electrochemical cell coupled to a source of electricity. With this construction, a gas is compressed by the operation of the electrochemical cell and the gas is subsequently passed to and from the gas expander whereby a refrigeration is produced.

BRIEF DESCRIPTION OF THE DRAWING

[0015] **FIG. 1** is a schematic view of the cryocooler of the present invention.

[0016] **FIG. 2** is a schematic view of the membrane electrode assembly of the cryocooler of **FIG. 1**.

[0017] **FIG. 3** is a schematic view of multiple membrane electrode assemblies being coupled in series.

[0018] **FIG. 4** is a schematic view of pressure conditioning system that may be utilized with the cryocooler of **FIG. 1**.

[0019] **FIG. 5** is a chart comparing the specific heat temperature dependence of normal hydrogen to helium over a range of pressures and temperatures.

[0020] **FIG. 6** is a schematic view of the cryocooler of the present invention in another preferred form.

DETAILED DESCRIPTION

[0021] With reference next to the drawings, there is shown a solid state cryocooler **10** in a preferred form of the invention. The cryocooler **10** is a closed system which includes a reservoir **11**, an electrochemical cell or proton conductive membrane (PCM) compressor **12** coupled to a source of AC current, and a gas expander in the form of a pulse tube expander module **13**.

[0022] As shown in **FIG. 2**, the compressor **12** includes an ion conductive membrane such as a proton conductive membrane **17** positioned between a pair of electrically conductive electrodes **18** and **19**, as details of which and the operation of which is described in U.S. Pat. No. 6,489,049 and incorporated herein by reference. The pulse tube expander module **13** includes a regenerator **21**, a pulse tube **22**, and in inertance tube **23**. The regenerator **21** has a heat rejection part or aftercooler **25** and a cooling part or cold heat exchanger **26**. The pulse tube **22** includes a heat rejection portion or hot heat exchanger **27**.

[0023] The expander module **13** is based upon the pulse tube design in which the gross refrigeration capacity is achieved passively through the use of fixed, carefully tuned flow geometry. The solid state PCM compressor **12** generates an oscillating hydrogen pressure wave by energizing a proton conductive membrane **17** with an AC current through the electrodes **18** and **19**.

[0024] The pressure differential across a proton conductive membrane (PCM) results in a chemical potential across the membrane that generates electricity. The use of the PCM compressor is based on the fact that the system is reversible in that ions can be made to flow against the pressure gradient though the application of an excitation current. The proton conductive membrane **17** and the pair of electrodes **18** and **19** form a compressor **12** that allows free passage of working fluid to and from the proton conductive membrane **17** as illustrated in **FIG. 2**. Electricity is supplied to force the ion flow against the pressure gradient. Positively charged ions pass through the membrane while electrons travel through the electrodes to and from the power supply. The electrodes include a catalyst to promote the electrochemical reactions occurring at each electrode-proton conductive membrane interface. If the system uses hydrogen, the hydrogen gas on the low-pressure side is oxidized resulting in the creation of protons and electrons. The protons are pulled through the membrane **17** by the chemical potential created by the reduction of the hydrogen ions back into hydrogen gas on the high pressure side. An oscillating flow, as is required to drive a pulse tube expander, is created by the excitation of the proton conductive membrane compressor **12** with an AC current.

[0025] The compressor **12** described herein has been evaluated against a representative set of pulse tube requirements assuming an arbitrary 70 degrees Kelvin refrigeration temperature (see Table 1). The baseline parameters are based upon a helium design; the actual flow rate is likely lower because of the higher volumetric heat capacity of hydrogen. Simplifying assumptions are made to obtain an input power estimate. It was assumed that hydrogen is compressed uniformly into the expander volume prior to any flow into the pressure reservoir **11**. It was further assumed that the amount of mass delivered is sufficient to achieve a stable pressure ratio of 1.3 under isothermal compression at the prescribed operating frequency.

Parameter	Value
Cryocooler operating point	2.0 W @ 70 K
Operating temperature of MEA	300 K
Pressure ratio across MEA	1.3
Expander volume	4 cc
Reservoir volume	50 cc
Mean pressure	3.0 MPa
Minimum pressure	2.6 MPa
Maximum pressure	3.4 MPa
EA material	example: ZrP
MEA electrolyte thickness	1 μm
MEA impedance	0.0123 Ωcm^2
Frequency	example: 60 Hz
Peak hydrogen mass flow	1.5 g/sec

[0026] Voltage is applied to each MEA cell in accordance with the Nernst equation:

$$V_{open\ circuit}=RT/2F(ln(P_{ratio}))$$

where R is the specific gas constant (8.314 kJ/kg° K), T is the cell operating temperature (K), and F is Faraday's constant (96,487 coulombs). For a pressure ratio of 1.3 and a MEA temperature of 300 K, the open circuit voltage is approximately 3.3 mV. Given an objective pumping efficiency of 80%, the maximum allowable voltage drop due to resistance losses must be limited to 0.66 mV. The total voltage across the compressor **17** is 3.96 mv.

[0027] Pressure pulses are supplied in sine waves having a RMS mass flow rate of 1.06 g/sec. The mass flow rate is directly proportional to the current flow through the proton conductive membrane compressor **12** stack as given by:

$$I = \frac{nAE\dot{m}}{\mathrm{MW}_{H_2}}$$

where n is the number of electrons involved in the process (2 for molecular hydrogen), A is Avogadro's number (6.02e23), E is the charge on a single electron (1.602e-19 C) and MW is the molecular weight of hydrogen gas. Substituting values gives an average current flow of approximately 102 kAmps. For a current flow of 102 kAmps, the proton conductive membrane compressor **12** impedance must be limited to 6.4e-9 ohms in order for the voltage loss due to internal resistance to remain below 0.66 mv. At a resistance of 0.0123 Wcm^2, the minimum proton conductive membrane **17** area required to achieve the desired electrical efficiency is 1.9 m^2. The corresponding current flux is 0.053 $Amps/cm^2$.

[0028] Though the design closes mathematically, the operating current is unacceptably high for practical application. By connecting proton conductive membrane compressors **12** in series (see **FIG. 3**), the required current can be sufficiently reduced. The voltage is additive due to the series connection. However, the hydrogen flow and current are in parallel across all the compressors **12**. Assuming a stack of 105 compressors **12** yields a pulse voltage of 39.6 Volts (3.96 mV each) and a much more practical pulse current of 10.2 Amps.

[0029] The required input power is in a range typical of present day pulse tube cryocoolers. The hydrogen is cycled in a sine wave, so pumping power is only applied for the compression half of each cycle. Using an engineering estimate of 60% for the portion of the compression energy recovered during the expansion phase, the power estimate for this analysis comes out to 70 W. Given the conservative assumptions that support this calculation, this estimate compares favorably with the approximately 50 W one would expect to achieve with current state of the art.

[0030] With reference next to **FIG. 6**, there is shown a cryocooler in another preferred form of the invention. Here the cryocooler is a recuperative cryocooler system, rather than the cryocooler of **FIGS. 1-5** which is shown to be a regenerative cryocooler system. The recuperative cryocooler system shown in **FIG. 6** is a simple Joule-Thomson cycle system, however, it should be understood that any recuperative or regenerative system which uses a compressor may be included in the present invention.

[0031] Here, the cryocooler **40** includes a compressor **41**, a liquid reservoir **42**, a first gas conduit **43** extending between the compressor **41** and the liquid reservoir **42**, a second gas conduit **44** extending between the liquid reservoir **42** and the compressor **41**, an expansion valve **45** coupled to the first conduit **43**, and a heat exchanger **46** is thermal communication with the first and second conduits to transfer heat therebetween. The compressor **41** is an electrochemical cell of the same construction and operation previously recited in detail with regard to the system of **FIGS. 1-5**.

[0032] The operation of the system is essentially the same as conventional Joule-Thomson cycle system except for the novel use of an electrochemical cell as the compressor. The electrochemical cell operates to compress the working fluid thereby forcing it to pass through the first conduit **43**, through the expansion valve **45**, into the liquid reservoir **42**, and then through the second conduit **44** back to the compressor. Here again, the cryocooler operates without vibration as it does not include the moving parts associated with cryocooler compressors of the prior art.

[0033] It is believed that the present invention improves the performance and reliability of cryocoolers by completely eliminating all moving components from the design. This approach is inherently reliable, very low in vibration, lightweight, compact, and structurally robust. Electronics are greatly simplified because the need for active vibration control is eliminated. All of these advantages are provided in a cryocooler with thermodynamic efficiency that is competitive with the much more complicated Oxford class designs.

[0034] It thus is seen that a cryocooler is now provided which overcomes problems with cryocoolers utilizing mechanical compressors of the prior art. While this invention has been described in detail with particular references to the preferred embodiments thereof, it should be understood that many modifications, additions and deletions, in addition to those expressly recited, may be made thereto without departure from the spirit and scope of the invention as set forth in the following claims.

1. A cryocooler comprising:

a gas expander;

a gas reservoir in fluid communication with said gas expander; and

a gas compressor in fluid communication with and between said reservoir and said gas expander, said gas compressor being an electrochemical cell coupled to a source of electricity,

whereby a gas is compressed by the operation of the electrochemical cell and the gas is subsequently passed to the gas expander whereby a transfer of heat occurs.

2. The cryocooler of claim 1 wherein said electrochemical cell comprises an ion conductive material, a first electrode mounted upon one side of said ion conductive material, and a second electrode mounted upon one side of said ion conductive material opposite said first electrode.

3. The cryocooler of claim 2 wherein said ion conductive material is a proton conductive membrane.

4. The cryocooler of claim 1 wherein said gas expander is a regenerative type unit.

5. The cryocooler of claim 4 wherein said regenerative type unit is a pulse tube cooler.

6. The cryocooler of claim 5 wherein said pulse tube cooler includes a regenerator and a pulse tube in fluid communication with said regenerator.

7. The cryocooler of claim 6 wherein said pulse tube pulse tube cooler further comprises an inertance tube in fluid communication with said pulse tube.

8. The cryocooler of claim 5 wherein said electrochemical cell comprises an ion conductive material, a first electrode mounted-upon one side of said ion conductive material, and a second electrode mounted upon one side of said ion conductive material opposite said first electrode.

9. The cryocooler of claim 7 wherein said ion conductive material is a proton conductive membrane.

10. The cryocooler of claim 1 wherein said gas expander is a recuperative type system.

11. The cryocooler of claim 10 wherein said recuperative type system includes a liquid reservoir, a first conduit extending between said compressor and said reservoir, a second conduit extending between said reservoir and said compressor, a heat exchanger positioned to exchange heat between said first conduit and said second conduit, and an expansion valve coupled to said first conduit between said heat exchanger and said reservoir.

12. The cryocooler of claim 1 wherein said electrochemical cell comprises a ion conductive material, a first electrode mounted upon one side of said ion conductive material, and a second electrode mounted upon one side of said ion conductive material opposite said first electrode.

13. The cryocooler of claim 12 wherein said ion conductive material is a proton conductive membrane.

14. A cryocooler comprising:

a gas reservoir;

an electrochemical cell coupled to a source of electricity and mounted in fluid communication with said gas reservoir;

a regenerator mounted in fluid communication with said electrochemical cell; and

a pulse tube mounted in fluid communication with said regenerator and said gas reservoir,

whereby a gas is compressed by the operation of the electrochemical cell and the gas is subsequently passed to the regenerator and pulse tube whereby a transfer of heat occurs.

15. The cryocooler of claim 14 wherein said electrochemical cell comprises an ion conductive material, a first electrode mounted upon one side of said ion conductive material, and a second electrode mounted upon one side of said ion conductive material opposite said first electrode.

16. The cryocooler of claim 15 wherein said ion conductive material is a proton conductive membrane.

17. The cryocooler of claim 14 further comprises an inertance tube in fluid communication with said pulse tube.

18. A cryocooler comprising:

an electrochemical cell coupled to a source of electricity;

a liquid reservoir;

a first conduit extending between said electrochemical cell and said liquid reservoir;

a second conduit extending between said liquid reservoir and said electrochemical cell;

a heat exchanger positioned to exchange heat between said first conduit and said second conduit; and

and an expansion valve coupled to said first conduit between said heat exchanger and said reservoir,

whereby a gas is compressed by the operation of the electrochemical cell and the gas is subsequently passed through the first conduit, the liquid reservoir, and the second conduit whereby a transfer of heat occurs at the liquid reservoir.

19. The cryocooler of claim 18 wherein said electrochemical cell comprises an ion conductive material, a first electrode mounted upon one side of said ion conductive material, and a second electrode mounted upon one side of said ion conductive material opposite said first electrode.

20. The cryocooler of claim 12 wherein said ion conductive material is a proton conductive membrane.

* * * * *