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Engineering Science & Technology Division

VALIDATION TESTING OF HYDROGEN GENERATION TECHNOLOGY

D. B. Smith
T. J. Toops

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Photech Energies, Inc.
207 Peterson Drive
Elizabethtown, Kentucky 42701

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
UT-BATTELLE, LLC
for the
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1. EXECUTIVE SUMMARY

This report describes the results of testing performed by ORNL for Photech Energies, Inc. The objective of the testing was to evaluate the efficacy of Photech's hydrogen generation reactor technology, which produces gaseous hydrogen through electrolysis. Photech provided several prototypes of their proprietary reactor for testing and the ancillary equipment, such as power supplies and electrolyte solutions, required for proper operation of the reactors. ORNL measured the production of hydrogen gas (volumetric flow of hydrogen at atmospheric pressure) as a function of input power and analyzed the composition of the output stream to determine the purity of the hydrogen content. ORNL attempted measurements on two basic versions of the prototype reactors—one version had a clear plastic outer cylinder, while another version had a stainless steel outer cylinder—but was only able to complete measurements on reactors in the plastic version. The problem observed in the stainless steel reactors was that in these reactors most of the hydrogen was produced near the anodes along with oxygen and the mixed gases made it impossible to determine the amount of hydrogen produced. In the plastic reactors the production of hydrogen gas increased monotonically with input power, and the flow rates increased faster at low input powers than they did at higher input powers. The maximum flow rate from the cathode port measured during the tests was 0.85 LPM at an input power of about 1100 W, an electrolyte concentration of 20%. The composition of the flow from the cathode port was primarily hydrogen and water vapor, with some oxygen and trace amounts of carbon dioxide. An operational mode that occurs briefly during certain operating conditions, and is characterized by flashes of light and violent bubbling near the cathode, might be attributable to the combustion of hydrogen and oxygen in the electrolyte solution.

2. INTRODUCTION

Photech has designed and tested an innovative method and device for producing large quantities of hydrogen, oxygen, and steam through electrolytic dissociation of water. Results of in-house tests at Photech indicated that electrolysis might be only a triggering process for other processes and phenomena that produce what appears to be sustained high-energy releases and gas production in the device. Photech regards the input energies required to initiate and sustain the production process to be extremely low when compared to the amount of reaction products generated, and production efficiencies appear to be orders of magnitude greater than other known processes used to generate hydrogen. Photech has duplicated the process with a number of different prototype reactors and testing protocols and they have acquired a high degree of confidence in the device's ability to function under differing operating conditions. Encouraged by these promising results, Photech determined that more sophisticated test facilities and more experienced researchers were needed to bring additional rigor to the development activity.

To this end ORNL was asked by Photech to propose a series of tests to verify certain results obtained by Photech and to generate additional data necessary to provide a better understanding of the processes taking place in the reactor.[1] The statement of work submitted by ORNL to Photech for their approval outlined the following measurement activities:

Measurement 1: Hydrogen purity in output stream

ORNL approach: Use capillary tube sampling of the output stream and mass spectrometry of the sample to determine the atomic and molecular species present in the gas stream. This will provide the relative abundance of hydrogen, oxygen, water and gas-phase contaminants in the output.

Measurement 2: Volumetric flowrate of output stream

ORNL approach: Use flow gauges provided by Photech and an ORNL mass flow meter calibrated for hydrogen gas to obtain volumetric flowrates as a function of input power.

Measurement 3: Power consumption

ORNL approach: This measurement will be done in conjunction with the hydrogen purity and volumetric flowrate measurements. We will use power supplies provided by Photech and possibly switch to ORNL programmable current limited DC power supply if it meets the input power requirements.

Measurement 4: Power curve relationship at variable power inputs.

ORNL approach: This measurement will be done as part of hydrogen purity, volumetric flowrate and power consumption measurements.

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[1] "Request for Proposal to Provide Facilities and Services for Validation Testing of Photech Energies, Inc. Hydrogen Reactor Technology," letter from Isaac W. Diggs, Sr., P.E., to Dr. Terry L. Payne, dated 11/30/06. (Mr. Diggs is a technical consultant and government liaison for Photech Energies, Inc.)

Upon the successful completion of the above measurements, Photech was given the option to expand the scope (at additional cost) to perform the following measurements (which they have not yet elected to do):

Optional measurement 5: Electrode degradation

ORNL approach: Gravimetric analysis and microscopy of cathode to evaluate erosion on electrode surface, and possible x-ray elemental analysis of surface contamination.

Optional measurement 6: Boiler power output

ORNL approach: Our testing facility is not approved for containment of pressurized steam. Therefore, will estimate the energy available as steam by measuring the steam temperature and the volume of condensed steam during reactor operation.

The performance period was three months from the project's contract approval date.

Prior to the submission of a statement of work, ORNL executed a nondisclosure agreement[2] with Photech regarding proprietary specifications on the construction of their apparatus and information for operating the apparatus. Accordingly, this report does not discuss aspects of the apparatus that Photech deems to be proprietary to their invention.

3. EXPERIMENTAL SETUP

We evaluated several configurations of prototype reactors, the principle differences between the configurations being the material of construction for the outer cylinder of the reactor and the number of anodes. Some reactors had a clear plastic outer cylinder while others had one made from stainless steel. The testing was done using a non-metallic cathode (negatively charged electrode where hydrogen is liberated during electrolysis) with the exception of one brief test done using a makeshift stainless steel electrode. A vertically oriented clear plastic tube, concentric with the outer cylinder, collected hydrogen produced at the cathode. The lower portion of the tube was partially immersed in the electrolyte such that its lower end surrounded the upper portion of the cathode. There was a gap between the bottom edge of the tube and the top surface of the plastic fixture on which the cathode was mounted. The upper end of the tube was connected to a port at the top of the reactor. The opening between the fixture and the end of

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[2] UT-Battelle Nondisclosure Agreement (NDA) No. 7901, effective date December 19, 2006.

the tube, as well as holes bored in the tube wall, allowed ions to be exchanged between the electrodes. A few test runs were done without the hydrogen collection tube in place, but no measurements of gas flow rates were done in these instances because the flow meter cannot accurately measure flow rates in a gas mixture without knowing the viscosity of the mixture.

During the tests the potential and current were measured at the electrode connections on the reactor and the input powers were calculated from these values. A Fluke model 87 III digital multimeter with 0.05% DC voltage accuracy was used to measure the potential between the electrode connections, and a Fluke model 337 clamp-on meter with 2% DC current accuracy was used to measure current flowing between the electrodes. The gas produced at the cathode during electrolysis bubbled up through the electrolyte in the vertically oriented plastic tube, emerged from the surface of the electrolyte in the tube, passed by convection up through a port at the top of the reactor, and flowed through a tap water-cooled condenser. The condenser was present to remove as much water vapor as possible from the gas stream so the flow measurements would not be adversely affected. The gas emerged from an orifice at the top of the condenser and passed through a short through run of ¼" stainless steel tubing into an Alicat Scientific gas flow meter model M-20SLPM-D/5V that was factory calibrated for hydrogen flow measurements. The flow meter had a specified accuracy of ±0.1 liters per minute (LPM) in the range 0-20 LPM. The flow tube in the meter was heated to a temperature of about 40°C to prevent water vapor from condensing inside the tube and altering the accuracy of the flow measurements. Prior to flow measurements in the reactors, we bubbled a calibrated Ar flow through a water bath to humidify the gas and then measured the resulting flow to test the affect of moisture on the flow measurements. We found that the flow measurements were accurate within the specification of the meter. Flow meter measurements were logged on a laptop PC using National Instruments' LabVIEW® software. To enable mass spectroscopy measurements, we installed a tee and a three-way valve in the tubing running from the condenser to the flow meter. This allowed us to insert a capillary tube into the gas stream to sample the flow before it entered the flow meter. The gas sampled in the capillary tube was drawn into a residual gas analyzer (RGA) used as a mass spectrum analyzer to measure the concentration of atomic and molecular species present in the gas stream. We monitored the electrolyte temperature in the volume of liquid above the anodes with a type K thermocouple connected to an Omega digital readout.

We used arc welding power supplies provided by Photech and a Sorensen programmable DC power supply to provide power for the electrolysis. The programmable supply was an ORNL instrument.

Figure 1 is a photograph of the apparatus setup during testing of one of the reactors.

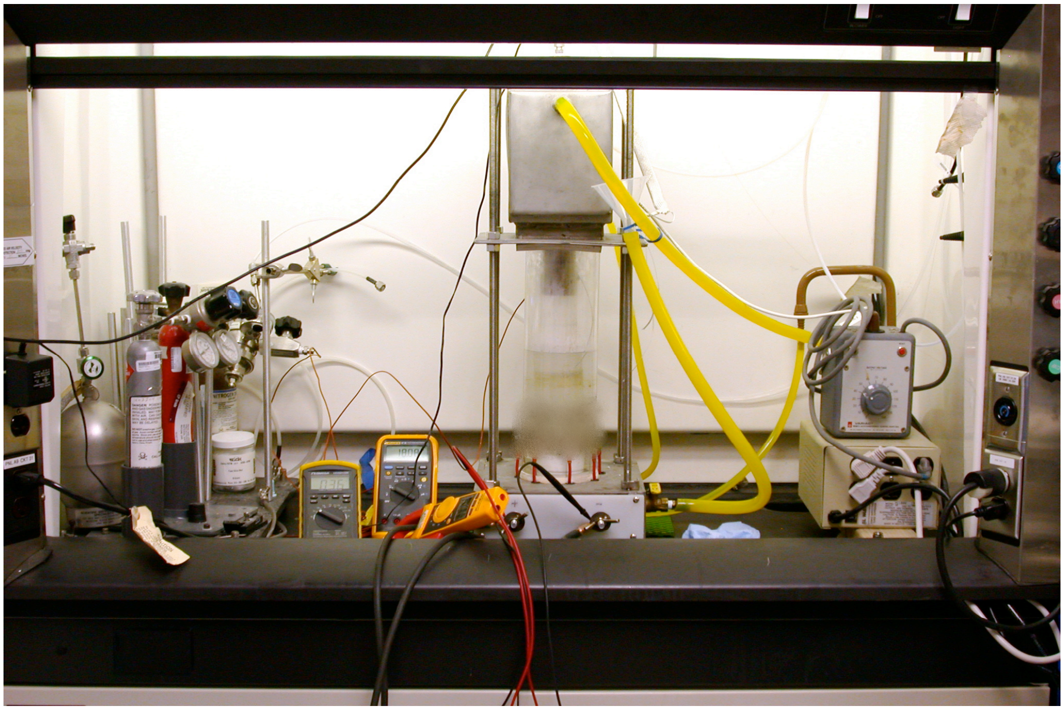

Figure 1. Photech prototype reactor with clear plastic outer cylinder situated in the ventilation hood where the measurements were carried out. The Alacat Scientific gas flow meter mounted on the condenser is above the hood opening and out of view. The image of the electrodes has been blurred to protect proprietary aspects of the configuration.

4. RESULTS

The initial prototype reactor that Photech provided for evaluation was a version with a stainless steel outer cylinder. Phototech furnished a 50-ampere (50-A) welding power supply to run the reactor, but we were unable to use this supply because it required 50-A electrical service that was not available in the laboratory. We used a 40-volt, 100-A programmable DC power supply we had on hand for the input power. We were unable to make measurements of hydrogen flow during this initial demonstration because the gas flow meter supplied by Photech was not operating properly and the plumbing for our Alicat meter was not readily adaptable to the plumbing connection at the cathode port at the top of the reactor. We deduced that hydrogen was being produced during reactor operation through the use of Photech's explosive gas detector, which indicated a 100% concentration of flammable gas at the port above the condenser.

A few weeks later Photech delivered another version of the reactor and a replacement welding power supply. This prototype reactor (plastic reactor #1) had a clear plastic outer cylinder that enabled us to observe the electrolyte and electrodes during its operation. The replacement power supply was a Lincoln Electric model V275-S arc welding power supply. Photech demonstrated that the reactor could be operated for short periods in a mode where bright flashes of light emanated from around the cathode.

We measured the production of gas at the cathode (hydrogen) port as a function of input power using electrolyte concentrations of 5, 10 and 20% in distilled water. The results are plotted in Figure 2 and displayed in Table 1.

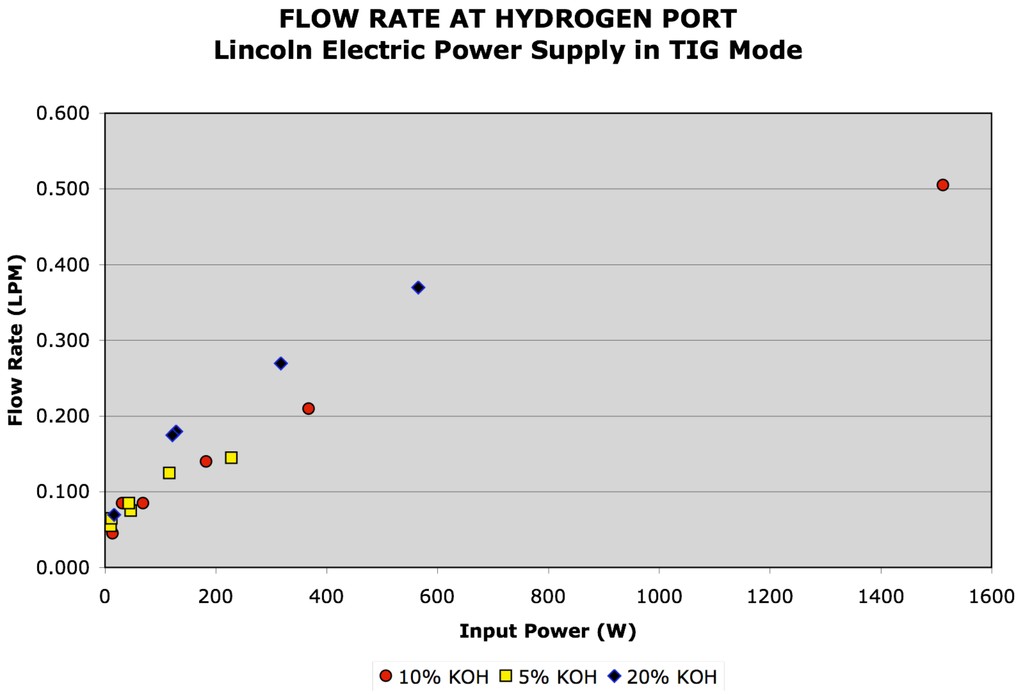

Figure 2. Volumetric flow rate of gas produced at the cathode of plastic reactor #1 as a function of input power and with three electrolyte concentrations. The Lincoln Electric power supply was used for all of the measurements.

The maximum volumetric flow rate of 0.51 liters per minute (LPM) occurred on the one occasion we were able to get the Lincoln Electric power supply to operate at an output control setting of 200 (1510 W input power). The Lincoln Electric power supply was taxed by the discharge conditions in the reactor at input powers above 600 W, causing it to go into a thermal-shutdown fault mode. The next highest flow rate was 0.37 LPM at 565 W input power. The flow rates at given powers were larger when the reactor ran with the 20% solution, and there was no discernable difference in flow rates with the 5 and 10% solutions. The flow rate rolled off as we increased the input power. We were not able to initiate the mode where bright flashes of light appear at the cathode.

Table 1. Parameter values measured in the flow rate versus input power curve for plastic reactor #1 shown in Figure 2. The measurements are organized by electrolyte concentration. A — indicates an instance where a parameter could not be measured.

Output Setting	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)	Flow Rate (LPM)
5% KOH					
5	8.49	1.2	10.2	37	0.06
15	16.5	2.8	46.2	37	0.08
40	15.98	2.7	43.1	38	0.09
95	25.26	4.6	116.2	38	0.13
150	34.04	6.7	228.1	39	0.15
200	—	—	—	—	—
5	8.09	1.4	11.3	51	0.07
10% KOH					
5	8.03	1.7	13.7	27	0.05
15	6.68	4.6	30.7	28	0.09
40	15.91	4.3	68.4	30	0.09
95	24.63	7.4	182	—	0.14
150	32.80	11.2	367	39	0.21
200	60.0	25.2	1510	72	0.51
20% KOH					
5	6.42	2.5	16.1	35	0.07
15	15.46	8.3	128.3	37	0.18
40	14.95	8.1	121.1	38	0.18
95	23.12	13.7	316.7	40	0.27
150	29.75	19.0	565.3	47	0.37

Photech subsequently replaced the Lincoln Electric supply with a Miller XMT 304 arc welding power supply. The Miller power supply worked flawlessly for the remainder of the tests. Furthermore, the Miller power supply enabled us to occasionally initiate the bright flashing mode. Figure 3 shows a graph of measurements made with the plastic reactor using the Miller power supply. The measurement data is tabulated in Table 2. For these measurements the input power was quickly stepped through a succession of input powers until the input current was just above 30 A. At this current setting the bright flashing mode began, and the power supply circuitry struggled to maintain regulation of the voltage and current. The flow rate decreased rapidly during the approximately 30 seconds that the reactor operated in the flashing mode. The maximum flow rate of 0.75 LPM occurred when the input current was above 30 A (input power unknown). The second highest flow rate was 0.62 LPM at 1077 W input power.

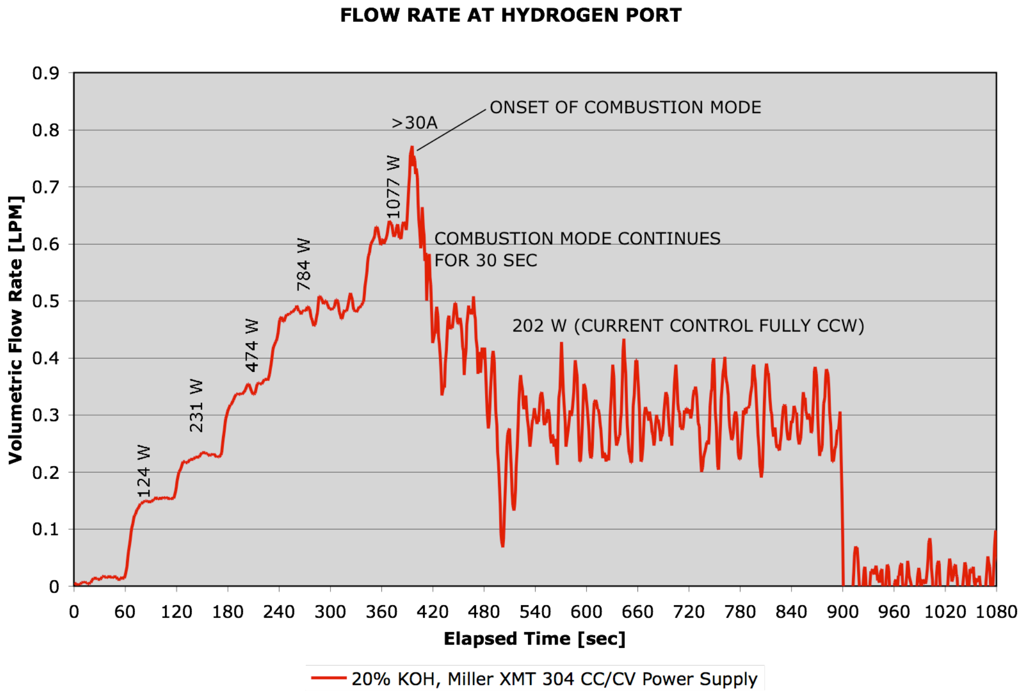

Figure 3. Volumetric flow rate of gas produced at the cathode of plastic reactor #1 as a function of input power. The input power levels are indicated above the flow curve. The combustion mode began after the input current was increased from 26.8 A to a value slightly above 30 A. All results were obtained using the Miller power supply.

Table 2. Parameter values measured in flow rate versus input power curve for plastic reactor #1 that is shown in Figure 3. A — indicates an instance where a parameter could not be measured. Between 180 and 530 seconds the thermocouple meter indicated erratic, unrealistic temperature readings.

Elapsed Time (s)	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)	Flow Rate (LPM)
60-120	17.4	7.1	124	24	0.15
120-180	22.6	10.2	231	24	0.22
180-240	31.0	15.3	474	—	0.35
240-340	37.5	20.9	784	—	0.49
340-380	40.2	26.8	1077	—	0.62
400	—	>30	—	—	0.75 (peak)
530-880	16.4	12.3	202	88-90	0.2-0.4

Figure 4 shows a graph of flow rate versus input power in the same apparatus. We produced the flashing mode by stepping quickly from the initial (minimum) input power. Table 3 displays the measurement data. The flashing mode lasted about 30 seconds, during which time we again observed a rapid decrease in flow rate. The flow rate continued to decrease after the cessation of the flashing mode even though the input power remained constant.

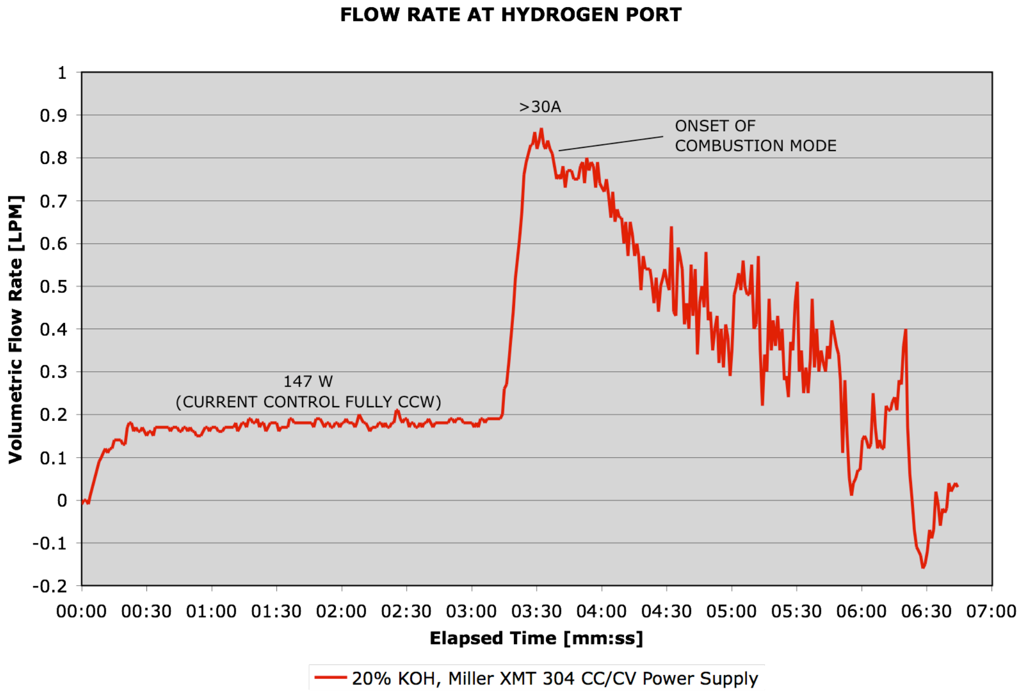

Figure 4. Volumetric flow rate of gas produced at the cathode port of plastic reactor #1 as a function of input power. The combustion mode began as soon as the current was ramped from 8.6 A to >30 A, and it persisted for about 16 seconds. The results were obtained using the Miller power supply.

Table 3. Parameter values measured in flow rate versus input power curve shown in Figure 4. A — indicates instance where a parameter could not be measured.

Elapsed Time (mm:ss)	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)	Flow Rate (LPM)
0:30-3:00	17.1	8.6	147	35	0.17
3:25-3:41	—	>30	—	100	0.85-0.75

We used the mass spectrum analyzer to determine the composition of the gas flowing from the cathode port in the reactor. Figure 5 shows flow rate measured during the analysis. We ran the test for more than 2.5 hours in an attempt to purge the ambient (atmospheric) air from the reactor and reach a steady state concentration of the gases present due to electrolysis. (We were never completely successful in purging the reactor. This is discussed in the following paragraph.) The Miller power supply current control was at its lowest setting (turned fully ccw) during the test and it provided a constant input power of approximately 140 W. The temperature of the electrolyte increased steadily even at this low power, and at the end of the test it had reached a value just below 100°C. The average flow rate during the test was 0.2 LPM. The test ended when the plastic outer cylinder deformed slightly due to the heat and the electrolyte leaked from the reactor.

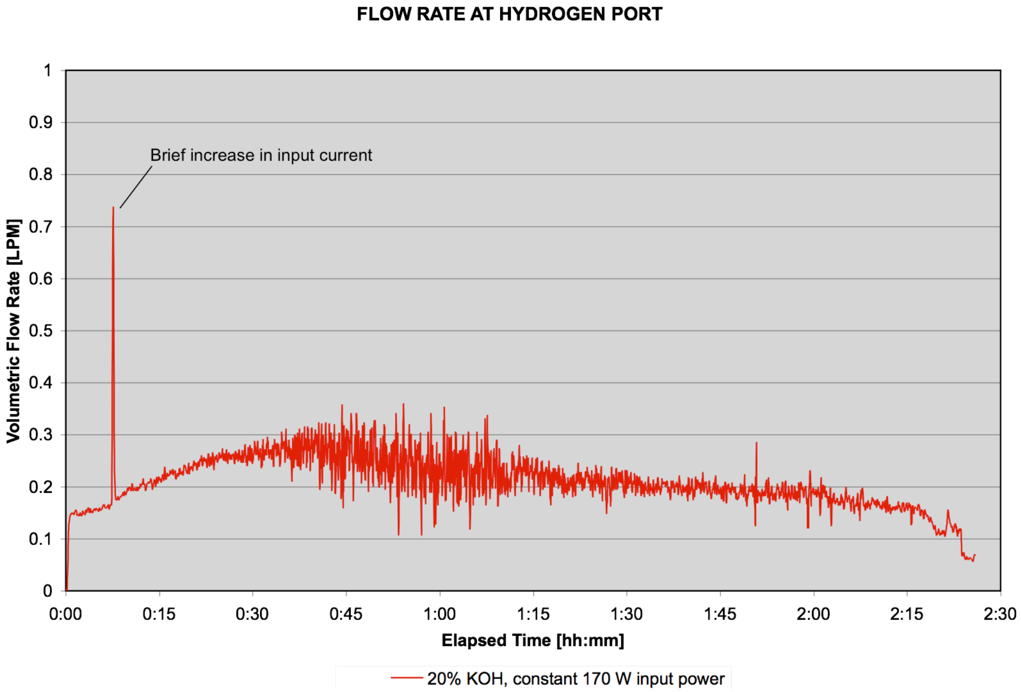

Figure 5. Volumetric flow rate of gas at the cathode port of plastic reactor #2, measured as a function of elapsed time from the initial application of a constant input power. The input power was the minimum possible input from the Miller power supply. The flow rate values recorded by the flow meter have not been corrected for the error introduced by the presence of oxygen, water, and nitrogen gases that were present in the flow. These gases affect the indicated flow values because their viscosities are different from that of hydrogen.

Table 4. Parameter values measured in flow rate versus input power curve shown in Figure 5. A — indicates instance where a parameter could not be measured.

Elapsed Time (hh:mm)	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)	Flow Rate (LPM)
0:02-0:07	17.0	8.5	145	30	0.15
0:07-0:09	—	>30	—	40	0.75
0:09-2:15	17.0	9.9	168	40-90	0.10-0.35

The composition of the flow at the end of the test, determined by mass spectroscopy, was 83% H_2, 6.7% N_2, 4.1% O_2 and 5.8% H_2O. The presence of N_2 in the flow indicates that some air was re-entering the reactor, probably through the anode (O_2) port but possibly through the flow meter as well since the flow rate was low. To correct for the contributions of N_2 and O_2 from the air, we assumed all the N_2 was attributable to air and ¼×6.7% of the detected O_2 was attributable to air since the ratio of N_2 to O_2 in air is approximately 4 to 1. Therefore, the concentration of non-atmospheric O_2 in the stream was approximately 2.4%. Normalizing the concentration of the remaining constituents to sum to 100%, we arrived at the following gas species concentrations in the flow: 91% H_2, 3% O_2, and 6% H_2O.

The third prototype reactor had a stainless steel outer wall. Its dimensions were nearly identical to the plastic-wall reactor. As received it was missing an exit port for the gas produced at the anodes, so we bored a hole near the top of the outside wall and installed a bulkhead tubing fitting to allow gas to escape. When we ran the initial test of the reactor we detected no flow at the hydrogen port, even at an input power of 1000 W. We then plugged the anode port momentarily and observed an immediate increase to 0.80 LPM flow at the hydrogen port. From this observation we deduced that very little hydrogen was actually being produced at the cathode. With input power applied to the electrodes, we measured the potential between the anode and the steel wall of the reactor and found that the wall was energized to a potential that was a mere 2.3 V below the potential on the anodes! With the wall thus energized, it was apparently functioning as the *de facto* cathode and hydrogen was being produced at the wall rather than at the center cathode. Since the hydrogen and oxygen were mixed in the space above the electrolyte in the anode region of the reactor, it was impossible to separate the two gases to determine the amount of hydrogen produced by the reactor.

The final reactor prototype was a plastic wall reactor with additional anodes. This reactor had the same outside diameter but it was a few inches shorter in length. To allow the center tube to fit in this shorter reactor we reduced its length by cutting it. We cut the tube so the gap between top of the cathode fixture and the bottom of the tube was the same as in the original reactor. This reactor was also missing an anode gas port, and we again bored a hole and installed a tubing fitting near the top of the cylinder to allow the gas to escape and to allow the insertion of the thermocouple wire. We used a programmable DC power supply (Sorensen model DCR150-18B with a maximum output of 150 V and 18 A) to provide input power to this reactor. Figures 6 and 7 show the flow rates measured with this configuration. In Figure 7, where the graph shows the flow rates measured during gradual increases of input power (not possible when using the welding supplies), there is a distinct change in the slope of the data at 50 W. Below 50 W input, the slope of the flow rate versus input power curve was 4 times larger than it was at higher powers. The onset of hydrogen production, as determined by the observation of a faint stream of bubbles emanating from the cathode, occurred at about 1.4 V potential between the electrodes. The production of hydrogen at this minimum power was too small to be detected by the flow meter. The measurements shown in Figure 7 are tabulated in Table 6.

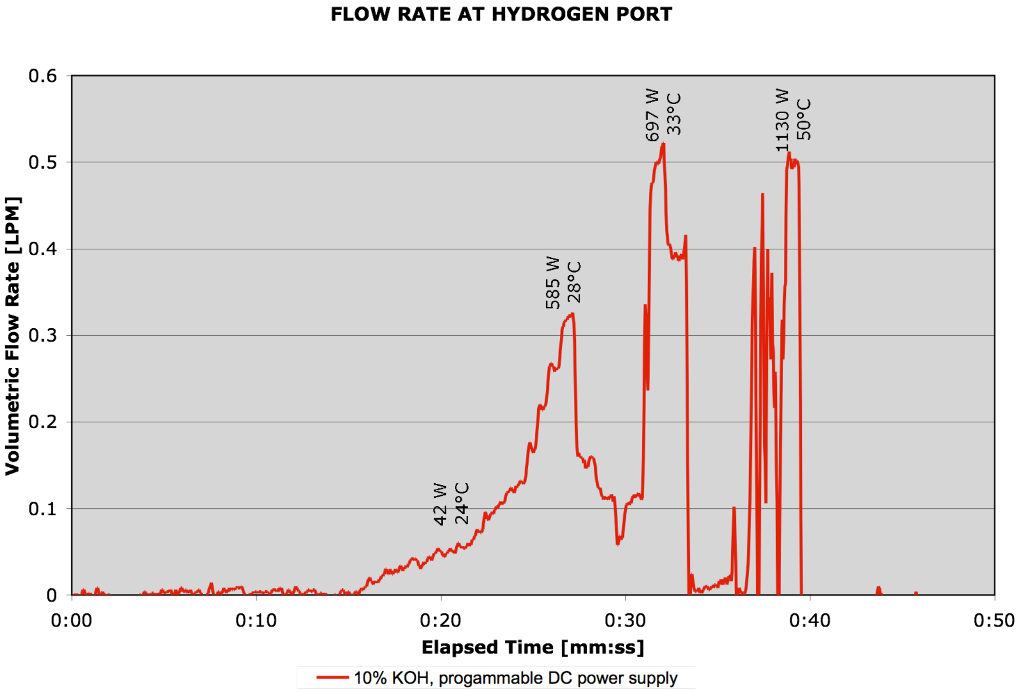

Figure 6. Volumetric flow rates measured at the cathode port of the plastic reactor #2, measured as a function of elapsed time from the initial application of a constant input power. The input power was the minimum possible input from the Miller power supply.

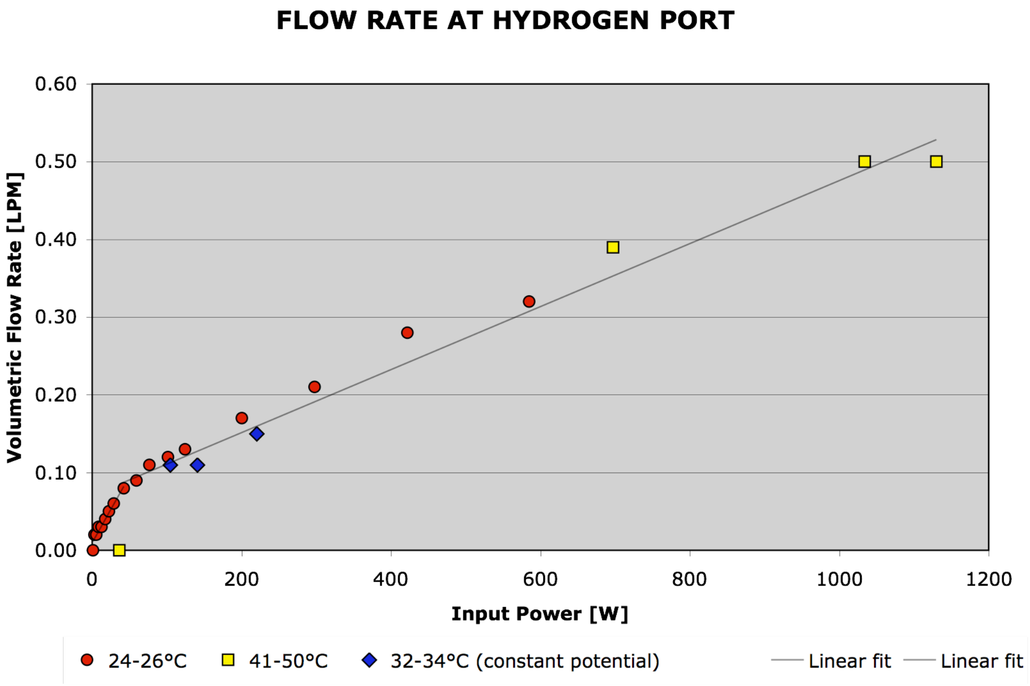

Figure 7. Volumetric flow rate measured as a function of input power in plastic reactor #2. The electrolyte concentration was 10%. Separate linear fits to the data are shown for the low power (<50 W) region and the higher power region.

Table 5. Parameter values measured in flow rate versus input power curve shown in Figures 6 and 7.

Graph Legend	Elapsed Time (mm:ss)	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)	Flow Rate (LPM)
🔴	0:01	3.01	0.4	1	24	0.00
🔴	0:02	4.00	0.7	3	24	0.02
🔴	0:05	5.01	1.1	6	24	0.02
🔴	0:08	6.03	1.4	8	24	0.03
🔴	0:12	6.97	1.8	13	24	0.03
🔴	0:15	8.00	2.2	18	24	0.04
🔴	0:18	9.00	2.5	23	24	0.05
🔴	0:20	10.00	2.9	29	24	0.06
🔴	0:21	12.02	3.5	42	24	0.08
🔴	0:22	14.03	4.2	59	24	0.09
🔴	0:22	15.90	4.8	76	24	0.11
🔴	0:23	18.08	5.6	101	25	0.12
🔴	0:23	20.04	6.2	124	25	0.13
🔴	0:24	25.00	8.0	200	26	0.17
🔴	0:25	30.08	9.9	298	26	0.21
🔴	0:26	35.15	12.0	422	28	0.28
🔴	0:27	40.35	14.5	585	30	0.32
🔷	0:28	25.03	8.8	220	32	0.15
🔷	0:30	20.06	7.0	140	33	0.11
🔷	0:30	17.40	6.0	104	34	0.11
🟨	0:31	50.70	20.4	1034	37	0.50
🟨	0:31	41.00	17.0	697	41	0.39
🟨	0:32	45.20	25.0	1130	50	0.50

The final measurement performed was an analysis of the hydrogen concentration in the gas flow from the plastic wall reactor with the additional anodes. We powered the electrolysis reaction with the

Miller power supply, using the lowest possible input power to minimize the rate at which the electrolyte temperature increased. Table 6 displays the voltage, current and input power values during the test.

Table 6. Change in input power to the reactor during the gas composition analysis. The Miller power supply remained at its minimum setting, but input power increased 62% during the 87 minute long test.

Elapsed Time (min)	Input Potential (V)	Input Current (A)	Input Power (W)	Temperature (°C)
0	18.4	5.0	92	21
15	18.1	5.7	103	34
44	17.6	7.0	123	56
76	17.3	7.7	133	77
85	17.3	8.6	149	80
87	(1.46)	0	0	81

The input power increased about 60% during the 87 minute-long test period, despite the fact that the Miller power supply remained set at its minimum output. The steadily increasing temperature in the electrolyte solution was probably responsible for the upward drift in input power because the conductance of the solution increases with temperature, allowing more current to flow between the electrodes while the potential remained nearly constant. The magnitude of the increase in power was actually relatively small—less than 60 W—so we neglected the changing input power in our analysis of the gas composition.

We installed a backflow preventing valve on the anode gas port to prevent atmospheric gas from entering the reactor and we purged the reactor with argon for about 30 minutes before beginning the measurements.

The experiment ran until the electrolyte solution reached a temperature of about 80°C, at which point we became concerned about deforming the cylinder and we stopped the measurement. Figure 8 shows the evolving concentrations of hydrogen, water vapor, oxygen and carbon dioxide in the gas flow from the cathode port. (The dashed lines connect discontinuities in the curves that occurred when we experienced an instrumentation problem in the interval 19 to 43 minutes, resulting in the loss of measurement data in that interval.) The concentrations of H_2, H_2O and O_2 are presented in units of mol %

(mol % = moles of a particular gas in proportion to the total number of moles of all gas species in the flow, expressed as a percentage). The mol % scale is on the left-hand *y*-axis. The concentration of CO_2 is presented in parts per million (ppm) and this scale is on the right-hand *y*-axis. The electrolyte temperature is also shown on the graph; its scale in °C is on the right-hand *y*-axis.

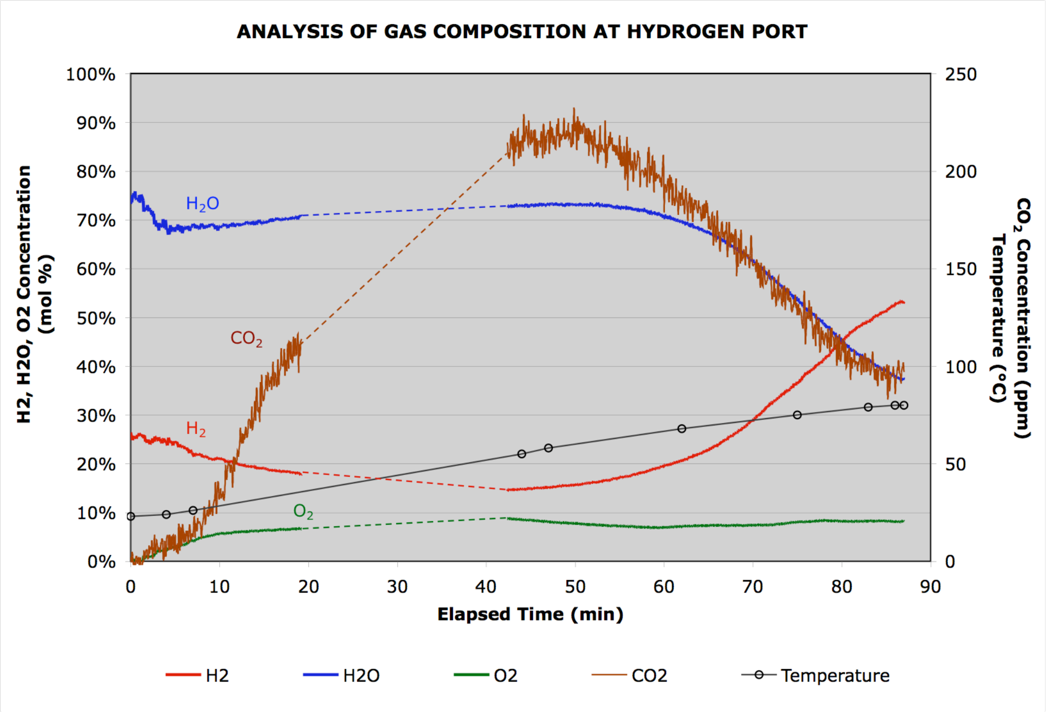

Figure 8. Time-dependent concentrations of H_2, H_2O, O_2 and CO_2 in the gas flow from the cathode port. The electrolyte temperature is also shown on the graph. Dashed lines represent the interval during which an instrumentation problem caused a loss of data.

The concentration of H_2 in the flow was initially 25 mol %. The H_2 concentration decreased slightly to a value of 15 before increasing to 53 at the end of the measurements. The concentration of water vapor was surprisingly high throughout the measurements, starting at a value of 75 mol % and decreasing to 37 mol % by the end. The concentration of O_2 was initially zero but within 30 minutes it rose to just under 10 mol % and remained there for the duration of the measurements.

The presence of the water vapor is likely due to recombination of hydrogen and oxygen near the cathode. This is evidenced by the close correlation between the increase in H_2 and the decrease in H_2O that began in the 40 to 50 minute interval. Remarkably, the rapid turnover in increasing CO_2

concentration occurs during this same interval. The origin of the CO_2 is puzzling, although it might be attributable to reactions between the cathode and oxygen dissolved in the electrolyte solution.

Figure 9 shows the flow rate during the concentration measurements. The red curve is the indicated flow rate data, uncorrected for the error introduced by the large concentrations of gas species other than hydrogen in the flow. The flow meter calculates the volumetric flow rate using the Poiseuille relationship, which relates the flow rate in a gas to the pressure drop the gas experiences as it flows through an orifice. In the Poiseuille relationship the volumetric flow rate is inversely proportional to the viscosity of the gas. At temperatures near 25°C, hydrogen has a lower viscosity than water vapor or oxygen or carbon dioxide. This means that the indicated flow, determined using the viscosity of hydrogen, is larger than the actual flow of the mixed gases.

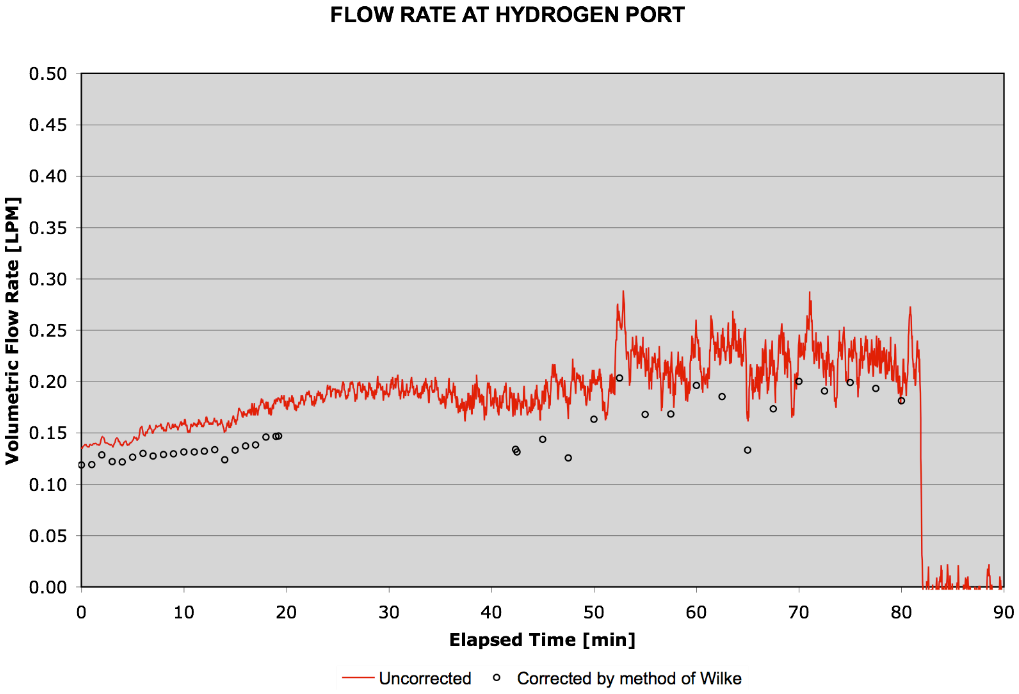

Figure 9. Volumetric flow rate measured at the cathode port during the gas concentration measurements (solid red line). The rates were corrected using the concentration values of gas species in the mixed gas flow and the method of Wilke (open circles).

Correcting the flow values in Figure 9 required a knowledge of the viscosities of the mixed gases during the measurement time. This was done by using the concentrations shown in Figure 8 to calculated the viscosity of the gas mixture by the method of Wilke.[3] This was done for the indicated flow rate measurements, and the corrected flow rate values are shown as open circles in Figure 9. The corrected flow rates are 15 to 20% lower than the indicated rates.

5. DISCUSSION OF RESULTS AND RECOMMENDATIONS

Measurements of the flow from the cathode port in the clear plastic prototype reactors indicate that the flow is comprised of a mixture of hydrogen, water vapor and oxygen. When operating the original plastic wall reactor at low input power, we found that the flow composition was approximately 91% hydrogen, 3% oxygen and 6% water vapor. When operating the reactor with the additional anodes, the flow composition was primarily water vapor, with hydrogen concentrations ranging from 25 to 53 mol %. The concentration of oxygen was below 10 mol %. Carbon dioxide was also present in the flow, and its concentration increased to a maximum of just under 225 ppm before decreasing to just under 100 ppm. There was a strong correlation between the concentrations of water vapor and hydrogen: a decrease in water vapor corresponded very closely to an increase in hydrogen. The concentration of contaminants such potassium in the flow was below the level of detection.

The presence of oxygen in the flow is likely due to oxygen at the anodes migrating toward the cathode and bubbling up through the center tube. The electrolysis produces a vigorous bubbling action in the electrolyte that could enhance oxygen diffusion through the solution. The center tube does not adequately suppress migration of gases between the electrodes. It is also possible that oxygen is being produced at steel screws in the plastic fixture on which the cathode is mounted, and this oxygen bubbles up into the center tube.

Most of the water vapor present in the flow can be attributed to the recombination of hydrogen and oxygen at the cathode. Some of the water vapor might be attributable to the humidification of hydrogen and oxygen bubbles as they rise from the cathode to the surface of the electrolyte. The tap water-cooled condenser was not capable of condensing all the moisture present in the gas flow.

In both versions of the clear plastic reactor, the production of hydrogen, indicated by volumetric flow of gas from the cathode, increases monotonically with increasing input power. In the reactor with

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[3] C. R. Wilke, "A Viscosity Equation for Gas Mixtures," J. Chem. Phys. 18 (4), pp. 517-519, 1950.

additional anodes, the flow rate increased much faster at low input powers than it did at the higher input powers. The demarcation point between flow rate increases was near 50 W of input power. The rate increased about 4 times faster at low input power than it did at high input power. This could be an indication that the electrode configuration is not optimized for higher currents or input powers.

The two parts of the plastic mount for the cathode were fastened together with steel cap head screws. The screw heads are exposed to the electrolyte and they are in close proximity to the cathode. We observed bubbles emanating from screw heads when the reactor was operating. The screws are electrically isolated from the electrodes, but since gas is being produced there must be some conduction of charge to the screws. Without knowledge of the ion flow and the electrical potential of the screws it is not possible to predict whether the screws are producing hydrogen or oxygen.

The reactors can sometimes operate in what might best be described as "combustion mode," where bright flashes of light emanate from the volume surrounding the cathode. This transient mode was initiated shortly after the reactor was turned on, before the temperature rise was significant, and at an input power of just above 1000 watts. The combustion mode was characterized by recurrent flashes of bluish-white light near the midpoint of the cathode and by an especially violent bubbling around the cathode. The mode persisted for about 30 seconds before it decreased in intensity and was quenched. Once the flashing stopped it was not possible to restart the combustion mode until the electrolyte cooled to near room temperature. Since the hydrogen flow rate decreased upon the onset of this mode and bright flashes are present, it's plausible that the phenomenon was caused by the combustion of hydrogen and oxygen in the electrolyte solution near the cathode. Oxygen generated either at the anodes or at the cap screws in the plastic mount diffused through the electrolyte, came into contact with hydrogen near the cathode surface, and the elevated temperature, intense ion current and high potential created conditions in which combustion could occur. The transient nature of the mode and its eventual quenching can possibly be attributed to the rapidly increasing temperature in the electrolyte: at some point the temperature is too high to allow the combustion conditions to continue.

The prototype reactors with the stainless steel outer wall reactor operate much differently than the plastic (non-conducting) wall reactors. With the hydrogen collection tube in place in the reactor, no flow was detected at the hydrogen output port, while there was considerable flow at the anode (oxygen) port. Furthermore, the stainless steel wall became energized at a potential just a few volts below the potential on the anodes. It appears that hydrogen was produced at the wall and the hydrogen then mixed with the oxygen produced at the anodes. The energized reactor wall was thus supplanting the cathode, preventing the production of hydrogen below the center tube. This phenomenon prevented us from analyzing the composition of the hydrogen product flow since we could not separate the hydrogen from the oxygen in the gas flow at the anode port.

The reactors need a better method for maintaining separation of the gases produced at the cathode and anodes. The holes drilled at the base of the plastic center tube are large in diameter and they are situated such that there is a direct line-of-sight between the anodes and cathode; this allows gas to migrate easily from one electrode to the other. A glass frit or Kevlar fabric might be configured to allow ions to pass while reducing the ability of gases to mix.

At high input powers, typically above 500 watts input, the temperature rise in the reactor is rapid. This temperature rise increases the conductance of the electrolyte solution, causing difficulties for the power supply's regulation of voltage and current. Some method for recirculating the electrolyte between the reactor and a reservoir could slow the temperature rise in the reactor.

The tap water-cooled vapor condenser did not have a significant effect on reducing the moisture content of the hydrogen gas product. The bubbling hydrogen will reach a saturation point (100% relative humidity) that corresponds to the temperature of the electrolyte solution. A refrigerated condenser might chill the gas mixture below its dew point, thereby removing a larger portion of the moisture.

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