Developments of water electrolysis technology by solid polymer electrolyte

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Water electrolysis by solid polymer electrolyte is the most promising technology for large-scale hydrogen production for future. The concept introduced by General Electric Co. (U.S.A) in late sixties has been adopted by Brown Boveri Research Center, Baden, Switzerland and more recently by Japan under WE-NET Japanese Hydrogen Programme Project. For the last 25 years, this field has witnessed a lot of activity, in research and development of energy efficient water electrolyzers. In this review, the selection of high activity electrocatalysts, methods to prepare SPE electrocatalyst composites, their stability, the pretreatment of solid polymer electrolyte membrane for the deposition of electrocatalysts, the fabrication of current collectors, the scale up of water electrolyzers and recent advances has been discussed.

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Introduction

Water electrolysis is the simplest method for producing pure hydrogen on a large or small scale. There are three major technologies for electrolytic hydrogen production depending upon the nature of electrolyte used in electrolysis cell i.e. alkaline, polymer membrane and ceramic oxide electrolyte. Alkaline electrolyte based electrolyzers are the oldest, least expensive and thus the most widespread of the various electrolysis technologies.¹ The alkaline water electrolyzers are constructed with a bipolar configuration in which a series of electrodes are arranged, vertical and parallel to one another. A gas separator is incorporated between two adjacent electrodes to form a hydrogen chamber on one side and an oxygen chamber on the other. The electrolyte is circulated through each electrode-separator space. By applying a voltage across the two end electrodes, each intermediate electrodes becomes bipolar, evolving hydrogen on one side and oxygen on the other. Generally nickel is used as the electrocatalyst for hydrogen and oxygen electrodes. The voltage efficiency of alkaline electrolyzer improves at high temperature but the corrosion of electrodes and other related materials also increases. Researchers have
attempted to find more rugged substitutes for the asbestos separator\textsuperscript{2-4} and nickel anode\textsuperscript{2,3} to increase the long time stability and energy efficiency. The interest in \( \text{O}_2 \)\textsuperscript{2+} conducting ceramic electrolytes based on yttria stabilized zirconia (YSZ) is due to their high temperature (>1000\textdegree C) operation which not only lowers the activation barriers for various electrode surface chemical reactions but beneficial for engineering designing as one has to work with an exclusively gas/solid system. But the problems of corrosion, thermal expansion and inter mixing of adjacent phases become important in these electrolyzers due to their high temperature operation.

The solid polymer electrolyte technology, now called proton-exchange membrane technology, consists of coating or pressing two electrodes on to a membrane used as electrolyte and it is the most promising candidate for low temperature fuel cells (the present review article deals only with this technology). The concept of SPE (solid polymer electrolyte) in water electrolysis was first introduced\textsuperscript{5,6} by General Electric Company in early 1970. Now, the hydrogen production by this method has been included in WE-NET. Japanese hydrogen program project\textsuperscript{7}. Brown Boveri Company of Switzerland is also very active in this field and has marketed its membrane process\textsuperscript{8,9}. The development of this technology has been delayed mainly due to investment costs. SPE or Nafion membrane has excellent chemical and mechanical stability, together with high ionic conductivity and good gas impermeability, but it is an expensive material. Secondly, due to its strong acidity the choice of electrocatalysts is limited only to costly platinum group metals or oxide electrocatalysts. In order to keep capital cost within economic bounds, to decrease the electrocatalyst loading and to increase the current densities a lot of work has been done. Typical noble metal loading of a few mg/cm\textsuperscript{2} and typical current densities of several A/cm\textsuperscript{2} are currently obtained. During operation of electrolysis cell, the electrocatalysts not only face highly acidic environment but also high mechanical tension due to gas evolution. Therefore, much attention must be devoted to the structure of the electrodes, to reduce the noble metal loading and also to strengthen the bonding of the electrodes on to the SPE\textsuperscript{10,11}.

2. Nafion membrane (solid polymer electrolyte)

Perfluorosulphonate polymers (Nafion) consist of a polytetrafluoroethylene backbone with side chains terminating in sulphonate ion exchange groups. Membranes of various thicknesses and equivalent weights are now commercially available (Dupont de Nemours Nafion products). The equivalent weight of Nafion membrane is defined as the weight of acid polymer that will neutralize one equivalent of base; eq. wt. is equal to the reciprocal of ion exchange capacity.

The water adsorption capacity of Nafion depends upon the pretreatment of the membrane\textsuperscript{13}. If it is heated to more than 100\textdegree C in air, then put in water, the water uptake is very less (called shrunken form). If it is just immersed in water at room temperature, it absorbs up to 17 weight \% water (called Normal form Nafion). Water up take increases to 30\% when boiled in water for 30 min (called Expanded form\textsuperscript{13,21}). There is further increase of water absorption if it is heated in water under pressure at higher temperatures. Number of studies\textsuperscript{13,22-28} have been made to establish the micro-structure and to explain peculiar properties of Nafion. Based on the results obtained by small angle X-ray scattering, mass transfer experiments, including hydraulic permeation and water diffusion and electron microscopy, Gierke et al.\textsuperscript{15} have proposed cluster-network to explain the properties of Nafion membrane. According to him, polymeric ions and absorbed water exist in approximately spherical domains as ionic clusters, separated from the polytetrafluoroethylene (PTFE) matrix. These clusters are connected by short narrow channels which have a diameter of about 10 \AA. The cluster size grows with increasing amount of absorbed water. However, there is a probability of some intrusion of the fluorocarbon phase into the aqueous phase to form an interfacial region that also contains some of the water\textsuperscript{21,29-31}. The permeability coefficients of gases through Nafion depend greatly on the water content, the cation form and the ion exchange capacity\textsuperscript{22,35}. The gas permeation rate through the same sample varies with temperature, pressure and membrane thickness. Permeability of H\textsubscript{2} gas is about twice as large as that of oxygen. When membrane absorbs water, the narrow channels are filled with water. The gas diffuses through water and it approaches the value of diffusion of H\textsubscript{2} and O\textsubscript{2} in water and becomes constant.

The Nafion membrane used for water electrolysis has to be pretreated with acids (H\textsubscript{2}SO\textsubscript{4} or HNO\textsubscript{3} or HCl or H\textsubscript{2}O\textsubscript{2}) to convert it into H\textsuperscript{+} form and to remove impurities it has to be boiled with water at high temperature. If the treatment temperature is very high, the water content in the membrane will also be high,
thus the resistance of the membrane decreases but at the same time the permeation rate of gases through the membrane increases. Generally, for the hydrothermal treatment, temperature range is between 100 to 150°C. This is because at temperatures below 100°C the adhesive strength between the membrane and the deposited metal tends to decrease and at temperature above 150°C the mechanical strength of membrane tends to decrease considerably.

3. Surface roughening treatment

An adequate surface roughening of Nafion membrane before deposition of electrocatalyst is one of the key technologies for developing SPE water electrolyzer, which can be used at higher current densities. It can be carried out by various methods such as oxygen plasma, sand blasting and wet abrasive blasting. It gives strong adhesion and larger contact area between membrane and plated electrode for lowering cell voltage and raising current densities. Gas permeability studies through membranes and their composites have revealed that the porous structure of the electrode formed by surface roughening facilitates the release of the evolving gas, leading to a decrease in the resistance due to gas bubbles and a decrease in the gas permeation rate through the membrane (i.e. an increase in current efficiency). A homogeneous roughness on membrane surface with an average depth of etching of 3-4 micrometers produces SPE-Pt composites, which have the lowest values of cell voltage, IR drop and highest current densities. Further, the non-treated membranes are found to suffer damage due to void formation during water electrolysis, which led to a significant decrease in its mechanical strength.

Takenaka et al. have etched the samples with oxygen plasma treatment at Radio frequency power varying from 100 w to 500 w. The etching depends upon the treatment time and Radio frequency power. The surface roughening treatment is also described as essential to prepare good SPE composite by hot press method. There the surface roughening is done by sand blast or by silicon carbide sheet to produce an etching of an average depth of ±6 microns.

However, the observations of Millet et al. are contrary to the above. They determined the active areas of Pt electrode of etched and unetched membranes, and found the difference to be low. They concluded that membrane surface etching results in the reduction of membrane thickness and as a consequence in lower mechanical strength, higher gas diffusion and lower faradic yield. They have prepared SPE composites without etching the SPE membrane and electrolysis cells are found to be quite stable at large-current densities and at high temperature for a long time. According to Liu et al. and Takenaka et al., the adhesive strength of electrocatalyst with membrane and its porosity depends upon factors like concentration, temperature and time of deposition of noble metals. In the experiments, all composites were prepared without surface etching treatment.

4. Basic design of cell

In SPE cells, Nafion membranes of varying thicknesses are used as the electrolytes. Charge carriers in the membrane are hydrated hydrogen ions (H⁺nH₂O) which move through the solid electrolyte by passing from one fixed sulphonic acid group to the adjacent one. On to the two faces of Nafion membrane generally platinum (for the cathode) and Ir or IrO₂/alloys of IrO₂ (for anode) are bonded (chemically or by hot press technique) using proprietary procedure. A stable conductive material used as a separator between the anode chamber of one cell and the cathode chamber of the adjacent cell also serves as a current collector in a bipolar configuration. During electrolysis deionized pure water is circulated, at a sufficiently high flow rate to remove the waste heat (Fig.1). Water decomposes electrochemically in the anode chamber producing O₂ gas, hydrogen ions and electrons. The hydrogen ions move through the SPE and recombine electrochemically with electrons.
which pass via external circuit, to form hydrogen gas in the cathode chamber (Fig. 2).

In order to achieve highly efficient SPE electrolysis operating at low voltage and at high current densities an ideal SPE electrode must have the following characteristics.

(i) Metal film deposition predominantly within the Nafion in a thin (sub micron) layer adjacent to the membrane surface; (ii) large electrode - SPE contact area to provide electrochemically large active surface area; (iii) good inter particle contact for low electronic resistance; and (iv) porous structure for free mass transfer of water and gases.

In order to achieve the above goals following techniques are employed to prepare SPE electrodes: (a) Chemical deposition; (b) electro-deposition; (c) hot press method; and (d) deposition of IrO$_2$ or alloys or platinum on porous titanium sheet/mesh followed by impregnation with Nafion and hot press.

5. Selection of electrocatalyst

For several years, studies on SPE water electrolysis technology had been mainly concerned with the survey of electrocatalysts and the methods of preparation of SPE-electrocatalyst composite. Since electrocatalyst has to be placed in highly acidic environment, the choice of metals as electrocatalysts is almost totally restricted to noble metals and their alloys. Many workers$^{33-57}$ have reported the characteristics of electrocatalysts of noble metals and alloys in acids solutions. Now it is confirmed that they behave in the same way as in acids when plated on SPE.

It has been found that platinum or other noble metal alloys have the same catalytic activity for the hydrogen evolution reaction but electrodes consisting of Ru, Ru-Ir, RuO$_2$/TiO$_2$/IrO$_2$, or Ir are the best noble metal electrocatalysts for oxygen evolution. The oxides of Ir or Ru (IrO$_2$ and RuO$_2$) are unusual with respect to their high electronic conductivity. Pure ruthenium has the high initial catalytic activity, but, it corrodes during oxygen evolution. Therefore, it is not recommended as anode electro-catalyst. The anodic voltage for different noble metals and alloys follow the sequence: Ir<Rh<Pt<Ru<Pt<Pd.

Low catalytic activity of Pt and Pd at the anodic side may be due to the formation of high resistance oxide films on their surfaces.

Now, Pt or Ir-Pt as cathode and Ir-Pt, Ir, IrO$_2$ as anode are generally used as electrocatalysts. The electrocatalytic activity for hydrogen evolution of RuO$_2$, IrO$_2$ and mixed RuO$_2$ and IrO$_2$ have been studied by many researchers$^{58-63}$ and their use as cathode electrocatalysts have been proposed due to their insensitivity towards catalytic poisoning by metal ions.

6. Chemical deposition

Chemical deposition of electrocatalysts on SPE faces can be carried out either by impregnating Nafion membrane with cations of noble metals, then reducing, these cations by suitable reducing agent or by circulating the anionic solution of metal salts to one side of membrane and reducing agent to the other side of it. The catalytic activity and the adhesive strength of the composite depend on factors such as the kind of metal salt and reducing agent used, concentrations and temperature of their respective solutions, the time of reduction and the conditions needed for the pretreatment of membrane (e.g. thermal treatment and surface roughening treatment).

6.1. Chemical deposition of platinum

Generally, dilute solution of Pt(NH$_3$)$_4$Cl$_2$H$_2$O is used to saturate the SPE with Pt ions then reduction of the same is carried out with NaBH$_4$ solution.

According to Her et al.$^{53,64-66}$ the best fabrication conditions found, are the impregnation of SPE for 40 minutes in 0.6 mM Pt(NH$_3$)$_4$Cl$_2$ solution followed by reduction with 1 mM NaBH$_4$ solution for 2 h. The temperature for impregnation and reduction is 50°C and Pt-loading obtained varied from 0.4 to 0.6 mg/cm$^2$. The platinum film is found to be dense but porous and is concentrated with in 0.3 µm (micrometer) from the surface. Sakai et al.$^{48}$ have
obtained thin continuous layer of Pt (0.8 mg/cm²) by saturating SPE with Pt(NH₃)₄Cl₂ solution, then reduction with NaBH₄ at 50-60°C. The second cycle of deposition was carried out to prepare an efficient composite with 1.5 mg to 2.5 mg/cm² loading. The two cycle preparation of SPE/Pt composite is also achieved by Millet et al.⁴⁹ by loading membrane with 0.01molar Pt(NH₃)₄Cl₂ solution for 15 min. and then reduction with 0.3% NaBH₄ solution at 25°C for 2 hours. Platinum loading of 1.13 mg/cm² was obtained.

Fedkiw and Raleigh⁶⁷ have described the formation of Pt and Pt alloys (Pt-Pd, Pt-Ru) to form thin continuous, porous films at and within the Nafion membrane surface using 0.026% of Pt(NH₃)₄Cl₂ salt dissolved in 1:2:CH₃OH:H₂O solvent. The membrane was dipped for 24 h at 50°C. Then reduction was carried out with 0.1M NaBH₄ for 2 h to obtain a 10-micron thick Pt film of loading 4 mg/cm². Effect on the morphology and other properties of the film formation by other reducing agents like SnCl₂, N₂H₄ and methanol have also been discussed. The reductant NaBH₄ is found best to prepare a good SPE/Pt composite suitable for water electrolysis. With the use of 3% H₂PtCl₆ solution on one-side of membrane and 1% NaBH₄ or N₂H₄ solution on the other side of the membrane, the deposition of platinum was carried out by Takenaka et al.⁶⁰.

Electrolytic deposition of platinum has been achieved by Nagel et al.⁶⁹ first dipping SPE in 0.5% solution of Pt(NH₃)₄(NO₃)₂ complex at 90°C for 30 min and then pressing it between platinum anode and graphite cathode. The electrolysis was carried out for 1 h at 0.5A/cm² current density to obtain 0.7 mg/cm² deposition of Pt on cathode side. Banziger et al.⁶⁹ have described a method for continuously coating the SPE membrane electrolytically. First 0.5% Pt(NH₃)₄(NO₃)₂ solution at 90°C was ion-exchanged with Nafion for 30 min. Then electrolysis was carried out to result in the formation of 0.5mg/cm² of Pt layer on the cathode side.

Chemical plating of platinum anode is achieved by number of workers³⁷,⁸⁵,⁵²,⁷⁰ by impregnating membrane in Pt(NH₃)₂Cl₂ solution and reducing in NaBH₄. Further in the second step, an additionally required amount of the same metal or a different metal is plated on the thin metal layers in a chemical plating bath containing a mixed solution of metal complexes, a reducing agent, and buffer agent to maintain pH. The electrodes with Ir plated on platinum are used because of high cell performances in cell voltage and gas purity and good durability. A one-side catalyst loading obtained is 1-2mg/cm².

6.2. Deposition of iridium
Millet et al.⁴⁹ have deposited iridium electrochemically inside the platinum surface coated on SPE membrane by impregnating the membrane with the cationic solution of [Ir(OH)(H₂O)₅]⁺[Ir(OH)(H₂O)₅]²⁺. An iridium deposition of 0.2 mg/cm² on the cathodic side was found to be sufficient for its catalytic activity as anode. Takenaka et al.⁶⁰ have reduced the mixed solution of IrCl₃ and RuCl₃ on the SPE surface by NaBH₄ solution that penetrated through the membrane. The plating of iridium on the earlier Pt deposited SPE surface has been obtained in a chemical plating bath having amine complex of iridium cations, reductant and a buffer agent. The amount of plated catalyst was controlled by the concentration of metal ions. Yasuyoshi et al.⁷¹ have described a plating bath solution consisting of H₃PtCl₆, IrCl₃, and NH₂NH₂ compounds. The pH of the solution was adjusted with NaOH and maintained between 5-6 by a buffer solution of citric acid and sodium citrate. The NaOH solution is allowed to penetrate from one side of membrane and the reducing reaction of Pt and Ir with N₂H₄ in the presence of penetrating alkali is brought out on the other surface of membrane. An electrolyte iridium plating bath containing iridium halide and hydrazine or hydroxylamine salt having pH(3-10) has been described in ref.(72). The deposition of iridium is carried out electrochemically,⁶⁰ first impregnating the Ir cations from the mixed solution of IrCl₃H₂O, NH₄OH and N₂H₄H₂O at 80°C for 30min. The condition for electrolytic deposition were 140°C at 17 atmosphere pressure in a closed vessel at a current density of 0.035A/cm² for 30 min. A shining metallic iridium layer resulted on the cathode side.

Hiroaki et al.⁷³ have described number of electroless plating baths for the deposition of iridium on the earlier deposited platinum surface on SPE membrane. The details of three baths are as follows:
K[Ir(N₂H₅)Cl₃] = 1.0 gm, water = 750 ml, pH = 2.8, temp= 70°C, pH adjuster = 0.1 N N₂H₅H₂O, deposition = 4.04 mg/cm² in 4 h, and plating yield = 94.2%.

K₂IrCl₆ = 1.1 g, N₂H₅HCl = 0.31g, water = 750 ml, pH = 2.8, temp= 70°C, pH adjuster = 0.1 N N₂H₅H₂O, deposition = 4.35 mg/cm² in 4 h and plating yield = 99.9%.

Na₂IrCl₆ = 1.0 g, N₂H₅HCl = 0.28 g, water = 750 ml, pH = 2.8, temp= 70°C, pH adjuster = 0.1 N N₂H₅H₂O, temp = 70°C, deposition = 3.83 mg/cm² in 4 h, and plating yield = 89.1%.

7. Hot press method

In the pioneering work of the U.S. firm General Electric Company for the development of large scale hydrogen generators, the preparation of electrodes is based on the coating by heat and/or pressure of a mixture of a catalyst powder and a binder (such as teflon) on each side of the SPE. In number of U.S. patents, a thin layer of metallic particles was prepared in the hydrophilic, thermo-plastic ion exchange material solution and it was then mechanically hot pressed to Nafion to form a SPE electrocatalyst composite. Lawrence et al. have also prepared SPE electrocatalyst composite by hot pressing Ir and Pt black powder on the abraded surface of Nafion membrane at 182-188°C at 980 lbs/cm² pressure for 8 min. With 1.4 mg/inch² and 2 mg/cm² loading of Ir and Pt respectively an efficient SPE metal composite suitable for water electrolysis has been obtained.

Nakanore et al. have prepared a cell of electrode area 200 cm² by hot press method with IrO₂ (4mg/cm²) as anode and Pt (3mg/cm²) as cathode while, Nagai et al. have prepared a cell of 50 cm² area with IrO₂ loading (3mg/cm²) for efficient water electrolysis. The SPE electrode composite obtained by Petrov et al. by hot press technique consists of platinum plated titanium mesh as cathode and Ru, Ir and Ta oxide coated Ti mesh as anode. In order to create a three dimensional reaction zone, Ti meshes were loaded with 0.8 g/cm² with Nafion with the help of Nafion solution. These were hot pressed to Nafion at 130°C at 200 atm/cm² pressure. In place of titanium mesh, titanium porous sheets of 1mm thickness were used to prepare IrO₂ electrodes by Andolfalta et al. These were again impregnated with Nafion solution before hot pressing with Nafion membrane.

8. Current collectors

The role of current collectors in SPE water electrolysis system is as important as electrocatalysts. Through these, the transfer of electrons from anode to cathode takes place in the outer circuit. They not only act as separators of hydrogen and oxygen evolved in cathode and anode chambers but also give a mechanical support to SPE membrane under operational differential pressures.

These materials should have high electric conductivity, low contact resistance with the electrocatalysts, sufficient corrosion resistance, impervious to hydrogen and oxygen and stable for long time. Expanded titanium meshes or perforated titanium screens plated with platinum were used as cathode and anodic support collectors at the early stage. However, the hydrogen embrittlement takes place on the cathodic current collector in long time operation. According to Lacanti et al. the hydrogen embrittlement of materials follow the sequence.

Ti = Ta > Nb > Zr > graphite

Therefore the use of moulded carbon current collectors was proposed. Takenaka et al. have developed a new type of porous carbon sheets and made special graphite filters as cathodic current collectors. It was further observed that Ti mesh anode collectors caused pin holes on the membrane-electrocatalyst composites due to the large current-concentration locally at the contact points. A new anode current collector with a double layer structure of thin and finely porous layer and a coarsely porous substrate was developed. The new collectors are prepared by sintering or plasma spraying titanium powders on a substrate of porous sheet made of titanium fibers. Nakanori et al. have used sintered titanium fiber plate electroplated with platinum as anode and sintered stainless fiber plate electroplated with gold as cathode, because stainless fiber is more resistant to hydrogen embrittlement than titanium fiber. Ara et al. have proposed a method for preparing electrode and current collectors in situ for SPE water electrolysis. Porous metal sheets of Ti were used as current collectors on which catalyst was deposited and catalyst layer was then coated with solid polymer electrolyte.

Two platinum current collectors made of Pt gauze (196 mesh cm⁻²) welded on to a perforated Pt foil (0.2 mm) thick are used by Millet et al.₄⁹. 
9. Sensitivity to poisoning

In SPE water electrolysis generally, metallic platinum is used as cathodic electrocatalyst due to its high catalytic activity. However, its activity is not selective and it is also highly sensitive to poisoning by under potential deposition of monolayers of other metals\(^8\), such as copper\(^8\), lead\(^4\), nickel\(^8,5\) and iron\(^5\). Once the platinum surface is covered by such monolayers, hydrogen discharge takes place on the new surface and the cathodic over voltage increases drastically. In water electrolysis, the deionised water circulated in the cell stack becomes poisoned by metallic cations because of the slow but steady corrosion of the steel piping. Therefore the incorporation of ion exchangers in the anodic and cathodic water circuits have been proposed by Andolfatto et al.\(^5\). Another alternative proposed by many researchers\(^9,5,4\), is to use the Ir\(_2\)O\(_3\) or RuO\(_2\) based alloys as cathodic materials in place of platinum, because of their insensitivity to poisoning.

The use of Nafion also increases the problems of electrode poisoning. The equilibrium between the membrane and the solution leads to an exchange of protons of the membrane with the cations of the solutions. The amount of particular ion exchanged can be determined quantitatively from the selectivity coefficient of various ions\(^5\). Therefore, a large increase in poly cations concentrations inside the membrane can take place with time. The electrode in membrane faces more impurities than in solution and the electrodes kinetics can, therefore, be modified. This ion exchange of protons with metallic cations also leads to an increase of the resistivity of the membrane. The resistivity is at least, five times higher for a Nafion-membrane in Ni\(^2+\) form than in H\(^+\) form and a dramatic increase of the ohmic drop is observed, when it is ion exchanged with Ni\(^2+\) ions\(^5\).

10. Recent advances and scale up of SPE water electrolyzer

SPE electrolyzers of small size with (50 cm\(^2\) electrode area) were made available as early as in mid seventies. But these units were not practical and economical for large scale production of hydrogen\(^7\). Now a lot of progress has been made in this area. Hot press method and chemical plating methods have been adopted for the preparation of SPE electrocatalysts composites by various research groups.

In early eighties an electrolysis module consisting of two cells with electrode area 1,600 cm\(^2\) (40 cm x 40 cm) was tested successfully\(^1\) which operated at 80°C. 1A/cm\(^2\) current density and 5 atmospheric pressure with 1.7 volts. H\(_2\) and O\(_2\) purities obtained were 99.999% and 99.88% respectively.

Recently a novel method\(^15,5\) to increase reaction area in three dimensional zone has been proposed and tested at laboratory scale with 5 cm\(^2\) electrode area. RuIr, Ta oxide or IrO\(_2\), coated Ti gauze or perforated Ti sheets are used as anode and Ti or stainless steel gauze coated with Pt or IrO\(_2\) used as cathode. The electrodes are impregnated with Nafion with the help of Nafion solution to create a three dimensional reaction zone before hot press to Nafion membrane. The cell has been tested for continuous operation up to 5,000 hours at 25°C and 80°C at 1 A/cm\(^2\) current density with cell voltage 2.23 volts and 1.85 volts respectively.

Mc Elroy\(^8\) has designed a SPE water electrolyser for space applications based on nuclear submarine SPE electrolyzer, with incorporated capability to operate at high differential pressures of O\(_2\) and H\(_2\) up to 3,000 psi.

At present, an electrolyzer with 2,500 cm\(^2\) electrode area with four stacks prepared by hot press and chemical plating method has been tested.
successfully at 80°C and at current densities ranging from 1A to 4A/cm². The energy efficiency obtained is more than 94% (Figs 3-5). In WE-NET project of Japan Hydrogen Program (1998-2003), phase II, the projected scale up of electrode area for the water electrolyser is greater than 10,000 cm² which should operate at 1 to 3 A/cm² current density, with energy efficiency >90%.

In order to reduce initial investment cost, the development of new solid polymer electrolyte material is the need of the hour. Partially fluorinated membrane (with low cost) has been suggested as a substitute for Nafion®. Linkowu et al. have studied several polymeric materials like aromatic polyesters, polybenzimidazoles, polyphenylene sulphides, polysulphones, polyethersulphones, polyketones and polysiloxanes to develop a new solid polymer electrolyte. A new ionomer with the same material is the need of the hour. Partially fluorinated membrane (with low cost) has been suggested as a substitute for Nafion®. Linkowu et al. have studied several polymeric materials like aromatic polyesters, polybenzimidazoles, polyphenylene sulphides, polysulphones, polyethersulphones, polyketones and polysiloxanes to develop a new solid polymer electrolyte. A new ionomer with the same capabilities as that of Nafion, has been reported. But a cheap and better alternative of Nafion is still awaited.

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