

## Title

# **“HIGH RATE AND HIGH EFFICIENCY HYDROGEN GENERATION VIA WATER ELECTROLYSIS CATALYZED BY NANO POWDERS.”©**

By

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## **ABSTRACT**

Over 90% of all hydrogen used today is made from steam-reformed petroleum. This process produces greater than 5 kg of carbon dioxide for each kg of hydrogen if using methane and even more if using natural gas. Hydrogen made from this process is about 70% energy efficient and costs about \$4.50 per kg of hydrogen<sup>2</sup>. Hydrogen from electrolyzed water dates to 1800; however, the process has been very energy inefficient and expensive. This Whitepaper discusses a three-dimensional electrode used for water electrolysis. The surface of the metallic reticulate electrode is coated on all surfaces with a mixture of nano catalysts adhered by a unique electrochemical process that produces excellent electrical contact with the powders while allowing them to interact with the electrochemical boundary layer. The result is a very high rate, solid-state, three-dimensional (3D) electrode. Data shared here is first in the half-cell, then in the full cell and shows consistently high rates and high energy efficiencies.

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<sup>2</sup> [http://www.hydrogen.energy.gov/pdfs/5038\\_h2\\_cost\\_competitive.pdf](http://www.hydrogen.energy.gov/pdfs/5038_h2_cost_competitive.pdf)

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# 3D Water Electrolysis

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# 3D Water Electrolysis

## 1. Mathematical Basis:

**Appendix 1** contains the algorithmic logic, unit conversions and assumptions made in the calculations used in the paper. All are public knowledge, but shared here for background. Some definitions are needed to understand the body of this paper and are listed below with the equation reference number below:

Energy Efficiency (EE): 
$$\text{EnergyEfficiency} = \frac{\text{BTUinH}_2}{\text{BTUtoMakeH}_2} = \frac{1.482}{\text{CellVoltage}} \quad (9)$$

Gallon of Gas equivalent (gge): 
$$\text{GallonsofGasEquivalent} = \text{gge} = 125,000 \text{ BTU}_{\text{H}_2} \quad (16)$$

**1 gge = 125,000 BTU and 1 kgH<sub>2</sub> = 134,483 BTU, so 1 gge is ~ 1 kg H<sub>2</sub>.**

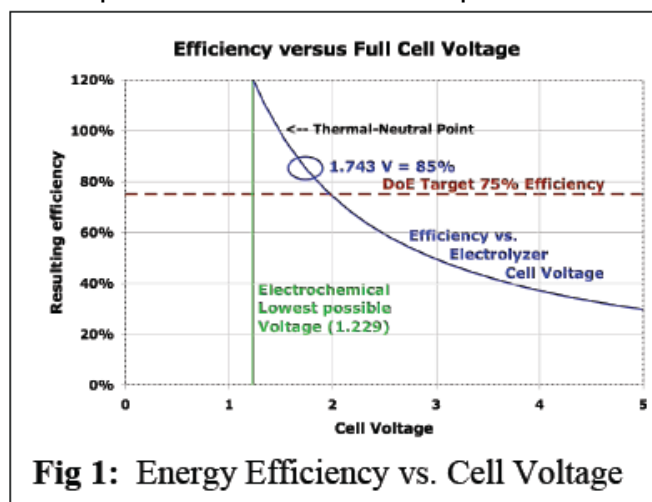
Production efficiency as kWhr/kgH<sub>2</sub> produced: 
$$\frac{\text{kWhr}}{\text{kgH}_2} = \text{CellVoltage} * 26.5905 \quad (20)$$

## 2. Hydrogen sources and DoE Targets

Over 90% of all hydrogen used today is made from steam-reformed petroleum costing about \$4.50 per kg of hydrogen<sup>3</sup>. Hydrogen from electrolyzed water is an old technology dating to the beginning of the 19<sup>th</sup> century; just weeks after Volta introduced his pile in 1800. Until recently, however, electrolysis has been slow, energy inefficient and expensive due to the use of platinum and due to inefficiencies. The U. S. Department of Energy (DoE) target for water electrolysis is to exceed 75% Energy Efficiency  $\left( \frac{\text{Energy\_in\_Hydrogen}}{\text{Energy\_to\_Produce\_H}_2} \right)$  for the total

electrolysis plant. However, the DOE does not indicate at what current density that 75% Energy Efficiency (EE) needs to be. At very low rates most any electrode is highly efficiency. For example, at 1 mA/cm<sup>2</sup> two graphite electrodes run at 90% EE in half cell tests. Typical electrolyzers today run from 10 to a few hundred mA/cm<sup>2</sup>. This rate necessitates large units to produce usable quantities of hydrogen in practical time frames. Our target is to be as high as possible at rates above 500 mA/cm<sup>2</sup> for flat plate bifunctional electrodes and above 1 Amp/cm<sup>2</sup> for porous nonfunctional electrodes. This will produce smaller units to produce the same amount of hydrogen. It also will allow for smaller and more physically stable electrodes.

**Figure 1** shows the relationship between full cell voltage and the Energy Efficiency of the cell. The ability to theoretically reach efficiencies above 100% (albeit at very low rates) is due to Gibb's free energy (1.229V or 120%) and Entropy at the Thermoneutral voltage (1.482V or 100%). In other words, the system draws energy from the environment at low rates. It does suggest very high efficiency electrolyzers are plausible.



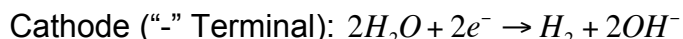
<sup>3</sup> [http://www.hydrogen.energy.gov/pdfs/5038\\_h2\\_cost\\_competitive.pdf](http://www.hydrogen.energy.gov/pdfs/5038_h2_cost_competitive.pdf)

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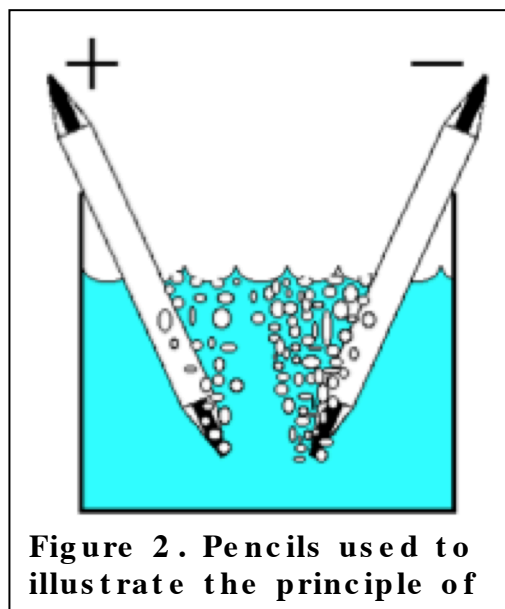
## 3. Principles of Electrolysis

Water electrolysis to produce hydrogen and oxygen is an old technology originating just weeks after Volta introduced his Pile in 1800 by William Nicholson and Anthony Carlisle. The principle chemical equations are shown below, where the electrochemical flow is shown for alkaline environments, which is the condition used in this research. The anode produces one water molecule, but the cathode consumes two, resulting in a net loss of one water and the production of one mole of hydrogen and half a mole of oxygen.

### Alkaline Water Electrolysis forming Hydrogen and Oxygen Gasses



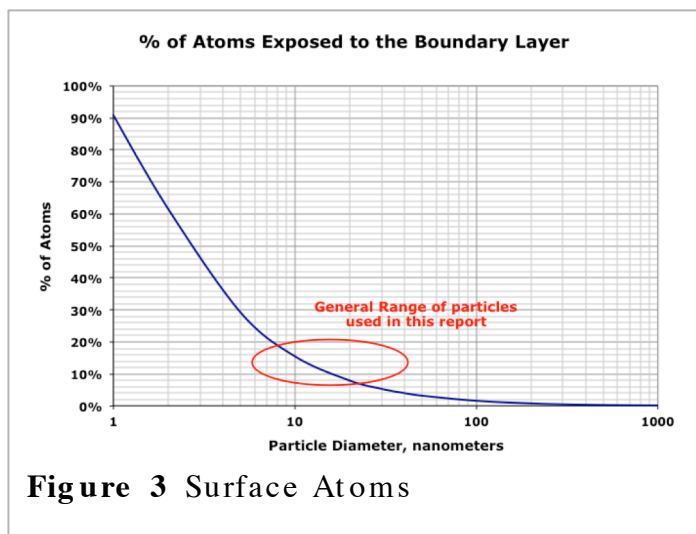
To understand the principles of electrolysis, perhaps the most basic experiment is the use of two pencils sharpened at both ends with the top being connected to a battery and the bottoms inserted into alkaline water. **Figure 2** illustrates the concept showing many bubbles appearing at the negative pencil and half that many appearing at the positive. At very low rates ( $<1 \text{ mA/cm}^2$ ), even these graphite electrodes are very high efficiency, but produce very little hydrogen over time. This is the same principle of even the most sophisticated water electrolysis machines with the difference being in efficiency and production rate.



**Figure 2. Pencils used to illustrate the principle of**

## 4. Nano-particle Surface Area Effect

As a material is divided into smaller and smaller particles, the three-dimensional surface area per gram increases logarithmically. For example, a one-gram pellet of nickel is 0.6 cm in diameter and has a surface area of  $1.12 \text{ cm}^2$ . One gram of 10 nm particles has a total surface area of  $67 \text{ m}^2$  or 27 feet on a side - a 60 million-fold increase. By mixing particle sizes, the pack-density increases, so even larger surface area gains can be made per volume of particles. This surface area increase improves electrochemical reactions due to the increase in the ratio of surface atoms. Bulk atoms have 12 neighbors and are unattainable to the liquid boundary layer. Surface atoms have 6 to 9 neighbors and are able to interact with their electron clouds in the reactive boundary layer. As **Figure 3** illustrates, this gives nano-coated surfaces more exposure for a higher electrochemical activity.



**Figure 3 Surface Atoms**

# 3D Water Electrolysis

## 5. Types of Electrolyzers

Electrolyzers can be separated into two categories: Monopolar and Bipolar.

### 5.1 Bipolar Electrolyzers

Bipolar electrolyzers are used for producing mixed gasses or pure gasses depending on design. **Figure 4** shows a block diagram of a bipolar stack. The end plates are necessarily monopolar, but the inner plates are bipolar. A bipolar electrolyzer uses electrodes that function as a cathode on one side of a solid metallic surface liberating hydrogen diatomic molecules and hydroxyl ions. The electrons pass through the body of the electrode to the anodic surface of the same electrode liberating nascent oxygen atoms, which soon combine to form diatomic oxygen while consuming hydroxyls. Electrodes are often built as large stacks of parallel plates separated by a thin insulator producing a stoichiometric mixture of hydrogen and oxygen sometimes called “HHO” or “Browns Gas” among other names. Bipolar electrolyzers are always relatively low rate per surface area due to gas masking, which is why we are working with monopolar, high-rate designs.

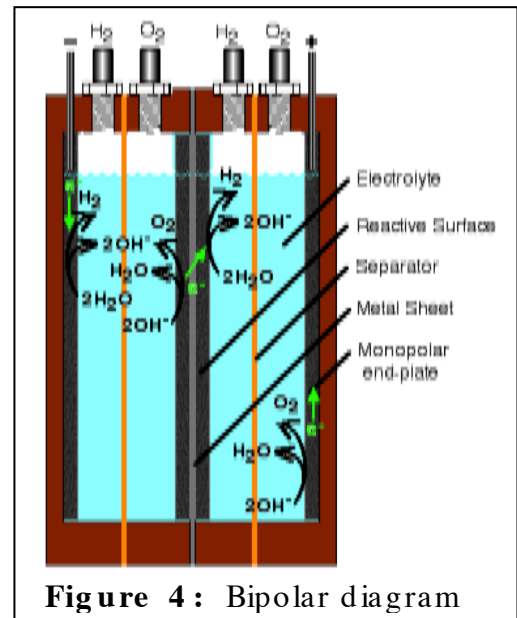


Figure 4: Bipolar diagram

### 5.2 Monopolar Electrolyzers:

In Monopolar designs, the gasses and ions do not compete for surface area and thus they can be much higher rates than bipolar designs. Our 3D electrolysis units are Monopolar electrolyzers using porous electrodes and producing essentially pure gasses. Each porous electrode is either an anode or a cathode with ions passing between them through a separator. **Figure 5** shows a diagram of an alkaline monopolar cell in which electrons are fed into the cathode where two water molecules are split to form hydrogen gas and two hydroxide ions. The hydrogen escapes by buoyancy while the hydroxyls diffuse through the separator into the anode porous electrode. Electrons are drawn out of the anode electrode, oxidizing two hydroxyls and producing one water molecule while liberating a nascent oxygen atom. This atom is very reactive, producing diatomic oxygen in a very short time, which escapes via buoyancy. The reaction occurs along the entire electrode surface. Because our electrodes are high rate and high efficiency, the electrodes themselves are smaller in dimensions making them more robust and the entire unit more compact. An electrolyzer built using our technology could be a drop-in change for electrolysis machines that now use reverse PEM electrolyzers that are low rate and require expensive platinum catalysts.

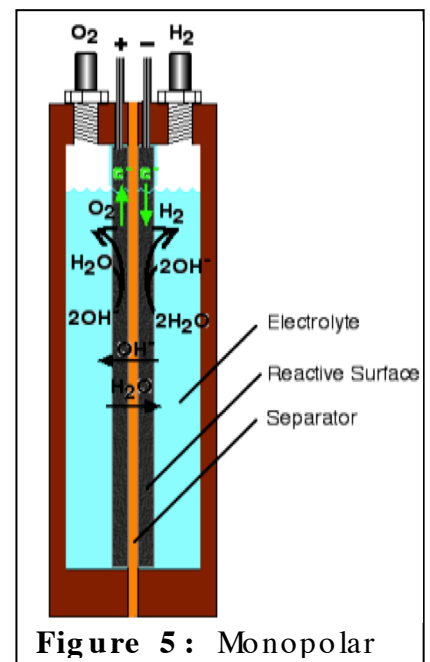


Figure 5: Monopolar

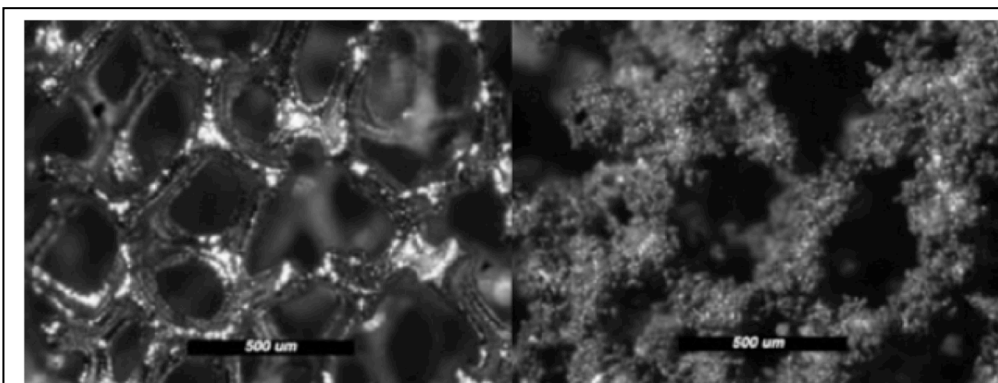


## 3D Water Electrolysis

### 6. Coating a Metallic Surface with Nano-catalyst

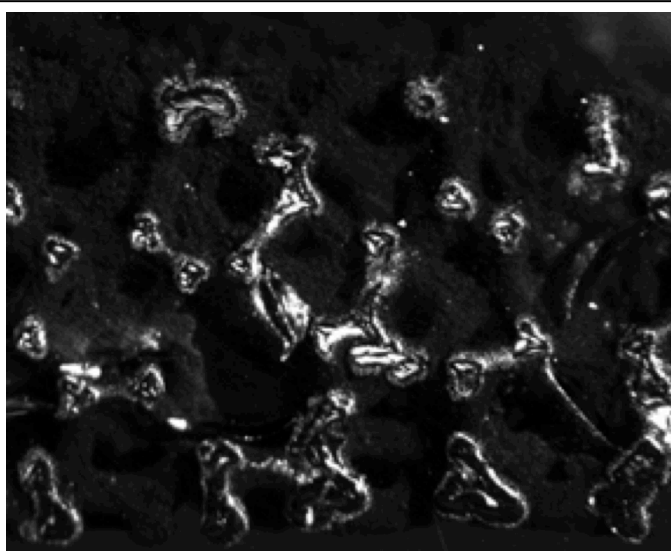
We used both linear and  $2^3$  full factorial experimental designs to evaluate about 20 different nano catalysts to find the best recipes for the anode and cathode coatings. We use no Noble metals in our work (i.e. no platinum). We then developed a novel way to adhere these powders to a metallic electrode surface. Efforts to coat an electrode with nano powders have been attempted by many researchers. The techniques often are slow and energy consuming such as Raney Nickel (or similar) applications, sputtering or using thermal flow characteristics of other metals such as silver to act as an adhesive. All of these have serious problems when scaled up for large volume hydrogen production, are energy expensive to make and/or are not robust enough to withstand the rigors of an electrolyzer.

We have developed a unique method to attach nano catalysts to a metallic surface in a way that has very low impedance to the reaction sites, covers all surfaces of a



**Figure 6:** nano coating on a porous surface

porous structure and leaves the particles well exposed to the boundary layer. Many nano catalysts have been used in our experiments, with none being noble metals. Both factorial and linear experiments have lead to the best recipe for the anode and the cathode. At the time of this writing, we are using two catalysts in the anode (Oxygen generating) electrodes and three different catalysts in the cathode (Hydrogen generating) electrodes. The coating is uniform on all surfaces within a three-dimensional metallic surface such as metallic foam or metallic “paper” made from fibers or other porous surfaces. **Figure 6** is a comparison of an uncoated and coated



**Figure 7:** Cross section of nano catalyst-coated metallic foam.

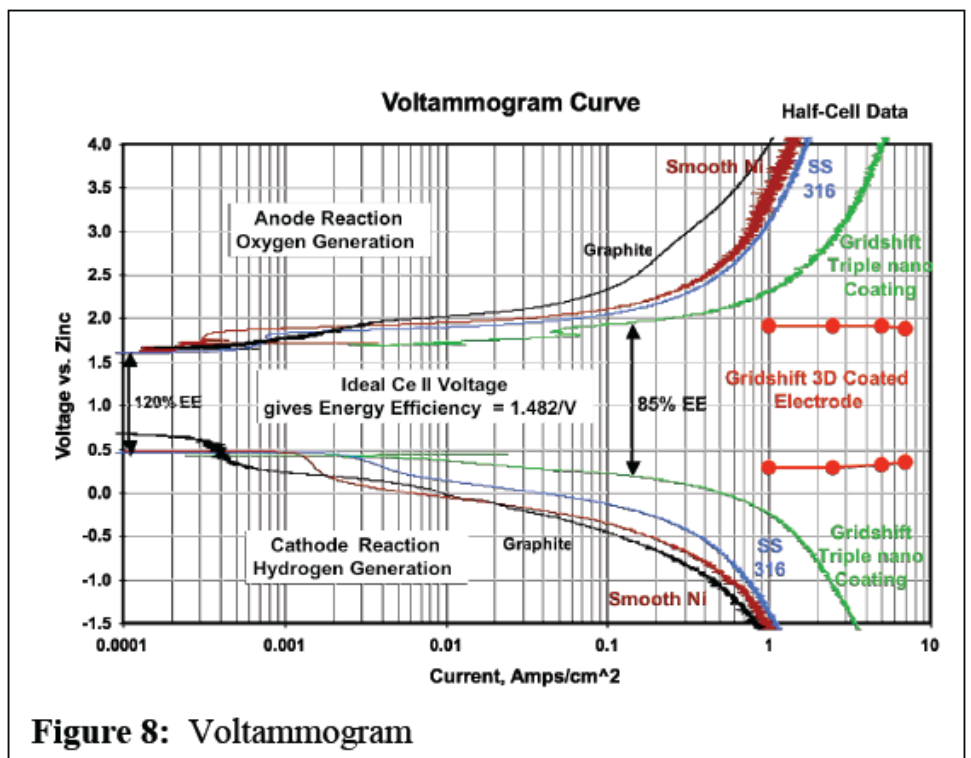
porous surface. **Figure 7** is a cross section showing the excellent coverage on all surfaces of foam nickel. The coating extends into all internal intricacies of the porous metal substrate greatly extending the reactive surface area.

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## 7. Electrochemical Data

### 7.1 Half-Cell Voltammogram

Figure 8 shows a Voltammogram of several current collectors and the 3D coated electrode (shown as red dots). These data are done in the half-cell. That is, all data was read one scan at a time using a reference electrode of pure zinc. The voltages shown are the voltages versus zinc. Therefore, this graph shows an ideal state with no losses in the electrolyte or separator. It shows the best that a catalytic recipe and coating method can produce. The ideal full cell voltage is the



**Figure 8: Voltammogram**

distance between the anode line and the cathode line. The energy efficiency is proportional only to the reciprocal of the full cell voltage by  $EnergyEfficiency = \frac{1.482}{CellVoltage}$ . A double-headed

arrow is included showing the voltage which is equivalent to the equilibrium hydrogen/oxygen potential of 1.229 volts (on the left) and the 1.743 volt ideal that gives 85% EE (mid-graph). At very low rates any electrolysis apparatus runs at very high efficiencies. At 1 mA/cm<sup>2</sup> even graphite electrodes are near 90% ideal EE. Current density is directly related to the amount of gas produced per surface area of the electrode by the relationship:

$$\frac{grams_{H_2}}{Hr} = Amps * 0.0376 * \#ofcells * Hrs.$$

Most alkaline electrolyzers today are flat plate bipolar apparatuses in which the solution ions approach the reactive surface from the same side as the gasses are escaping. This causes a dramatic drop-off of performance as rates increase. The first four lines (graphite, nickel, stainless steel 316 (SS316) and tri-nano coated SS316) are all flat plates showing the beneficial effect of the coating process on flat plates. However, they still exhibit the rapid drop-off at high rates.

Our new 3D electrodes (shown as red dots) has the ions coming from one side while the gasses escaping from the opposite side of the vertical-standing electrode, thus eliminating this masking effect. The results are in the red dots, which show an ideal efficiency that approaches Thermoneutral values. They are individual datum due to the high current level exceeding the capability of the Solartron equipment used for the other scans.

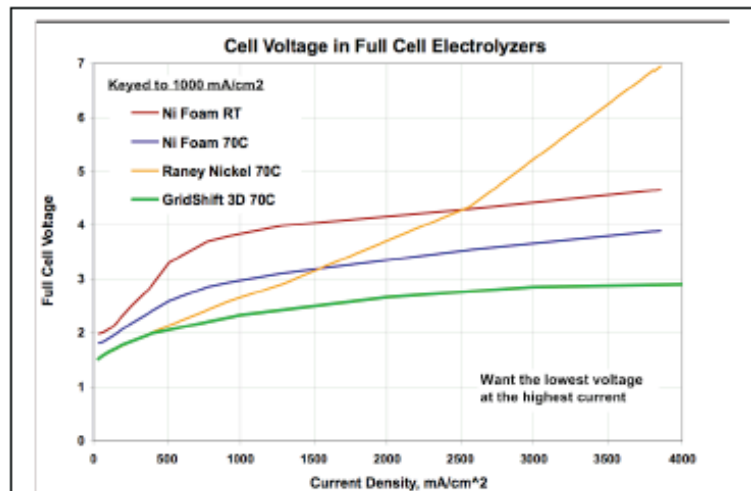
# 3D Water Electrolysis

## 7.2 Full Cell Evaluations

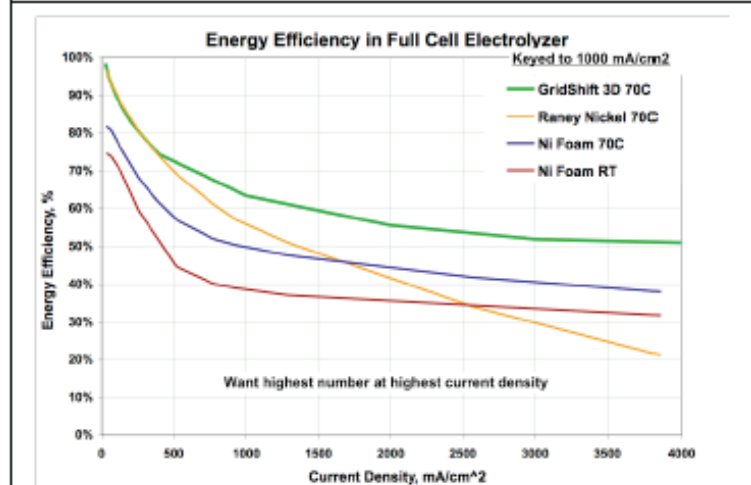
The half-cell above was essential for developing the recipes for the anode and cathode because it is specific to the catalyst being studied with no effect of the electrolyte and separator. These data in section 7.2 and 7.3 are from whole cells, so all internal losses are expressing themselves. Over 12 separators were evaluated allowing us the lowest impedance loss from this essential component. **Figure 9** is the full cell voltage of key designs, all using a 3D monopolar design. The lower the voltage, the higher the energy efficiency. A lower voltage also allows for more cells to fit between the voltage rails of the system. For example, 40 cells at 2.117 (70% EE) volt cells will fit in an 85 VDC (rectified 120 VAC) range, while 48 cells at 1.75V (85% EE) will fit within the same constraints. That is a 20% increase in hydrogen generation for each amp that passes through the electrolyzer series stack.

**Figure 10** is the same data as **Figure 9** but expressed as the cell Energy Efficiency rather than cell voltage in the dependent axis. **Figure 10** is instructive for the changes shown. The lowest efficiency is a nickel foam electrode with no coating at room temperature. Next the advantage of heating the cell to reduce iR losses is observed. All the rest are at elevated temperature. Next is a commercial Raney Nickel electrode. The top is our present 3D electrode using three transition metal, non-noble, nano-metal catalysts. We still are seeking the best separator, electrolyte additives and perhaps a power supply wave-shape.

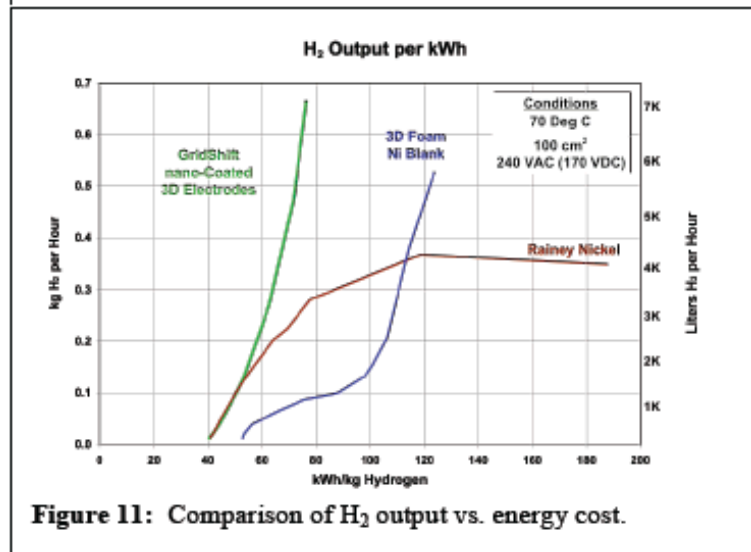
**Figure 11** compares the hydrogen output as a function of the cost. The graph shows output in kg/Hr and kLiters/hr for a hypothetical electrolyzer running on 240 VAC (170 VDC) and having 100 cm<sup>2</sup> electrodes as a function of the kWh/kg of hydrogen. This shows that high rate hydrogen outputs are possible at reasonable energy costs.



**Figure 9: Full Cell Polarization**



**Figure 10: Full Cell Set as %EE**



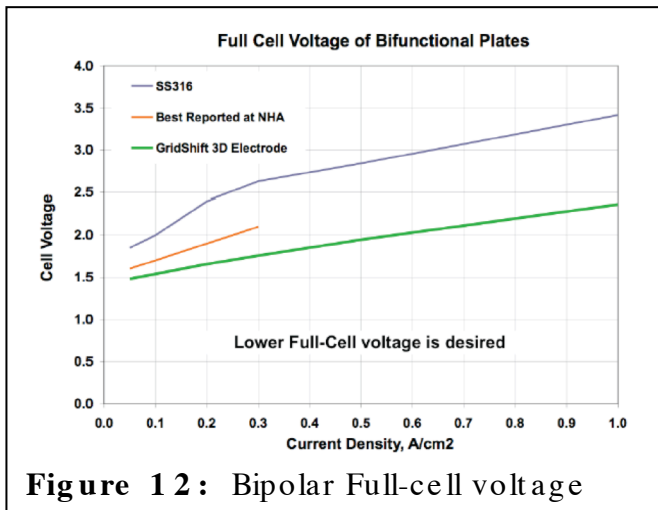
**Figure 11: Comparison of H<sub>2</sub> output vs. energy cost.**



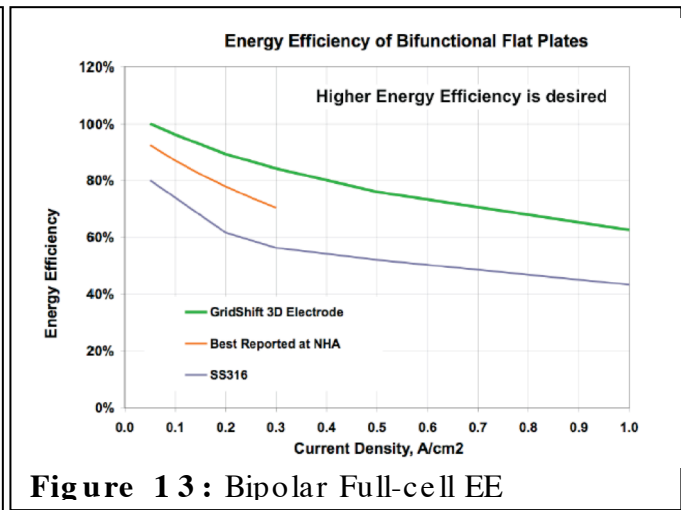
# 3D Water Electrolysis

## 7.3 Flat-Plate Bifunctional Cells

There are applications that require flat-plate designs. This is particularly useful in tight spaces like “On Demand” electrolyzers under the hood of motor vehicles. Using this coating process, coated nickel foam panels were welded to SS316 flat-plate bifunctional electrodes. **Figure 12** shows the cell voltage of an electrolyzer using flat SS316 plates (the typical electrodes used today) and with the GSI coated plates. Also shown is the best performing bifunctional electrodes presented at the National Hydrogen Association meeting last year by a large corporation. **Figure 13** shows the same data, but recorded as Energy Efficiency. The advantage of our coating technique is unambiguous.



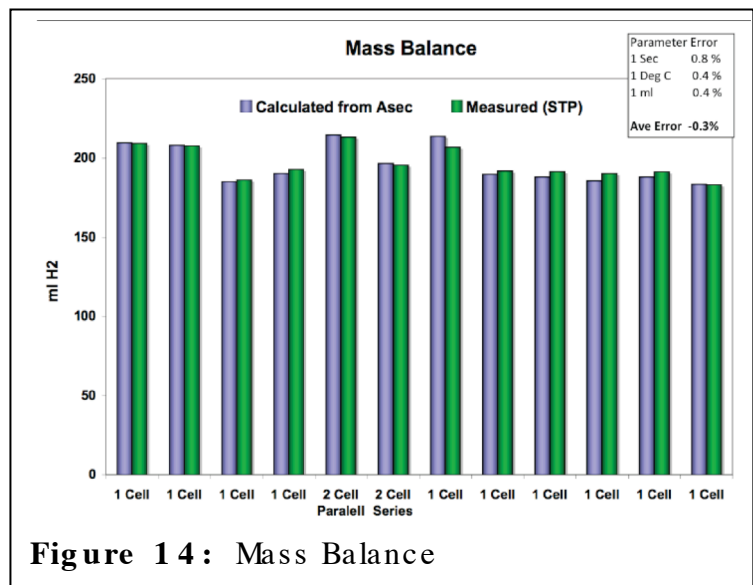
**Figure 12:** Bipolar Full-cell voltage



**Figure 13:** Bipolar Full-cell EE

## 8. Mass Balance

It is important to know that all electrons are performing electrolysis and not being shunted via some ionic “short”. Another worry may be that the gasses are re-combining rather than remaining discrete. **Figure 14** shows consecutive experiments where hydrogen was collected, ml measured (using displacement) and time recorded. The values were then converted to STP and compared to the amount calculated from Faraday’s conversion (See equation 10 below). Measurement errors are shown in the box in the upper right. The average disagreement with the calculated value was only -0.3%, well within experimental error. Therefore, all of the electrons are indeed producing gasses and there is no internal ion shunting or physical shorting in the experimental apparatuses.

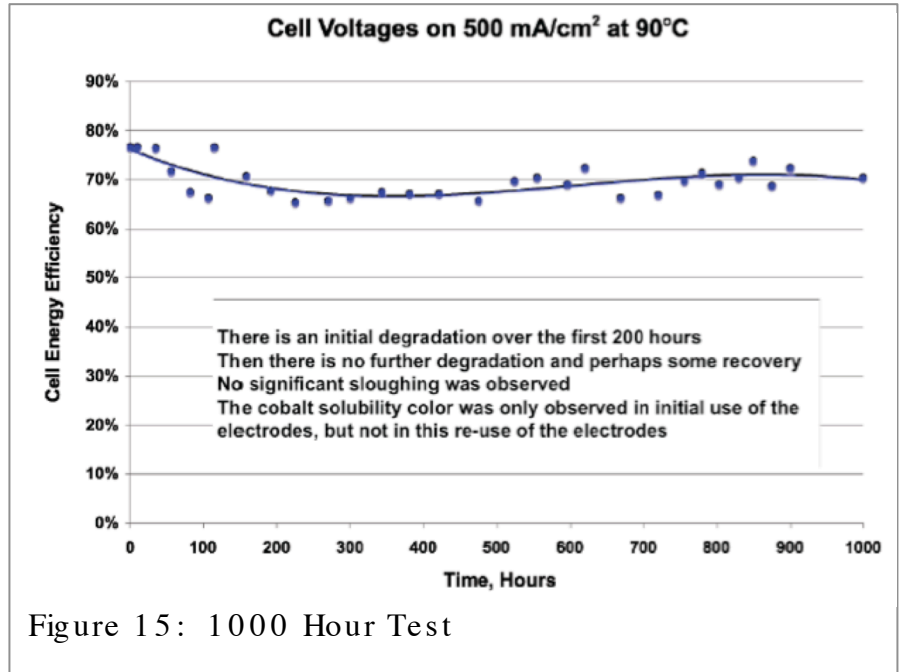


**Figure 14:** Mass Balance

## 3D Water Electrolysis

### 9. Stability Testing

The results of the 1000-hour test is shown in **Figure 15**. There was some minor sloughing but it is unclear if it was nano powders or the external buildup on the test fixture. The rate chosen was 0.5 Amp/cm<sup>2</sup>. This is higher than anyone is reporting. This electrode had been used in several previously experiments so had been through at least four use, wash, dry and reuse cycles. Both need to be examined to understand the causes. In total, the electrode performed very well over the 41.7 days of the test.



### 10. Alkaline Fuel Cells

William Robert Grove invented the fuel cell in 1839. This device used Sulfuric Acid electrolyte. Francis Thomas Bacon invented the Alkaline Fuel Cell (AFC) in the 1930's. Today AFC's are used in space applications and some terrestrial applications. They use platinum as catalysts and are low rate devices. Our electrode works well as an AFC. The data gathering has just started and will be reported in subsequent reports as data is collected. The data gathered on initial full fuel cells is very encouraging.

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## **12. Conclusions**

- Our nano-coated 3D electrolyzer is a very high rate, high efficiency water electrolysis unit.
- We have developed recipes for the anode and cathode electrodes using inexpensive, common elements and no precious metals.
- Our coating method covers all surfaces inside and outside of a complex porous electrode greatly increasing the catalytic surface area.
- The electrodes are high rate per surface area, so they can be smaller for the same hydrogen output. This results in stronger electrodes and more compact finished units.
- We have identified an excellent separator for the apparatus.
- Our successes are based on sound electrochemistry.
- Full-cell data confirms half-cell predictions.
- There are no ionic or electrical shunts occurring in our electrolyzer.

## **13. Acknowledgements**

- We thank Khosla Ventures for funding this research.
- Senior Laboratory Assistant Crawford McCarty worked tirelessly in the laboratory and contributed greatly to the success of this project. His many insights and imagination proved invaluable to our progress.

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### **13. Profile of Robert Dopp**

#### **Robert Dopp, President, DoppStein Enterprises, Inc.**

Mr. Dopp is one of the foremost authorities on zinc-air fuel cells and air electrode technologies and a leading expert in the field of water electrolysis and alkaline fuel cells. During his 18-year career as an engineer at Rayovac Corporation, he was a principal developer of the zinc-air hearing aid battery and lead engineer in the development of the air-cathode component. Previously, he also served as the Director of Research for Electric Fuel Corporation of Beit Shemesh Israel for five years.

Mr. Dopp has significant expertise in a wide range and depth of knowledge in battery, fuel cell, and hydrogen generation systems. Forming his own R&D consulting firm and laboratory in 2002 (DoppStein Enterprises Inc., DSE), he consults to battery, fuel cell, and hydrogen generation related industries. He has developed components and designs resulting in longer-life batteries with over four times the energy density of alkaline cylindrical cells, and many tens of times higher energy than many rechargeable batteries. His work in water electrolysis is paradigm changing. His onsite laboratory in Marietta, Georgia provides him considerable flexibility, consulting on the electrochemistry and design of gas electrodes and building cathode machines among other development projects. Mr. Dopp has 39 issued patents and 16 pending patents as of July '10.

As chief scientist and CEO of DSE, Mr. Dopp is working in renewable energy related fields including electrodes for batteries, metal-air fuel cells and hydrogen production through water electrolysis utilizing cutting edge nano-scale catalysts. Mr. Dopp has been a guest lecturer on university campuses and at technical associations including the National Hydrogen Association and Sandia National Laboratories.

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# 3D Water Electrolysis

## Appendix 1. MATHEMATICAL BACKGROUND and TARGETS

### A1.1 Energetics

The energy contained within the hydrogen generated ( $H_2$ gen) can be calculated by employing Faraday's electrochemical law and the higher heating value of hydrogen (HHV = 134.4 BTU/gH<sub>2</sub>).

$$BTU_{h_2gen} = \left( \frac{ASec}{F * 2} * H_2gmw \right) * \frac{BTU}{gH_2} \quad (1)$$

$$BTU_{h_2gen} = \left( \frac{Amp * Hr * 3600 \frac{Sec}{Hr}}{96487 \frac{ASec}{eq} * 2 \frac{eq}{mol}} * 2.0159 \frac{gH_2}{mol} \right) * 134.483 \frac{BTU}{gH_2} \quad (2)$$

$$BTU_{h_2gen} = A Hr * 5.058 \frac{BTU}{A Hr} \quad (3)$$

This then gives the BTU in hydrogen per Amp-hour. Using Ohm's Law, we can calculate the energy required to electrolyze water, expressed with the units of Watt-hours.

$$BTU_{used} = (Amp * CellV * Hr) * \left( \frac{BTU}{WHr} \right) \quad (4)$$

$$BTU_{used} = (WHr) * \left( 3.413 \frac{BTU}{WHr} \right) \quad (5)$$

The energy efficiency of the reaction is then expressed as the ratio of (3) and (5):

$$EnergyEfficiency = \frac{BTU_{h_2gen}}{BTU_{used}} \quad (6)$$

Or, preserving units:

$$EnergyEfficiency = \frac{\left( \frac{Amp * Hr * 3600 \frac{Sec}{Hr}}{96487 \frac{ASec}{eq} * 2 \frac{eq}{mol}} * 2.0159 \frac{gH_2}{mol} \right) * 134.483 \frac{BTU}{gH_2}}{(Amp * CellVoltage * Hr) * \left( \frac{BTU}{WHr} \right)} \quad (7)$$



### 3D Water Electrolysis

$$\text{EnergyEfficiency} = \frac{\text{Amp} * \text{Hr} * 5.058}{(\text{Amp} * \text{Hr} * \text{CellVoltage}) * 3.413} \quad (8)$$

$$\text{EnergyEfficiency} = \frac{1.482}{\text{CellVoltage}} \quad (9)$$

Energy Efficiency is dependent only on the reciprocal cell voltage.

#### A1.2 Production Rate

Production of hydrogen per electrolysis cell per hour is dependent only on the current by equations 10 and 11 assuming one hour of operation:

$$\frac{\text{Liters}_{H_2}}{\text{Hr}} = \left( \frac{\text{Amp} * 1\text{Hr} * 3600 \frac{\text{Sec}}{\text{Hr}}}{96487 \frac{\text{ASec}}{\text{eq}} * 2 \frac{\text{eq}}{\text{mol}}} * 22.414 \frac{\text{Liters}_{H_2}}{\text{mol}} \right) \text{ Or } \frac{\text{Liters}_{H_2}}{\text{Hr}} = \text{Amps} * .41815 \quad (10, 11)$$

Notice that efficiency only plays a role in dictating the number of cells one can have for any one voltage source. The relationship of current to output is absolute with no relationship to current density. The Current density effects efficiency, which dictates how many cells, which in turn gives the ability to have more gas output.

If the desired units are gravimetric, then the algorithms become:

$$\text{grams}_{H_2} = \left( \frac{\text{Amp} * 1\text{Hr} * 3600 \frac{\text{Sec}}{\text{Hr}}}{96487 \frac{\text{ASec}}{\text{eq}} * 2 \frac{\text{eq}}{\text{mol}}} * 31.999 \frac{\text{Grams}_{H_2}}{\text{mol}} \right) * \text{Hrs} \text{ or } \text{grams}_{H_2} = \text{Amps} * \text{Hrs} * 0.0376 \quad (12, 13)$$

This output can be multiplied by the number of parallel cells available between the rails of the voltage. For example, if each cell requires 1.74 volts (85% efficiency) and there is 12 volts available, then six (6) cells will fit between the voltage rails, thus changing the equations to:

$$\text{Liters}_{H_2} = \text{Amps} * .41815 * \# \text{ of cells} * \text{Hrs} \quad \text{and} \quad \text{grams}_{H_2} = \text{Amps} * 0.0376 * \# \text{ of cells} * \text{Hrs} \quad (14, 15)$$

This paper deals only with hydrogen output. Some applications use the combined hydrogen and oxygen output (referred to by many names including "Brown's Gas", "HHO", and "Hydro-gas" among dozens of others). To convert equations 10 through 13 for the combined gasses,

## 3D Water Electrolysis

simply multiply by 1.5 since for each mole of hydrogen, you produce  $\frac{1}{2}$  mole of oxygen. Efficiency algorithms are unchanged.

### A1.3 GGE:

**Gallon of gasoline equivalent (gge)** refers to the amount of hydrogen, which is energy equivalent to one gallon of gasoline. Coincidentally, one gge is nearly equivalent to one kilogram of hydrogen, so it may also be utilized as a gravimetric unit. The energy value of gasoline greatly depends on the grade and testing facility, but the average value calculated by the US Department of Energy is about 125,000 BTU's.

$$\text{Gallons of Gas Equivalent} = \text{gge} = 125,000 \text{ BTU}_{H_2} \xrightarrow{\text{About}} 1 \text{ kg}_{H_2} \quad (16)$$

Taking all parameters into account to comparing production rate, the unit **gge/hr/m<sup>2</sup>** can be employed. Simply stated, it is the gallons of gasoline equivalents that could be produced from a 1 m<sup>2</sup> electrode:

$$\text{Production Rate as } \text{gge}/\text{Hr}/\text{m}^2 = \frac{\text{Amp}}{\text{cm}^2} * 0.405 \quad (17)$$

### A1.4 Cost Efficiency:

The most useful way of rating the efficiency of a hydrogen generator is by calculating the energy required to make one kg of hydrogen. If the cost of electricity is known, it is simple to convert to the cost of a kg of hydrogen, essentially the cost of a gge.

$$\frac{\text{kWhr}}{\text{kg}} = \frac{\text{Whr}}{\text{g}} = \frac{\text{Amps} * \text{CellV}}{\left( \frac{\text{Amp} * \text{Hr} * 3600 \frac{\text{Sec}}{\text{Hr}} * 2.0159 \frac{\text{gH}_2}{\text{mol}}}{96487 \frac{\text{ASec}}{\text{eq}} * 2 \frac{\text{eq}}{\text{mol}}} \right)} \quad (18)$$

$$\frac{\text{kWhr}}{\text{kg}} = \frac{\text{Whr}}{\text{g}} = \frac{\text{Amps} * \text{CellV} * 96487 \frac{\text{ASec}}{\text{eq}} * 2 \frac{\text{eq}}{\text{mol}}}{\left( \text{Amp} * \text{Hr} * 3600 \frac{\text{Sec}}{\text{Hr}} * 2.0159 \frac{\text{gH}_2}{\text{mol}} \right)} \quad (19)$$

$$\frac{\text{kWhr}}{\text{kg}} = \text{CellV} * 26.5905 \quad (20)$$

Cost per unit is commonly described with respect to \$/gge. Using this unit is ambiguous due to the fact that it is highly dependent on the cost of electricity. This makes it difficult to critically evaluate data across different systems if baseline electricity cost is not disclosed. **Figure 15** is an illustration of this, where 85% efficiency is assumed. The cost per gge is anywhere from \$1.90 to \$9.25 depending on whether the cost of electricity is the industrial rate in Georgia or California.

**Figure 15. Cost per gge as a function of electricity cost.**

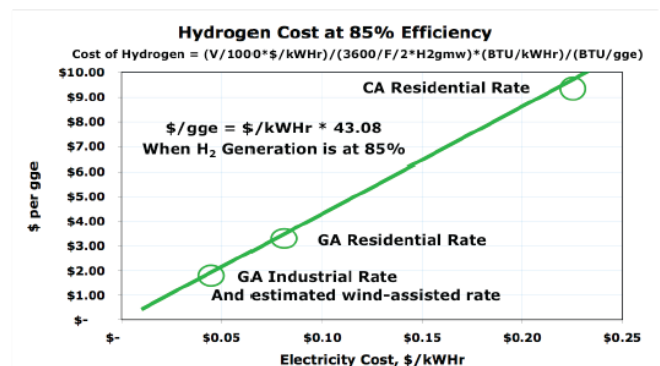


Figure 15. Cost per gge as a function of electricity cost.

## 3D Water Electrolysis

### A1.5 Summary and Conversions:

**Below** is a set of summaries from above and conversions between commonly used units for production rates. The numbering is included for derivation.

#### A1.5.1: Summary Equations

$$BTU_{h_2gen} = AHR * 5.058 \quad (3)$$

$$BTU_{used} = WHr * 3.413 \quad (5)$$

$$EnergyEfficiency = \frac{1.482}{CellVoltage} \quad (9)$$

$$Liters_{H_2} = Amps * .41815 * \# of cells * Hrs \quad (14)$$

$$grams_{H_2} = Amps * 0.0376 * \# of cells * Hrs \quad (15)$$

$$GallonsofGasEquivalent = gge = 125,000 BTU_{H_2} \quad (16)$$

$$\text{Production Rate as } gge / Hr / m^2 = \frac{Amp}{cm^2} * 0.405 \quad (17)$$

$$\frac{kWhr}{kg} = CellV * 26.5905 \quad (20)$$

#### A1.5.2: Conversions

Below is a set of common units used when discussing hydrogen generation. The normalizing time unit is uniformly “hours” in the table below. The ratios can be used to convert between units found in the literature. All are relate to hydrogen gas only (not mixed H<sub>2</sub> and O<sub>2</sub>).

Unit	In Words	Ratio
kg/hr	Kilogram of hydrogen/Hr	1
gge/hr	Gallon of Gasoline Equivalent/Hr	1.076
nm3/hr	Normal Cubic Meter/Hr	11.12
SCF/Hr	Standard Cubic Feet/Hr	392.6
l/hr	Liters/Hr	11118
BTU/Hr	British Thermal Units/Hr	134483

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