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(54) **METHOD AND APPARATUS FOR DISSOCIATING WATER**

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(57) **ABSTRACT**

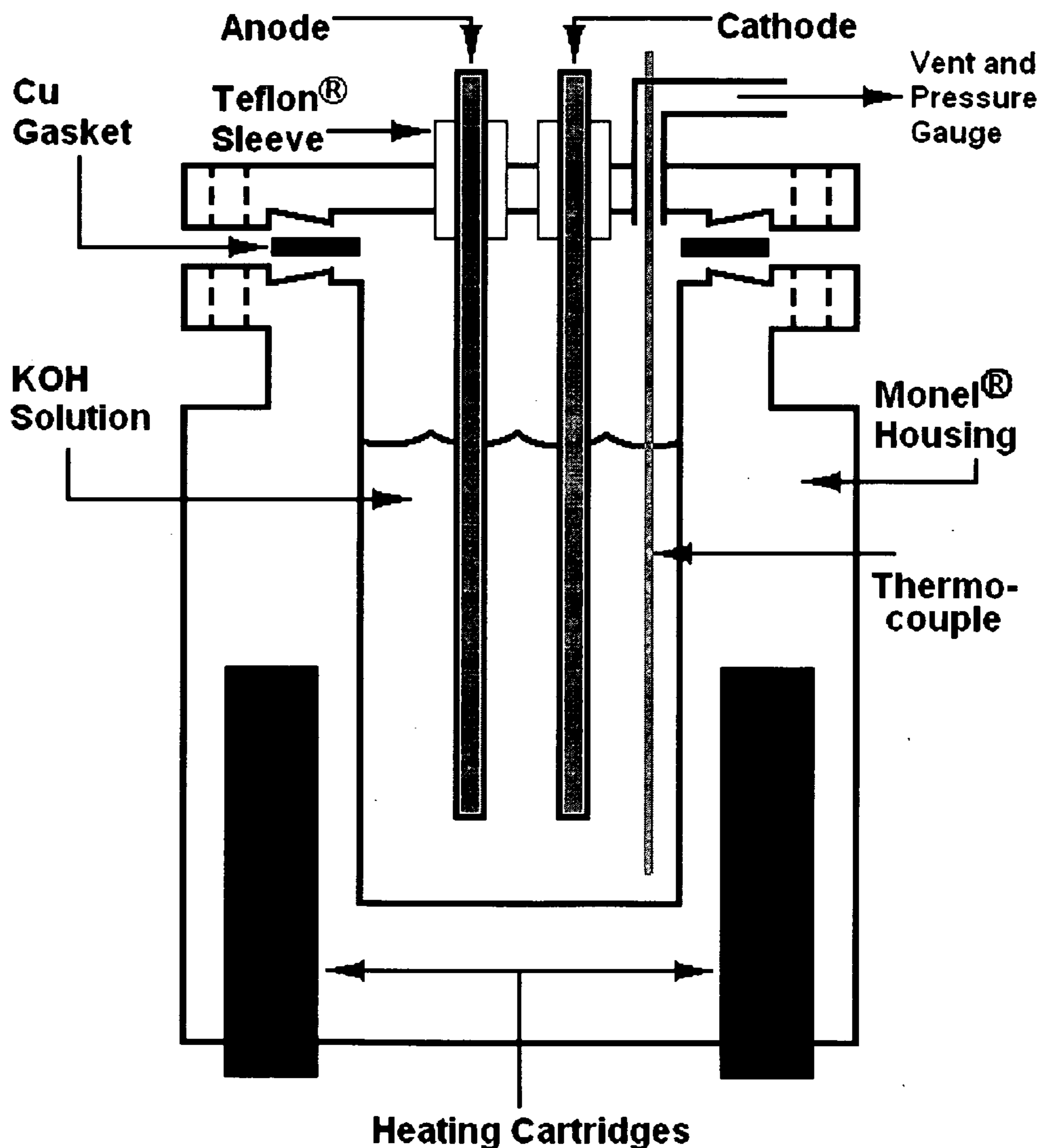
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A method and apparatus for dissociating water. A reaction chamber contains an anode and a cathode submerged in an aqueous hydroxide electrolyte. The temperature of the aqueous hydroxide electrolyte in the reaction chamber is elevated to at least 280° C. The pressure of the aqueous hydroxide electrolyte in the reaction chamber is likewise elevated to at least 2 atmospheres. An electrical voltage is applied across the anode and cathode using an electrical power supply and oxygen and hydrogen are formed from the water contained in the aqueous hydroxide electrolyte.

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# Figure 1

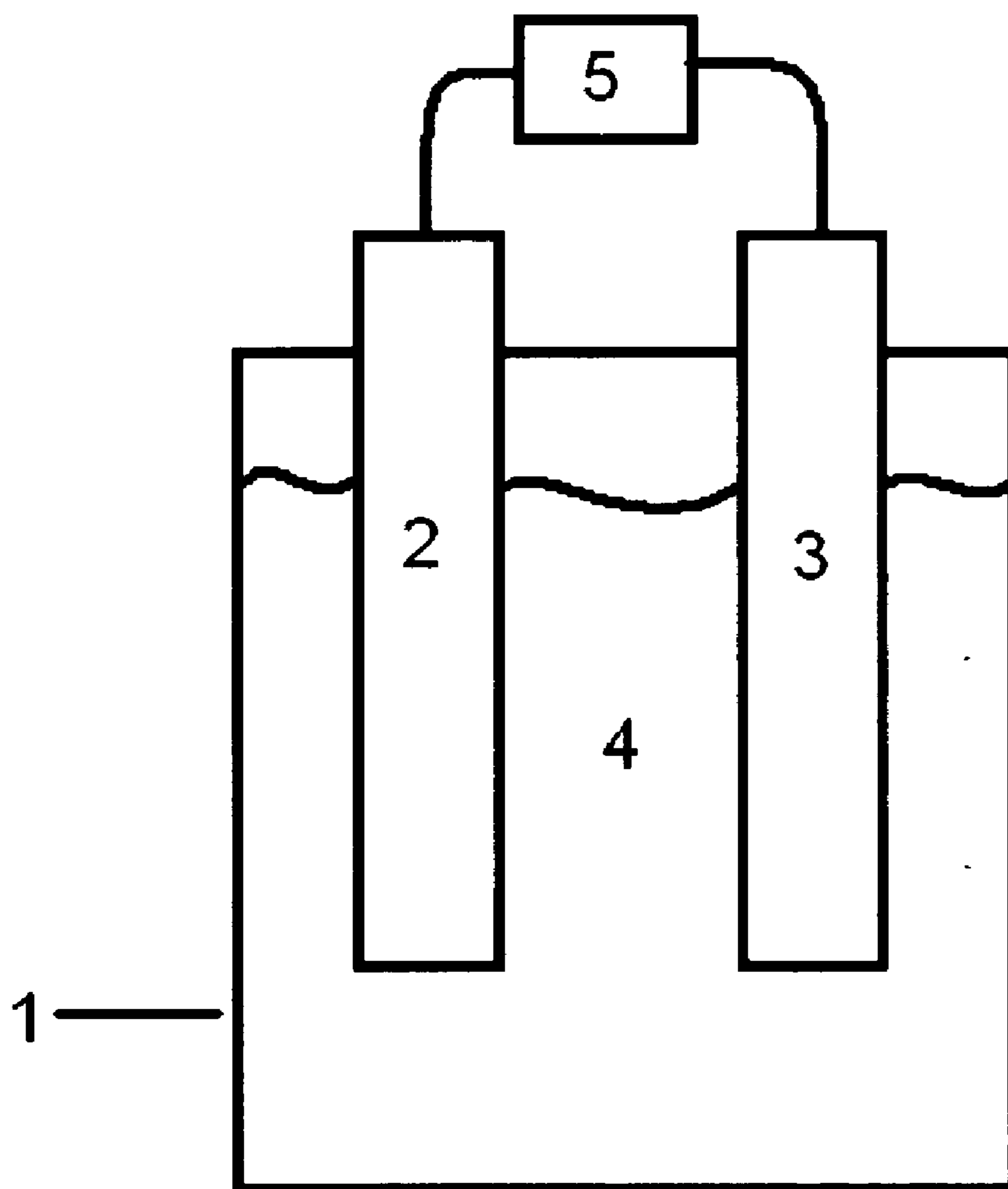
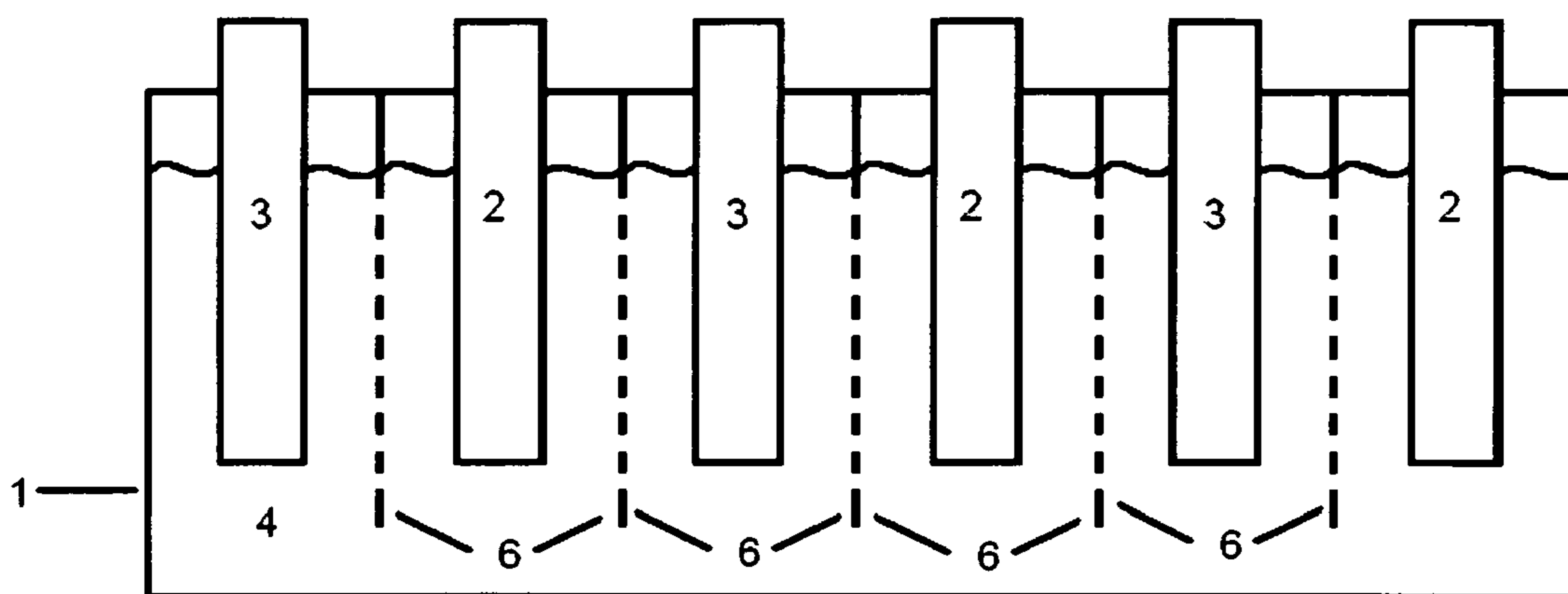


Figure 2



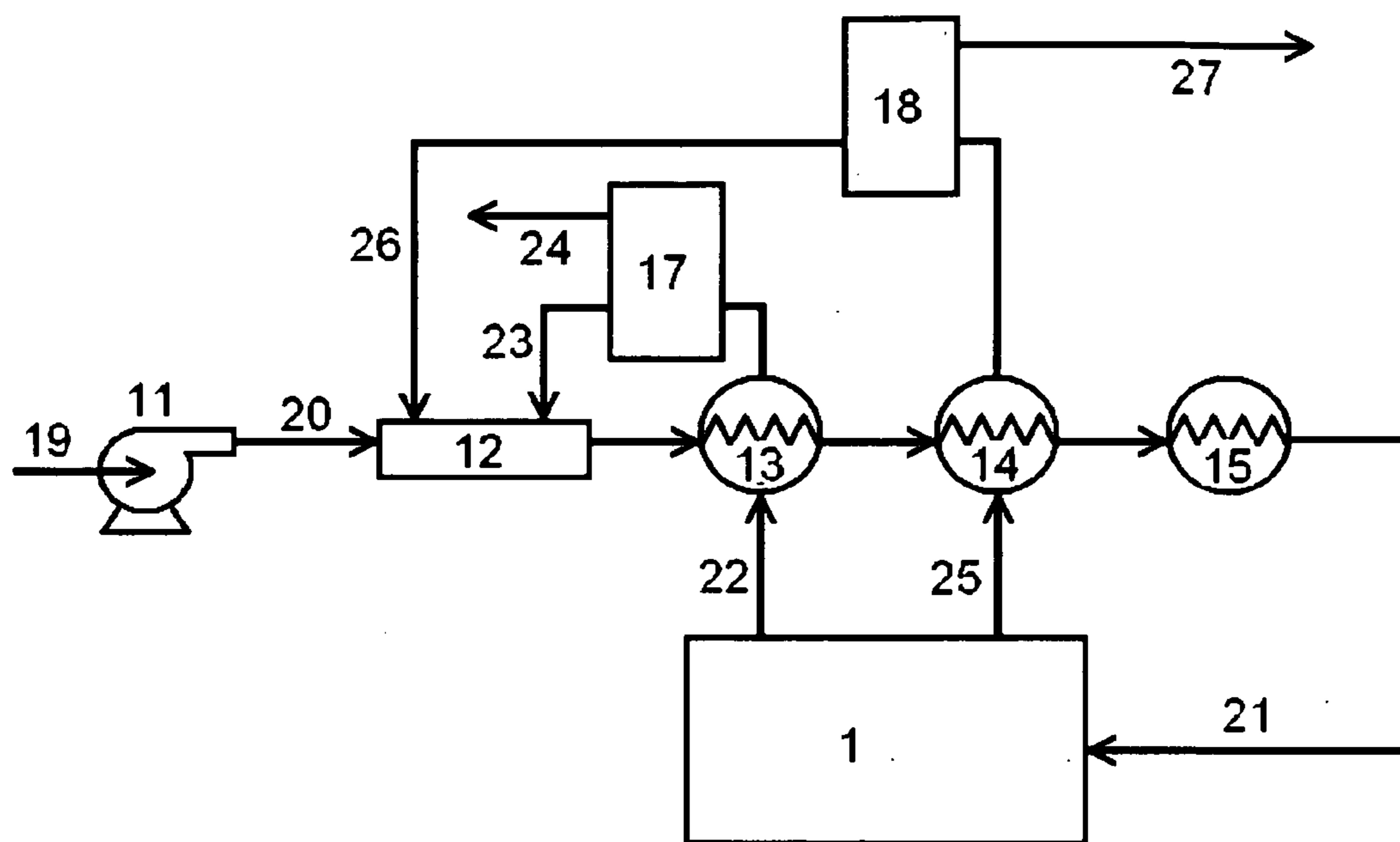


Figure 3

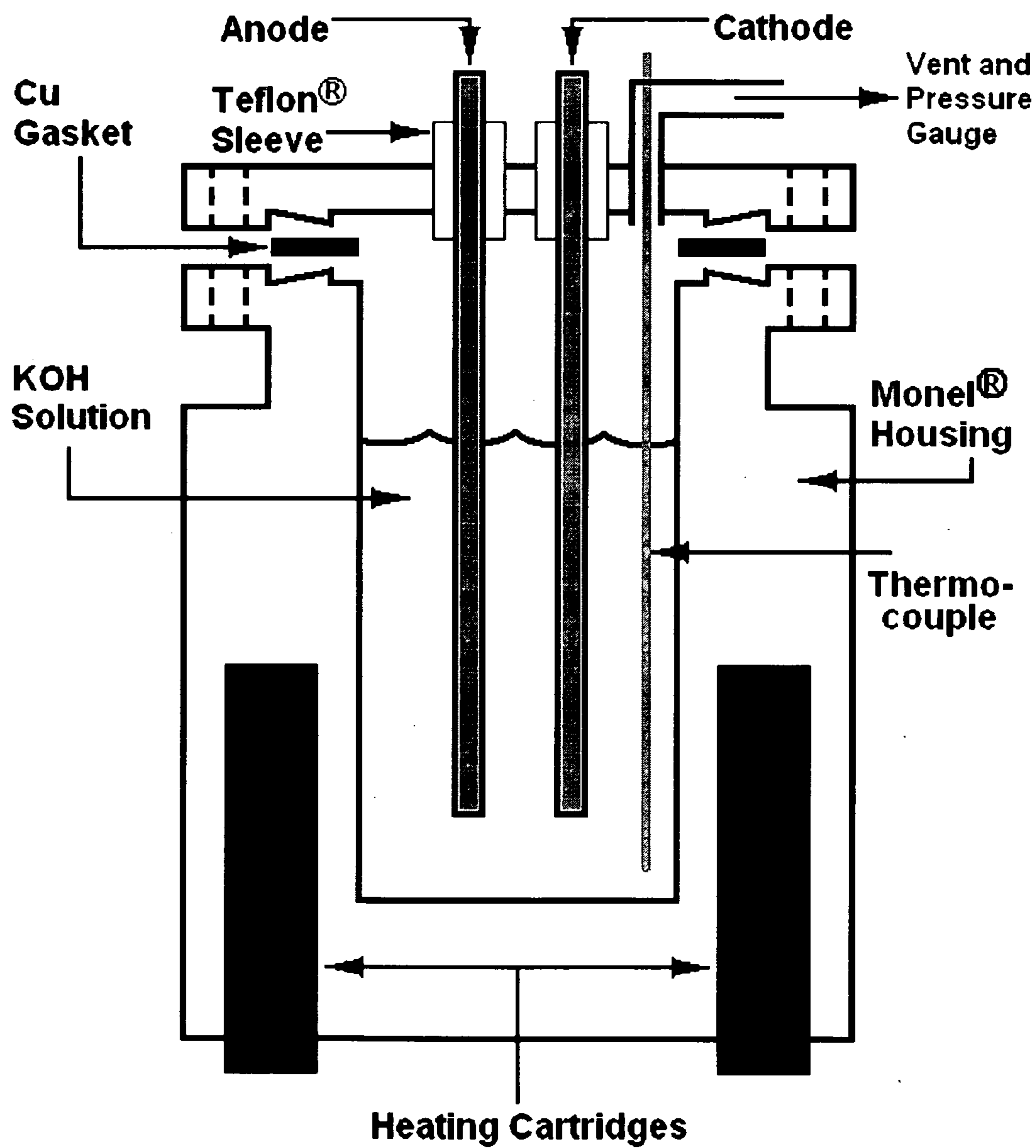


Figure 4

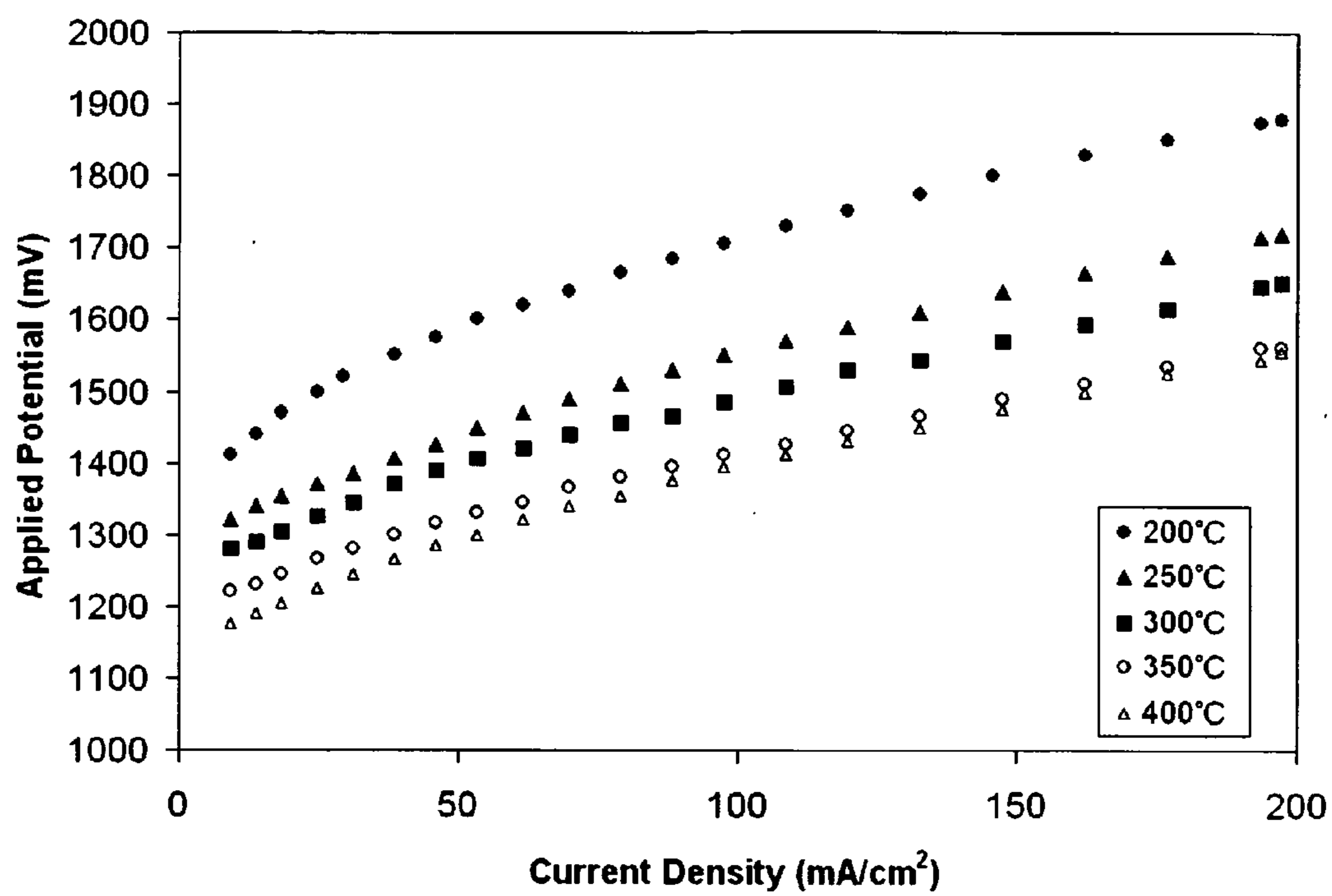


Figure 5

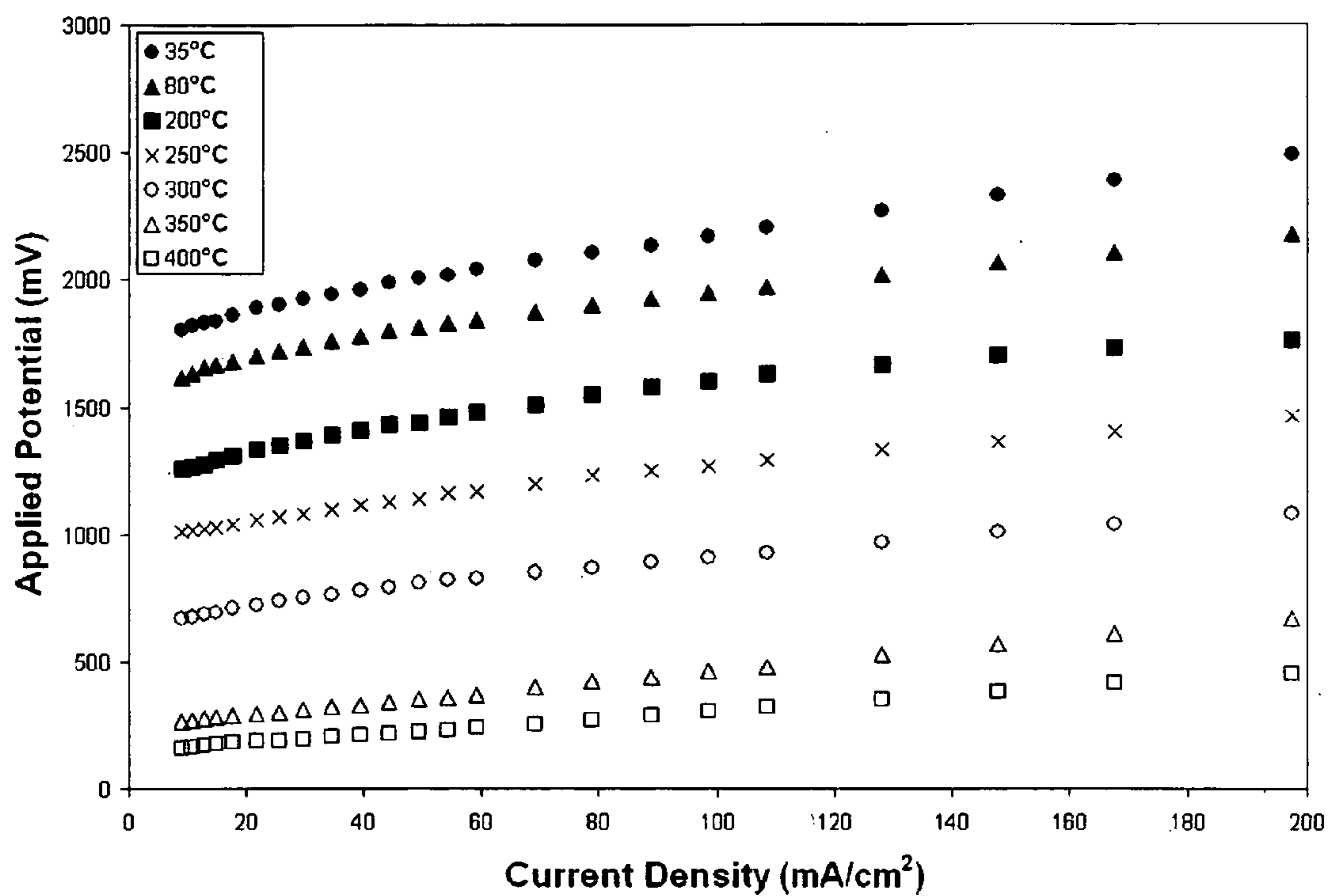


Figure 6

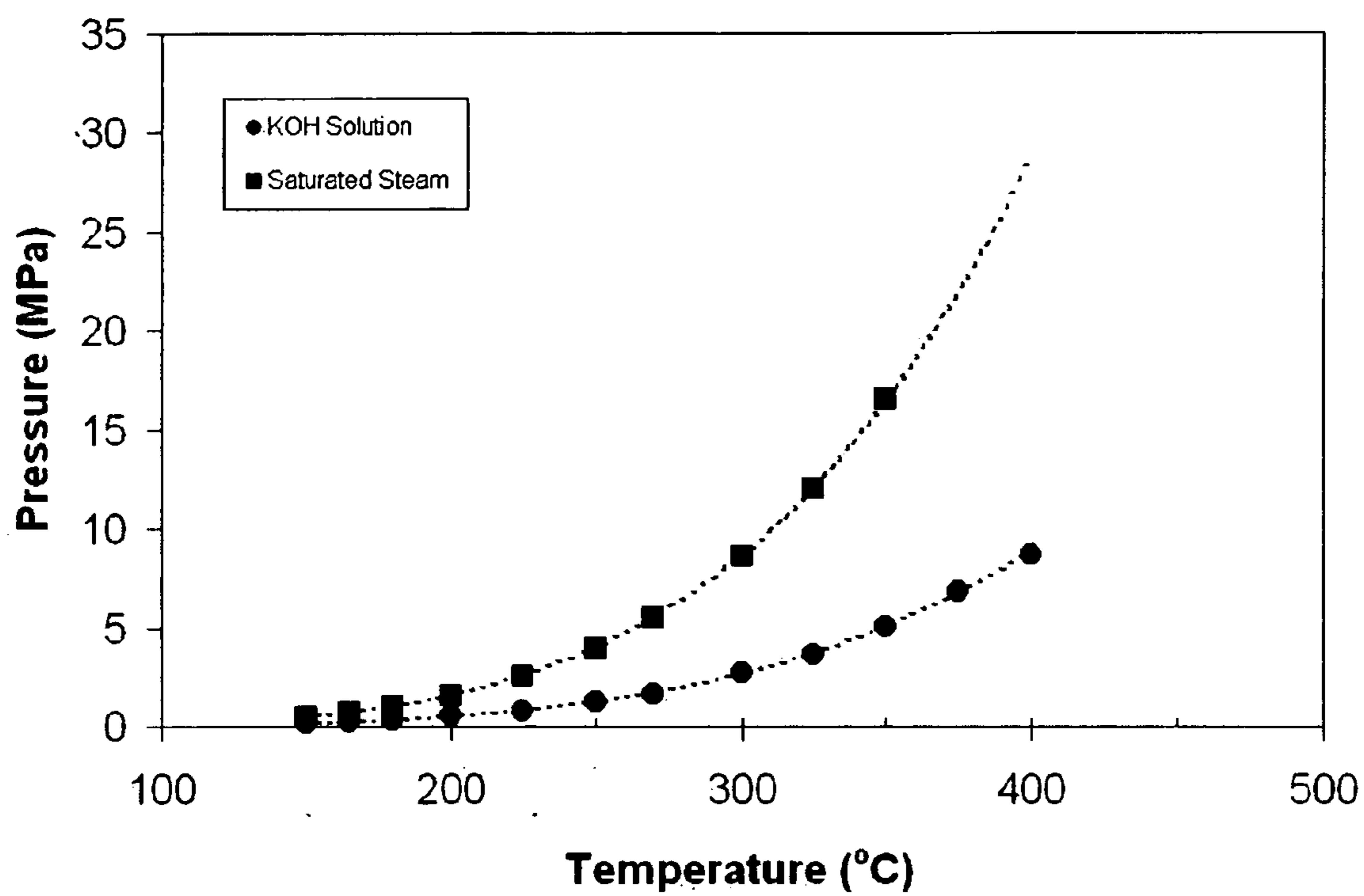


Figure 7



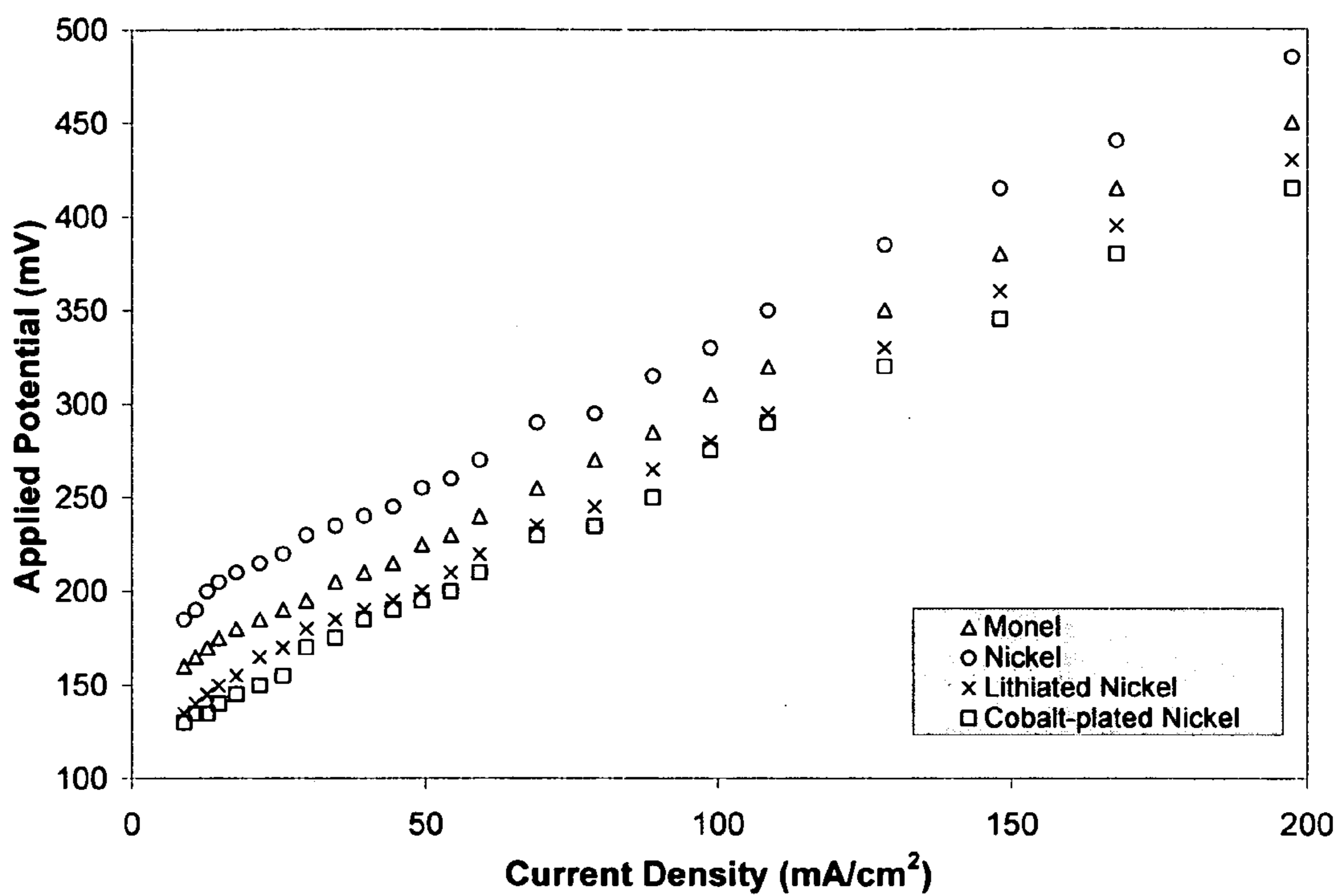


Figure 8

## METHOD AND APPARATUS FOR DISSOCIATING WATER

### TECHNICAL FIELD

**[0001]** This invention relates to electrolysis. More specifically, this invention relates to an improved method and apparatus for dissociating water to produce hydrogen and oxygen.

### BACKGROUND OF THE INVENTION

**[0002]** The first electric battery was described in a letter from Volta dated Mar. 20, 1800 to the President of the Royal Society, Sir Joseph Banks ‘On the electricity excited by the mere contact of conducting substances of different kinds’. Shortly thereafter, Anthony Carlisle and William Nicholson replicated Volta’s experiments. Because they sought to use a doubler to show charges on the upper and lower plates, they had to connect them to the electroscope, and it was not easy to maintain a good contact. To overcome this problem they added a drop of water to the uppermost disc and inserted the wire into the drop. They were surprised to note the appearance of a gas, soon shown to be hydrogen. They then took a small tube filled with water from the New River (an artificial channel completed in 1613 to bring water from Hertfordshire to the City) and inserted wires from the Voltaic pile at each end. To their astonishment the other suspected constituent of water, oxygen, did not appear at the same place but at the other wire ‘at a distance of almost two inches’. They had discovered electrolysis. The present invention is an improvement on that process.

**[0003]** In 2005, the United States Department of Energy (DOE) updated its goals for hydrogen production. The DOE noted that one kilogram of hydrogen contains approximately the same energy as one gallon of gasoline, termed as a “gallon of gasoline equivalent,” or “gge.” The DOE therefore set the goal for the DOE’s hydrogen program to develop methods and techniques capable of producing hydrogen for between \$2-\$3 in 2005 dollars per gge by 2015. In the intervening three years, the DOE has funded millions of dollars of research at universities and DOE owned federal laboratories to attain this goal. To date, no one has reported any results that have done so. Accordingly, there is a long felt need by those having ordinary skill in the art to devise less expensive methods and apparatus for making hydrogen that will meet the DOE goal. The present invention provides such a method and apparatus.

### SUMMARY OF THE INVENTION

**[0004]** The present invention is a method and apparatus for dissociating water into its elements. The present invention is shown in FIG. 1. As shown, the invention provides a reaction chamber 1, an anode 2, a cathode 3, and an aqueous hydroxide electrolyte 4 positioned between the anode and the cathode in the reaction chamber. The temperature of the aqueous hydroxide electrolyte in the reaction chamber is elevated to least 280° C. The pressure of the aqueous hydroxide electrolyte in the reaction chamber is likewise elevated to least 2 atmospheres. As used herein, an “aqueous hydroxide electrolyte” is a solution of water and a hydroxide electrolyte. An electrical voltage is applied across the anode 2 and cathode 3 using an electrical power supply 5. The resulting electrolysis of the water in the aqueous hydroxide electrolyte produces hydrogen and oxygen gas, and does so more efficiently than any electrolytic process described in the prior art. As hydro-

gen and oxygen are evolved from the anode and cathode, additional water, preferably in the form of steam, may be added to the aqueous hydroxide electrolyte 4 to provide a fresh source of hydrogen and oxygen for the reaction. The process of adding additional water may be performed as a continuous or as a batch process.

**[0005]** Preferably, to protect against corrosion, the reaction chamber 1 is formed of, or coated with, a protective metal. Suitable metals include nickel, titanium, zirconium, molybdenum, chromium, platinum, gold, palladium, copper, cobalt, silicon, alloys containing the foregoing, and combinations thereof. Preferably, the hydroxide electrolyte 4 consists of alkaline hydroxides and alkaline earth hydroxides, and combinations thereof. Suitable alkaline hydroxides are LiOH, KOH, NaOH, CsOH, RbOH, and combinations thereof. Suitable alkaline earth hydroxides are Ba(OH)<sub>2</sub>, Sr(OH)<sub>2</sub>, Mg(OH)<sub>2</sub>, Ca(OH)<sub>2</sub>, and combinations thereof. Preferably, to protect against corrosion, the anode 2 and the cathode 3 are formed or coated with a noble metal. Suitable noble metals include palladium, platinum, and gold.

**[0006]** A preferred embodiment of the present invention is shown in FIG. 2. As shown, multiple anodes 2 and cathodes 3 are submerged in the aqueous hydroxide electrolyte 4. A plurality of separator plates 6 are interposed between the multiple anodes and cathodes to keep hydrogen and oxygen formed at the anodes 2 and cathodes 3 separated from one and another. Preferably, the separator plates are made a corrosion resistant material, or with a corrosion resistant coating. The lower portion of the separator plates 6 are submerged in the aqueous hydroxide electrolyte 4 and are configured as a solid barrier with perforations. In this manner, the separator plates provide fluid pathways to allow transfer of hydroxide ions from adjacent anodes 2 and cathodes 3, prevent bubbling oxygen and hydrogen evolving from adjacent anodes 2 and cathodes 3 from mixing. The upper portion of the separator plates 6 are not submerged in the aqueous hydroxide electrolyte 4 and are configured as a solid barrier with no perforations, to prevent oxygen and hydrogen evolving from adjacent anodes 2 and cathodes 3 from mixing in the space above the aqueous hydroxide electrolyte 4.

**[0007]** Another preferred embodiment of the present invention is shown in FIG. 3. A pump 11 is used to pressurize water 19 to a pressure greater than 2 atm 20. A mixing pipe 12 combines recycled water streams with feed water and is preheated in heat exchangers 13 and 14. Additional heat required to bring the water to the appropriate electrolysis temperature is added by another heat source 15 to produce superheated steam 21. This superheated steam is provided to the reaction chamber 1 of the present invention which produces mixed streams of oxygen and water 22 and hydrogen and water 25. Each stream is cooled by the water preheaters 13 and 14 and is fed to separation tanks 17 and 18 to produce streams of pressurized water 23 and 26 along with pressurized oxygen 24 and pressurized hydrogen 27.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0008]** The following detailed description of the embodiments of the invention will be more readily understood when taken in conjunction with the following drawings, wherein:

**[0009]** FIG. 1 is a schematic drawing of the present invention as previously described in the summary of the invention.

**[0010]** FIG. 2 is a schematic drawing of one aspect of a preferred embodiment the present invention as previously described in the summary of the invention.

[0011] FIG. 3 is a schematic drawing of an additional aspect of a preferred embodiment the present invention as previously described in the summary of the invention.

[0012] FIG. 4 is a schematic drawing of an alkaline electrolysis cell used in the proof of principle experiments described herein.

[0013] FIG. 5 is a graph showing the polarization behavior of the alkaline electrolysis cell used in the proof of principle experiments described herein operating under an open atmosphere at 200° C., 250° C., 300° C., 350° C., 400° C., and 450° C.

[0014] FIG. 6 is a graph showing the power production performance of the an alkaline electrolysis cell used in the proof of principle experiments under a self-generated steam pressure described herein operating at 200° C., 250° C., 300° C., 350° C., 400° C., and 450° C.

[0015] FIG. 7 is a graph showing a comparison of measured alkaline electrolysis cell pressures and the pressure of saturated steam at various temperatures. The trend line for saturated steam is extrapolated beyond the data available in commercial steam tables.

[0016] FIG. 8 is a graph showing a comparison of various anode compositions tested in the alkaline electrolysis cell at 400° C. and elevated pressure.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] For the purposes of promoting an understanding of the principles of the invention, a series of experiments were conducted reducing the present invention to practice. These experiments demonstrated the direct-current electrolysis of potassium hydroxide solutions at temperatures (up to 400° C.) and under various pressures. One example of a high-temperature alkaline electrolysis cell resistant to chemical attack from the highly corrosive electrolyte solution and capable of high pressure operation was designed and tested. The cell was constructed with a Monel® (66.5% Ni, 31.5% Cu, 1.2% Fe, 1.1% Mn) alloy housing and cathode, while various anode materials were compared. The anode materials tested included nickel, Monel® alloy, lithiated nickel, and cobalt-plated nickel. Preferred anode materials are conductive metals resistant to corrosive attacks by alkaline electrolytes. More preferred are these materials configured as having a high surface area to volume ratio, as is found in nano-engineered and catalytic materials. The advantages of operating an alkaline electrolysis cell at high temperatures include increasing the ionic conductivity of the electrolyte and enhancing the rates of surface chemical reactions at the electrode surfaces. Cell operation with high steam partial pressures above the solution is also shown to enhance cell performance. The prudent selection of anode material also impacts the cell polarization and consequently the cell power efficiency. The best cell performance was achieved using a cobalt-plated nickel anode at a temperature of 400° C. and a steam partial pressure of 8.7 MPa.

[0018] A cutaway schematic for the high-temperature, high-pressure alkaline electrolysis cell is shown in FIG. 4. The cell container was machined from 7 cm diameter Nickel bar stock cut to 15 cm in length. Nickel-400, also known as the commercial Monel® alloy, was chosen due to its resistance to corrosion by high-temperature alkali hydroxide solutions. The bar was internally bored to a depth of 11 cm with a diameter of approximately 3.8 cm. This central well served to store the electrolyte solution. The cell was heated by three 200

W cartridge heaters inserted into the bottom of the container. The top of the cell container was machined with a knife edge and bolt holes designed to mate with a standard 7 cm stainless steel Conflat® flange with a copper gasket, which served as a cap for the container. The cap provided three conduits: electrically isolated anode and cathode ports and a combined thermocouple port and steam vent, on which a needle valve and a high pressure steam gauge were each installed. The steam pressure gauge was protected by attachment to a short siphon tube which was charged with a small amount of distilled water prior to use.

[0019] The electrolyte used at the beginning of each experimental set (initially at room temperature) was a 19 M potassium hydroxide (KOH) solution prepared by mixing appropriate amounts of KOH purchased from Alfa Aesar with distilled water. Direct current electrical power was provided to the electrolysis cell using a digital power supply (Agilent Technologies, model E3617A). The power supply was placed in current-control mode at several pre-determined total electrical current increments ranging from 50 mA to 1000 mA, and the corresponding terminal voltage was measured and recorded using a digital multimeter (Extech Instruments, model 470). The electrolysis cell was allowed to stabilize at each current density for at least five seconds before the terminal voltages were measured and recorded. The resulting data was incorporated into polarization, or i-V, curves for each experimental set.

[0020] This design proved to be reliable for high cell operating temperatures and the associated elevated steam pressures without leaking. The cell was operated over a range of temperatures from 35° C. to 400° C. and total pressures from atmospheric to nearly 9 MPa.

[0021] The anode and cathode used in each experiment were solid metal wires 3.2 mm in diameter. The cathode in each experiment was Monel® wire, while several anode compositions were investigated in an attempt to mitigate electrode polarization, enhance surface reaction rates, and minimize corrosion. Anodic electrodes in electrolytic devices exist under relatively oxidizing conditions with respect to other locations within the cell, and as such are more prone to corrosion and polarization. This effect is most often observed as an increased overall electrolytic potential, which in turn leads to a decreased energy efficiency of the cell. The anode types tested in the present study included nickel (Alfa Aesar), Monel® (McMaster-Carr), lithiated nickel, and cobalt-plated nickel.

[0022] To produce the lithiated nickel anodes—which were nickel wires coated lithium-doped nickel oxide using a thermal-electrochemical treatment procedure. Nickel wire was treated in a 3 M LiOH solution maintained at 100° C. for 24 hours while applying an anodic current of 1 mA cm<sup>-2</sup>. In this single-step treatment, nickel metal is thermally and electrochemically converted first into a hydrated nickel oxide, which is further electrochemically oxidized and lithiated by cationic exchange to produce stoichiometric variants of LiNiO<sub>2</sub>.

[0023] The cobalt-plated nickel anodes were produced by electroplating cobalt on bare nickel wires at a current density of 10 mA cm<sup>-2</sup> for 1 hour from a 0.05 M solution of cobalt (II) sulfate with a supporting electrolyte of sodium sulfate and sodium citrate at concentrations of 0.1 M and 0.25 M, respectively. All chemicals used in the cobalt plating solution were purchased from Alfa Aesar. After electroplating, the electrode was observed to have a dull gray color. Each cobalt-plated electrode was gently polished by hand with wet 1200 grit

silicon carbide paper in order to remove dendrites and any other plating irregularities that might magnify the electrode surface area.

**[0024]** The electrode wires were isolated from one another and the cell housing by compression fitting-sealed Teflon® tubing sleeves, with a supplemental external wrapping of Teflon® tape at tubing and wire junctions, at the top of each electrode. The sleeves were placed approximately three centimeters above the cell cap. During cell operation, the upper region of each electrode was cooled externally by flowing tap water to prevent melting and failure of the Teflon® sleeves. While immersed in the electrolyte, each electrode was submerged to a depth of 5 cm, which corresponded to approximately 5 cm<sup>2</sup> of exposed electrode area for each wire. The two electrodes were separated by a lateral center-to-center distance of 1 cm.

**[0025]** The first series of experiments involved the measurement of electrolyzer performance while the electrolyte was exposed to ambient air. In each of these experiments, the ambient temperature was maintained at 22° C. and a relative humidity of 40% using laboratory climate controls. The atmospheric pressure naturally varied between 100 and 102 kPa. As cell temperature was adjusted from low to high, at least two hours were allowed for the electrolyte solution to establish equilibrium with the surrounding air. This was especially important at higher temperatures, where the potassium hydroxide solution would tend to quickly dehydrate with the rapid temperature step increase, and then slowly re-hydrate to a limited extent through contact with the surrounding humid air. Additionally, as the volume of the electrolyte would vary with temperature, the vertical position of each electrode was adjusted as necessary to maintain a 5 cm immersion depth. A polarization curve was created for the system at several temperatures. In each experiment at atmospheric pressure, both the anode and cathode were Monel® wires.

**[0026]** A series of electrolysis experiments involving elevated pressure over the KOH solution were carried out in the following way. At room temperature, the electrolysis cell was filled to the desired level with 19 M KOH solution and was tightly sealed. The unwetted space above the electrolyte, including the volume of the steam siphon tube, comprised a volume of approximately 50 cm<sup>3</sup>. A polarization curve was created for the system as described above. When each polarization curve was completed, the anode and cathode were electrically shorted in order to return the cell to electrical equilibrium as the cell temperature was raised to the next prescribed level. Electrical currents of several amperes were observed for short periods of time as the small amount of hydrogen and oxygen gases within the cell reacted, as in a fuel cell, to form water once again. When the cell reached the next temperature to be tested and the short circuit current had returned to zero, the total gas pressure over the melt was recorded. The partial pressure of steam above the electrolyte was estimated as the specific gauge pressure displayed. The polarization measurements were then repeated at the current temperature. The entire measurement process was repeated until all process temperatures had been investigated. The set of experiments at elevated pressure covered a range of temperatures from 35° C. to 400° C. and utilized Monel® electrodes only.

**[0027]** The attempt to reduce electrode polarization, enhance surface reaction rates, and minimize corrosion by changing the electrode material was one of optimization, and therefore a single operating condition for the electrolysis cell

was chosen to compare the effects of the different electrodes on cell performance. Specifically, the four types of anodes (nickel, Monel®, lithiated nickel, and cobalt-plated nickel) were examined with the cell sealed and operating at 400° C. Data was collected in the same manner detailed above for obtaining polarization curves at elevated pressure.

**[0028]** Polarization curves of the electrolysis cell operating between 200° C. and 400° C. under an open atmosphere are shown in FIG. 5. The general trend of reduced electrolytic voltage with increasing temperature is apparent, although it appears that the compounded magnitude of this effect is reduced at higher temperatures. Electrolyte ionic conductivity and surface reaction rates are expected to increase with temperature, and additionally the reversible cell potential for water splitting is known to thermodynamically decrease as temperature rises. The limit of cell performance improvement with increasing temperature is likely due to a combination of electrode oxidation/deactivation and a lower water activity in the solution as it becomes dehydrated. Accordingly, it is preferred that water be continually provided to the electrolyte. The concept of maintaining a high pressure of steam over the solution was introduced to the present study as a means to force water into the solution at high temperature, and to ensure its high activity within the solution.

**[0029]** Polarization curves of the sealed electrolysis cell operating between 35° C. and 400° C. under a self-generated equilibrium steam pressure are shown in FIG. 6. The improvement in apparent electrolysis effectiveness with respect to open-atmosphere tests is striking. Although the reversible cell potential for the electrolysis of water is above 900 mV for all temperatures up to about 415° C., an applied voltage of less than 500 mV was required to provide 200 mA cm<sup>-1</sup> at 400° C. under high steam pressure. A reduced voltage was expected due to the high water activity within the electrolyte, its impact on system free energy and equilibrium, and the consequent substitution of electrical energy with thermal energy.

**[0030]** An interesting illustration of the alkaline solution's affinity for water is displayed in FIG. 7. Here, the measured gauge pressure over the electrolyte at various temperatures is shown in comparison to the saturation pressure of steam at the same temperature. The cell pressure was measured at several points intermediate of polarization measurements in order to obtain a clear trend. Cell temperatures of up to 400° C. would not have been possible without the high temperature hygroscopic nature of the alkaline solution.

**[0031]** Cobalt-plated nickel wires were examined for their ability to reduce electrode polarization, enhance surface reaction rates, and minimize corrosion. Nickel and Monel® wires were used as received, while the lithiated nickel and cobalt-plated nickel wires were prepared as discussed previously. Polarization plots illustrating cell performance at 400° C. using various anode compositions are shown in FIG. 8. The general performance increased in the order of corrosion resistance, in the order of nickel, Monel®, lithiated nickel, and cobalt-plated nickel. Each electrode type except the lithiated nickel was observed to have a matte black film after use, which was likely a mixed layer of nickel oxides (or cobalt oxide, as appropriate). This indicates that the mixed layer is a stable, protective oxide film that protects the anode from corrosion. The lithiated nickel electrode remained dark gray in color. Since the anodic treatment process for this anode created a surface film prior to its use in the cell, it is likely that

this layer protected the underlying metal and prevented any further oxidation and discoloration.

**[0032]** The Monel® anode exhibited significantly less polarization than the pure nickel, which is somewhat surprising due to the fact that Monel® is an alloy with a high percentage of nickel. It is likely that any increased performance of the cell using a Monel® anode relative to nickel could be due to increased electrode surface area rather than simply an improvement in surface conductivity. Copper oxides are not stable in hot hydroxide environments, and in fact strong hydroxide solutions are often used in the electronics industry as a soldering flux. The result may be a surface de-alloying of the Monel®, producing a higher surface area nickel oxide relative to that forming on the pure nickel anode.

**[0033]** The lowest amount of electrode polarization was observed with the cobalt-plated nickel anode, although its performance lies quite close to that of the lithiated nickel anode. The oxides covering the surfaces of both of these electrodes probably created a significantly lower electrical resistance barrier in the anode region of the cell.

**[0034]** The United States Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) has specified cost targets for the production of hydrogen in order to ensure the cost-competitiveness of hydrogen fuel in relation to other available fuels. For example, in order to make hydrogen a competitive fuel alternative to gasoline in the light-duty vehicle market, hydrogen must be produced for a cost of less than three dollars per kilogram (one kilogram of hydrogen contains approximately the same energy content as one gallon of gasoline). For electrolyzer applications, the cost of hydrogen generation is largely determined by the cost of the electrical power used. For example, a typical room temperature and pressure alkaline electrolysis unit may operate with a cell potential of 1.8 V and a thermal efficiency of 80%, using electricity at an off-peak price of 7.5 ¢/k Wh to produce hydrogen at an electrical cost of about \$4.50/kg. If the cell potential is reduced to 600 mV under conditions of elevated pressure and temperature, as is possible with the invention described here, the electrical cost of hydrogen production drops to \$1.50/kg, well below the EERE production cost goal of \$3/kg of hydrogen.

**[0035]** While the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character. Only certain embodiments have been shown and described, and all changes, equivalents, and modifications that come within the spirit of the invention described herein are desired to be protected. Any experiments, experimental examples, or experimental results provided herein are intended to be illustrative of the present invention and should not be considered limiting or restrictive with regard to the invention scope. Further, any theory, mechanism of operation, proof, or finding stated herein is meant to further enhance understanding of the present invention and is not intended to limit the present invention in any way to such theory, mechanism of operation, proof, or finding.

**[0036]** Thus, the specifics of this description and the attached drawings should not be interpreted to limit the scope of this invention to the specifics thereof. Rather, the scope of this invention should be evaluated with reference to the claims appended hereto. In reading the claims it is intended that when words such as “a”, “an”, “at least one”, and “at least a portion” are used there is no intention to limit the claims to only one item unless specifically stated to the contrary in the

claims. Further, when the language “at least a portion” and/or “a portion” is used, the claims may include a portion and/or the entire items unless specifically stated to the contrary. Likewise, where the term “input” or “output” is used in connection with an electric device or fluid processing unit, it should be understood to comprehend singular or plural and one or more signal channels or fluid lines as appropriate in the context. Finally, all publications, patents, and patent applications cited in this specification are herein incorporated by reference to the extent not inconsistent with the present disclosure as if each were specifically and individually indicated to be incorporated by reference and set forth in its entirety herein.

We claim:

1) A method for electrolyzing water and aqueous solutions comprising the steps of:

providing a reaction chamber;  
providing an anode, a cathode, and an aqueous hydroxide electrolyte positioned between the anode and the cathode in the reaction chamber;

elevating the temperature of the aqueous hydroxide electrolyte in the reaction chamber to least 280° C.;

elevating the pressure of the aqueous hydroxide electrolyte in the reaction chamber to least 2 atmospheres;

providing a electrical voltage across the anode and cathode.

2) The method of claim 1 wherein dissociated water [in the form of hydrogen and oxygen gases] in the aqueous hydroxide electrolyte is removed from the reaction chamber and is replenished with steam.

3) The method of claim 1 wherein the hydroxide electrolyte is provided as an alkaline hydroxide, an alkaline earth hydroxide, and combinations thereof.

4) The method of claim 3 wherein the alkaline hydroxide is provided as LiOH, KOH, NaOH, CsOH, RbOH, and combinations thereof.

5) The method of claim 3 wherein the alkaline earth hydroxide is provided as Ba(OH)<sub>2</sub>, Sr(OH)<sub>2</sub>, Mg(OH)<sub>2</sub>, Ca(OH)<sub>2</sub>, and combinations thereof.

6) The method of claim 1 wherein at least one of the anode and cathode are formed of nickel, Nickel 400 (66.5% Ni, 31.5% Cu, 1.2% Fe, 1.1% Mn), lithiated nickel, cobalt-plated nickel and combinations thereof.

7) The method of claim 1 wherein at least one of the anode and cathode are coated with a noble metal.

8) The method of claim 7 wherein the noble metal is selected as palladium, platinum, gold, and combinations thereof.

9) The method of claim 1 wherein a separator plate is interposed between the anode and cathode to keep hydrogen and oxygen formed at the anode and cathode separated from one and another.

10) The method of claim 9 wherein the separator plate is provided as having a fluid pathway to allow transfer of hydroxide ions from the anode to the cathode.

11) The method of claim 1 wherein multiple anodes and cathodes are provided as submerged in the aqueous hydroxide electrolyte.

12) The method of claim 11 wherein a plurality of separator plates are interposed between the multiple anodes and cathodes to keep hydrogen and oxygen formed at the anodes and cathodes separated from one and another.

**13)** The method of claim **12** wherein the separator plates are provided as having fluid pathways to allow transfer of hydroxide ions from the anode to the cathode.

**14)** An apparatus for dissociating water comprising:  
a reaction chamber, the interior of said reaction chamber maintained at a temperature of least 280° C. and a pressure at least 2 atmospheres;  
an anode, a cathode, and an aqueous hydroxide electrolyte positioned between the anode and the cathode in the reaction chamber;  
a means for providing an electrical voltage across the anode and cathode.

**15)** The apparatus of claim **14** wherein the means for providing an electrical voltage is a power supply capable of providing a direct current.

**16)** The apparatus of claim **14** wherein the reaction chamber is formed of nickel, titanium, zirconium, molybdenum, chromium, platinum, gold, palladium, copper, cobalt, silicon, alloys containing any of the forgoing, and combinations thereof.

**17)** The apparatus of claim **14** wherein the hydroxide electrolyte is an alkaline hydroxide, an alkaline earth hydroxide, and combinations thereof.

**18)** The apparatus of claim **17** wherein the alkaline hydroxide is LiOH, KOH, NaOH, CsOH, RbOH, and combinations thereof.

**19)** The apparatus of claim **17** wherein the alkaline earth hydroxide is Ba(OH)<sub>2</sub>, Sr(OH)<sub>2</sub>, Mg(OH)<sub>2</sub>, Ca(OH)<sub>2</sub>, and combinations thereof.

**20)** The apparatus of claim **14** wherein at least one of the anode and cathode are formed of nickel, Nickel 400 (66.5% Ni, 31.5% Cu, 1.2% Fe, 1.1% Mn), lithiated nickel, cobalt-plated nickel and combinations thereof.

**21)** The apparatus of claim **14** wherein at least one of the anode and cathode are coated with a noble metal.

**22)** The apparatus of claim **21** wherein the noble metal is selected as palladium, platinum, gold, and combinations thereof.

**23)** The apparatus of claim **14** wherein a separator plate is interposed between the anode and cathode to keep hydrogen and oxygen formed at the anode and cathode separated from one and another.

**24)** The apparatus of claim **14** wherein the separator plate is provided as having a fluid pathway to allow transfer of hydroxide ions from the anode to the cathode.

**25)** The apparatus of claim **14** wherein multiple anodes and cathodes are submerged in the aqueous hydroxide electrolyte.

**26)** The apparatus of claim **25** wherein a plurality of separator plates are interposed between the multiple anodes and cathodes to keep hydrogen and oxygen formed at the anodes and cathodes separated from one and another.

**27)** The apparatus of claim **26** wherein the separator plates have fluid pathways to allow transfer of hydroxide ions from the anode to the cathode.

\* \* \* \* \*