Final Scientific Report

Project Title: Georgetown South Commercial Park Photovoltaic (PV) Generation Facility
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Working Partners: Texas Life-sciences Collaboration Center (TLCC)
Peterman Consulting Associates LLC (PCALLC)
Southwestern University
Quantum Logic Devices (QLD)
Georgetown Rail Equipment Company (GREX, Inc.)

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Project Objectives: This projects primary objective was to complete the design and installation of a nominal 10kW peak-power grid-connected solar PV system at the TLCC facility.

A second objective was to create community educational materials and seminars for incorporating and using PVs in commercial and community applications and to host a summer intern student over the summer period of 2011 as part of this grant.

The third objective included two R&D tasks to enhance the efficiency of solar PV and novel methods to develop solar photo-chemical oxidation techniques to minimize electric power consumption and to maximize indoor air quality within biotech facilities such as the TLCC.

Summary of Project Results

This project facilitated the design and construction of a commercial grid-tied PV system, the first of its kind for the City of Georgetown. The final system generates nominal 10kw of peak power and is in continuous use at the TLCC, a non-profit technology incubator partially funded by the City of Georgetown.

This project was completed successfully and a software dashboard was developed in conjunction with Enphase Energy, the company that was the supplier of the solar panel micro-inverters. This dashboard can be viewed at <https://enlighten.enphaseenergy.com/public/systems/3Wg83097>.

From the data available we show that since inception, this system has generated over 23 Mwh of electrical energy thus offsetting about 16 tons of carbon that was offset to generate the power.

Significant Accomplishments:

All scientific and commercial goals for this project have been met.

- PV System Installation and Testing is Complete
- Internships are complete
- R&D tasks are complete.

Status of Tasks:

Task I: Install Solar PV System

- The PV system has been installed, tested, and accepted. A total of 51 solar panels are active with 27 230W Schott panels being added with this project. There were previously 24 Sharp 180W active panels installed by the City of Georgetown in a pilot phase of the project.

Task II: Provide Pubic Communications and Educational Materials Including Internship

- The project team produced community educational materials to promote public understanding and information on the use of PV within the local community;
- A public rollout of the system was conducted on September 28, 2011 and included Congressman John Carter, T-31 as one of the speakers.
- This project supported a Southwestern University intern student over the summer period of 2011. His final report of the internship was submitted to the City of Georgetown.

Task III: R&D Tasks

- a) Conduct R&D subtask to increase the efficiency of novel PV storage is complete;
- b) Conduct R&D subtask to prototype PCO techniques and devices is complete;

Scientific reports for these two R&D subtasks were submitted to the City of Georgetown by the TLCC and are available upon request.

Patents:

Patent disclosures may be prepared for proprietary PowerCell and SolarIAQ techniques in follow on work. During the period of this grant, no patents or patent disclosures were filed.

Publications/Presentations/Travel: A public presentation was conducted during a press conference on September 28, 2011 at the TLCC facility.

Status Summary Tables:

Task (T) or Deliverable (D)		Task Title	Planned Completion % Complete	
1	T	4kW pilot system and 10kW final system	9-15-11	100%
2	T	Community educational activities / Internship	9-15-11	100%
3	T	R&D subtasks to increase the efficiency of novel PV and PCO techniques and devices	9-15-11	100%
4	T	Project Management and Reporting	Periodic	100%
4	D	Project reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist	As Required	100%

Final Installation of Commercial PV System at TLCC

Photo of Grid Tie-point Between TLCC Service Power and PV Power System

Attachments:

TLCC DOE Power Cell Report

TLCC PCO Techniques Report

2011 Summer Internship

(Texas Life-Sciences Collaboration Center)

My Texas Life-Sciences Collaboration Center (TLCC) internship began with an introduction to the business of TLCC a summary of objectives for the summer and introduction of TLCC's personnel. TLCC is an organization whose board of directors include but are not limited to the mayor of Georgetown, Texas, the head of Georgetown's chamber of commerce, Georgetown's chief of economic development and the executive advisor to the president of Southwestern University. The Purpose of TLCC is to actively lobby bio-technology companies already existing in other regions to consider a re-location to Central Texas, to encourage the start-up of bio-technology companies in central Texas, and to provide a location or locations for bio-technology companies to develop and function.

My initial objective for the summer internship was to develop, maintain and automate or perfect the acquisition of weather, solar, and energy-use data in Georgetown, Texas for the purpose of analyzing the feasibility of providing incentives for commercial use of solar panels in the Region. As time passed and I met or satisfactorily pursued objectives more were added.

These objectives include developing, maintaining and automating or perfecting the acquisition of weather data on rabbit hill for the purpose of analyzing the feasibility of the use of wind turbines in Georgetown, placing the integrated sensor suite at the TLCC office in a more advantageous position, working with the city of Georgetown to acquire energy use data for analysis, acquiring a new computer for use on the solar and wind projects, assisting a UT graduate student in building a humidifying system for an experimental PCO reactor, writing an analysis for the U.S. debt ceiling and the U.S. debt growth, running the front desk and responding to calls, as well as helping prepare for the fourth of July celebration at TLCC.

Besides working on these objectives TLCC interns were invited to listen to speakers from fields as divergent as UT physics graduate students on the development of the early universe its rate of expansion and what that means for understanding the precise relationship between matter and gravity, R.G. Converse of Fulbright & Jaworski L.L.P. attorneys at law whose firm brokers commercial deals in central texas and who was present at the successful attempts by which Texas attracted the semi-conductor industry, and Amy Stansbury of Stansbury public relations who spoke not only on her founding of her company but the means and caveats of her profession of developing relationships between firms and the public through media, as well as important ways to get experience and perspective on company building early.

Of my time at TLCC I specifically found the perspectives I got in my relationships and the experience I got from forging those relationships with contractors, physicists, graduate students, lawyers, professionals, bio-chemists, politicians, entrepreneurs and industry veterans as immensely beneficial and most certainly a benefit to my capacity as an economics major, and future economist.

Introduction

Much current effort is directed at alternatives to fossil fuels as energy sources. Aside from solar, wind, and various thermal conversion technologies, fuel cells have generated interest due to their reliability and portability. In general, solar and wind resources suffer from large infrastructure requirements and intermittent generation cycles due to their natural variability. Thermal technologies, such as solar powered Stirling generators or thermoelectric cells are either limited by the natural solar variability or the use of fossil-fuels as heat sources. (Waste-heat generators have been limited so far to large installations that generate significant thermal excess.) Batteries are still the primary source of portable power for many applications due to their simple system requirements and possible high power densities. For certain battery chemistries the reversal of oxidation-reduction reactions using an external

power source allows for “recharging” to restore utility and extend system lifetimes. Usually this means connection of the battery to solar, wind, or mains power for extended storage of energy.

This project explores the concept of battery chemistries that are thermally reversible, specifically by solar radiance. Of particular interest are “air battery” couples that consist of metal oxides that might be used as regenerable cathodes. If successful, such powercells might

provide a complement to photovoltaic (PV) technologies and generate power during darkness when PV units are inactive. The powercell concept is that energy is derived from the oxidation/reduction couple (i.e. battery mode) then the reaction is thermally reversed to restore the powercell for the next cycle (i.e. regeneration mode). A review of the literature finds very few attempts to implement thermally reversible batteries, although a few examples of thermally activated fuels cells exist. Several of the metal oxides have reduction temperatures that might be low enough to implement in the powercell, as shown in Figure 2. Another interesting material, not shown on the Figure, is graphene, which has been reported to be thermally reduced below 500°C. We believe that Fresnel-type solar concentrators can provide sufficient energy for the reduction of nanoscale thin film stacks of useful metal oxides and/or graphene.

Statement of Work

PowerCell Fabrication

Electrodes were fabricated at the University of Texas Microelectronics Research Center using metal deposition tools (e-beam evaporator or sputtering) or electroless/sol-gel type processes. Table 1

summarizes the materials used and their preparation method. The metals were selected based on reported thermal reduction temperatures, current use in metal-air batteries, and low cost. In some cases (steel, Cu, Al), metal foils or plates were used, purchased through local sources. The air-anode materials consisted of activated carbon or graphite or a mixture of the two, with electrical contact made through a small square of aluminum or copper foil, or steel plate.

Table 1 – ELECTRODE MATERIALS

Electrode	Processing Method	Properties
Aluminum	Electron beam evaporator	100nm thick on 2"x3" glass
Copper foil	Purchased	0.005" thickness
Chromium	Electron beam evaporator	100nm thick on 2"x3" glass
Iron	Medium Steel wool	Porous mesh
Silver oxide	Sol-gel deposition of Ag ₂ O from solution of ammoniacal silver	Grain sizes of 50-450nm (determined by AFM); rough granular films
Galvanized steel	Purchased plates	
Aluminum foil	purchased	0.003" thickness
Activated carbon	purchased	Grain size of approximately 1-2mm
graphite	Purchased	Ultra-fine particle lubricant

The cell schematic is shown in Figure 2. The electrolytes utilized consisted of a mixture of calcium oxide/calcium hydroxide/calcium carbonate prepared by mixing the components with distilled water to form a thick paste. This composition was chosen because of the known chemistry of carbon capture/release as well as hydration reactions with water vapor. These reactions have also been shown to mediate thermally activated metal reduction, which is the basis of the PowerCell concept. Activated carbon or graphite pastes were made similarly to form cell anodes.

Powercells were evaluated for energy generation and regeneration over several days/nights, using a

digital multimeter to measure output voltage and current through a ¼ watt, 10 kΩ resistor or 1W LED. Solar concentration was provided using a 100 sq.in. Fresnel lens mounted on a frame. Temperature measurements were obtained using a FLUKE infrared thermometer. The test system is illustrated in Figure 2. The thermal power of the Fresnel was measured to be 74°C for a 3” diameter spot and 180°C for a 1” diameter spot under mid-day sun. As this temperature was considered insufficient for some of the reactions, a butane torch was used to generate higher temperatures when needed.

Results

All PowerCells demonstrated the expected voltage output, as summarized in Table 2. All cells performed as expected with regards to voltage output. However, only the iron and silver chemistries displayed regeneration ability under thermal treatment (torch and solar heating, respectively). Plots of the voltage over time are shown below for these two cells.

POWERCELL SYSTEMS TESTED			
Cell construction	Cell chemistry	Output voltage	Notes
Al-air	Anode: $\text{Al(s)} + 3\text{OH}^-(\text{aq}) \rightarrow \text{Al(OH)}_3(\text{s}) + 3\text{e}^-$ Cathode: $\text{O}_2(\text{g}) + 2\text{H}_2\text{O(l)} + 4\text{e}^- \rightarrow 4\text{OH}^-(\text{aq})$	Calculated 2.06V Measured 1.68V	Failed to regenerate
Fe-air	$\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \leftrightarrow 4\text{OH}^-$ ($E_0 = 0.4\text{V}$) $\text{Fe}_2\text{O}_3(\text{s}) + 3\text{H}_2\text{O} + 2\text{e}^- \leftrightarrow 2\text{Fe(OH)}_2(\text{s}) + 2\text{OH}^-$ ($E_0 = -0.86\text{V}$) $\text{Fe(OH)}_2(\text{s}) + 2\text{e}^- \leftrightarrow \text{Fe(s)} + 2\text{OH}^-$ ($E_0 = -0.89\text{V}$)	Calculated 1.29V Measured 1.18V	Failed to regenerate, but observations suggest possibility at $T > 800^\circ\text{C}$
Cr-air	$\text{Cr}^{3+} + 3\text{e}^- \leftrightarrow \text{Cr(s)}$ ($E_0 = -0.74\text{V}$) $\text{O}_2(\text{g}) + 2\text{H}_2\text{O(l)} + 4\text{e}^- \rightarrow 4\text{OH}^-$	Calculated 1.18V Measured 1.03V	Failed to regenerate
Ag/Ag ₂ O-air	$\text{Ag}_2\text{O(s)} + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{Ag(s)} + 2\text{OH}^-$ ($E_0 = 1.17\text{V}$) $\text{O}_2(\text{g}) + 2\text{H}_2\text{O(l)} + 4\text{e}^- \rightarrow 4\text{OH}^-$ ($E_0 = 0.4\text{V}$)	Calculated 1.57V Measured 1.6V	Able to regenerate

In the case of iron battery regeneration, the iron oxides must be reduced to iron metal. The detailed mechanisms of the chemical system employed for the PowerCell have not been fully elucidated yet, but the materials chosen for construction of this cell are designed to provide for iron reduction via a nanoscale smelting chemistry. This process is outlined as follows:

The thermal decomposition of CaCO_3 eventually results in localized generation (within the paste in contact with the electrodes) of carbon monoxide which proceeds to reduce the iron oxides to metallic iron. Solar-generated temperatures proved insufficient to drive this complex series of reactions, so a handheld butane torch was used to provide heating of the cell (measured temperature $>800^\circ\text{C}$). Figure 3 shows thermal regeneration of a partially depleted iron Powercell. The voltage is restored from approximately 0.85V to 1.15V with 30 minutes of heating.

Figure 3 – thermal regeneration of voltage in Iron-Air PowerCell.

In the silver Powercell, a similar behavior is observed, although the chemistry is certainly different (and as yet not fully understood for this system). It is known that Ag_2O can be thermally regenerated merely by heating without the presence of catalysts, such as CaCO_3 or carbon. From the thermodynamic perspective, this decomposition of silver oxide can be described by:

$$\Sigma \mu : -22.6 < 0$$

$$\text{chemical drive } A : -22.6 \text{ kG}$$

The decomposition does not take place at room temperature due to the negative drive. However, since the reaction product O_2 is a gas, with a strongly negative temperature coefficient α , the process can be thermally driven at sufficient temperature.

Substance	Chemical potential $\mu \cdot [\text{kG}]$	Temperature coefficient $\alpha [\text{G/K}]$
$\text{Ag}_2\text{O} \text{s}$	-11.3	-121
$\text{Ag} \text{s}$	0	-43
$\text{O}_2 \text{g}$	0	-205

The minimum temperature T_D for the decomposition of Ag_2O is obtained from the condition that the combined chemical potentials of the initial and final substances must be equal and the chemical drive A changes sign:

$$A = A^\circ + \alpha \cdot (T_D - T^\circ) = 0.$$

Solving for T_D to obtain

$$T_D = T_0 - A/\alpha$$

Inserting the A° and α values which are calculated according to $\alpha = 2 \alpha_{\text{Ag}_2\text{O}} - 4 \alpha_{\text{Ag}} - \alpha_{\text{O}_2}$ results in $T_D \approx 465^\circ\text{K} = 187^\circ\text{C}$.

In consideration of the electrolyte system chosen for the PowerCell, a few observations regarding the reactivity of silver oxide are salient:

- Silver Oxide absorbs CO_2 from air when the humidity is $> 25\%$. (Normal air contains 249ppm CO_2)
- While absorbing CO_2 , silver oxide turns into the yellow-greenish silver carbonate (Ag_2CO_3). (In this case could also be provided by the electrolyte.)
- Silver carbonate can then be 'recharged' back to Silver Oxide by heating it.
- Silver carbonate begins to decompose to silver oxide as it approaches 160°C (320°F).
- Above about 210°C (410°F) the bulk silver carbonate completely decomposes to Ag_2O , Silver Oxide.
- Above about 280°C (536°F) Silver Oxide releases Oxygen to form Silver Powder.

Figure 4 – Thermal regeneration of voltage in silver-Air PowerCell at 180°C .

Figure 4 illustrates a thermal regeneration curve for the silver PowerCell, under concentrated solar illumination. The measured temperature was 190°C . The voltage is restored from a depleted value of near zero to approximately 1.6V within 30 minutes.

The absence of regeneration in the other systems (Aluminum and Chromium) is explained as failure to generate sufficient temperature to drive the reaction. Carbon is known to reduce aluminum oxide at temperature above 1200°C , which was unattainable by our Fresnel system (although within reach of larger such systems). Further exploration of these materials might be warranted from the perspective of materials costs.

Conclusion

Powercells were successfully fabricated using inexpensive materials and standard processing. During battery operation, all cells performed according to expectations, generating usable power. The cells can be scaled and arrayed for larger generation capacity. Powercells constructed with iron and silver anodes were thermally regenerable at temperatures in excess of 800°C and 180°C respectively. Anodes composed of Aluminum and Chromium were not restored with the current system, although higher temperature systems might prove successful. Other metals might be worth investigating, notably copper, zinc, and nickel.

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PCO Project Report

Status quo of PCO air filter

David Stump

10/5/2011

A photocatalytic oxidation air filter that utilizes ambient UVA light to break down formaldehyde is designed, constructed, and tested. Future projects will scale up the current design and test the efficacy of using this technology in residential and commercial HVAC systems. This project is approximately 60% complete, with an estimated \$2,500 in material costs and 60 hours of professional services remaining.

Executive Summary

Volatile organic compounds are a common problem in indoor air quality, and contribute to the development of asthma and other respiratory problems. Photocatalytic oxidation (PCO) is one of the few methods that can destroy VOC's, turning them into harmless bi-products upon complete combustion.

Photocatalytic oxidation occurs when a semiconductor is energized by a specific wavelength of light, acting as a catalyst for the production of hydroxyl radicals. These hydroxyl radicals are powerful oxidants, and can break down volatile organic compounds and other organics into carbon dioxide and water. The semiconductor used in this reactor is titanium dioxide (TiO_2), which is widely available and a common ingredient of sunscreen.

This experiment will prove that PCO reactions can be powered by ambient UVA light to remove formaldehyde, instead of relying on UV light bulbs, like the Lennox Pure Air HVAC filter system. Upon successful completion of this experiment, a full scale model will be tested to determine the efficiency and cost effectiveness in residential and commercial HVAC systems.

The bulk of the process design and reactor construction has been completed, with material costs totaling \$3,747, and 110 hours of professional services totaling \$3,850. The total project budget to date is \$7,597. Future material expenses should be less than \$2,500 for high performance liquid chromatography (HPLC) sample analysis, and approximately 60 hours of additional professional services at a value hitherto unknown. A line item breakdown of the material expenses can be found in Table 2.

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Purpose

A PCO reactor with a titanium dioxide (TiO_2) semiconductor will be designed and built to test the efficacy of using ambient UVA light to destroy formaldehyde. Using ambient light to power a PCO reactor could reduce the energy cost associated with PCO systems by eliminating the cost associated with purchasing and powering UVA lights.

Upon proof of concept, further funding will be pursued in order to scale this design up for use in commercial and residential HVAC air filter applications. Formaldehyde was chosen as the target gas because it is a suspected human carcinogen, and is released by many common household products (Kelly, Smith, & Satola, 1999).

Introduction to Photocatalytic Oxidation

PCO occurs when a semiconductor material, such as TiO_2 absorbs a photon and acts as a catalyst for the production of reactive hydroxyl radicals. These hydroxyl radicals can decompose volatile organic compounds (VOCs) and bio-aerosols (Goswami, 2003). UV light in the range of 385 nm is needed to activate TiO_2 . PCO has the potential to be easily integrated into HVAC systems because the pressure drop across the reactor is negligible, and because PCO destroys the contaminants rather than shifting them to another phase. (Stevens & Jacoby, 1998)

Process Overview

A 52 cubic foot aluminum compressed cylinder (7) of Zero air will blow through the humidification chamber (3), the formaldehyde offgassing chamber (4), and then through the TiO_2 reactor. Twenty samples will be collected using formaldehyde sampling tubes and two GilAir-5 constant flow air sampling pumps provided by EMSL. The basic system schematic is shown in Figure 1.

Figure 1: Reactor layout

Components

1. Pressure Regulator – between 0 psig to 20 psig
2. Flow Regulator – between 5 L/min and 10 L/min
3. Humidification chamber and RH meter
4. Formaldehyde off gassing chamber
5. GilAir-5 sampling pumps sampling at 200 mL/min each
6. PCO Reactor
7. Zero Air

Humidification Chamber

The humidification chamber consists of 4 unused quart sized aluminum paint cans that have been connected in series with $\frac{1}{4}$ " ID vinyl tubing. Each can contains approximately $\frac{1}{4}$ " of water in the bottom of the can and enough sodium chloride so that the water is saturated (Rockland, 1960). The last container in the series has an RH meter. The system reaches equilibrium after approximately 3 minutes at 77.5% humidity. This system has not been tested under experimental conditions yet, so the RH at the design flow rate is unknown. The easiest way to determine the RH under design conditions is to run the system. If the relative humidity drops below 50%, the residence time in the humidification chamber should be increased by increasing the volume (Yu & Brouwers, 2009). Increasing the surface area of the saturated salt solution, or putting the cans on hot plates would also increase the RH.

Formaldehyde Off-Gassing Chamber

The formaldehyde off-gassing chamber is made of welded stainless steel. The chamber is 3' long, and 6" in diameter. The target formaldehyde concentration of 206 ppbv can be generated with a 6" wide and 3' long piece of 5/8" particle board underlayment or a liquid 10% buffered formalin solution (Kelly, Smith, & Satola, 1999). The liquid formalin concentrations and surface areas needed to attain 206 ppbv under experimental conditions have not been calculated. A literature review of liquid formalin solutions would be useful. It might also be possible to solve this problem using Henry's Law, Raoult's Law, or Graham's Law.

The off-gassing chamber is not air tight as of the writing of this paper. There are three possible ways to make the chamber air tight. The first is to install one large gasket at each end of the chamber. The second is to take the chamber back to the fabricator to install threads on the caps, and the third is to use foil tape to seal the lids.

Reactor

The reactor is made of spot welded sheet metal. Figure 2 depicts the flow of the air through the reactor. The air flows into the chamber through the inlet and into the inlet sampling chamber. One GilAir-5 sampling pump will be plumbed into the inlet sampling chamber to take air samples. The catalyst is a Lennox TiO₂ air filter, which is part of the Lennox Pure Air cleaner, which can be view at the following URL:

http://www.lennox.com/pdfs/brochures/Lennox_PureAir_System.pdf

As of the writing of this paper, the loading rate of the TiO_2 on the filter is unknown. An effort should be made to determine this loading rate and compare it to the values in the literature before the test is run so that the best possible results are obtained. The reactor is not air tight enough either, and this could be fixed with foil tape, steel tape, or silicon.

Figure 1– Air flow diagram inside the PCO reactor

Process Design

The original process design was sized to minimize the amount of gas needed to conduct the experiment the size of the glass. Changing any one of the system parameters will have a significant effect on the operation of the system.

System Parameters

Up to 84% of UVA light is transmitted by standard picture frame glass, as measured by a UVA meter with a range from 320nm to 390nm with a peak at 360nm. On 7/17/11, at 15:20, the ambient UVA light was 2.5 mW/cm², and the glass transmitted 2.1 mW/cm² when perpendicular to the sun. Table 1 provides a summary of the critical system parameters.

Table 1 – System Parameters

Overall System Flow Rate: 7.9 L/min

Desired relative humidity: 50%, per (Yu & Brouwers, 2009)

Formaldehyde Concentration, C = 206 ppbv

Residence Time in Sampling Chamber = 5.43 seconds

Total Sampling Rate/ Total Flow Rate = 5.08%

Residence Time in Reactor = 5 seconds

Experimental Design

The experiment will be conducted in 3 stages. The three stages are system equalization, control testing, and process testing. The system equalization stage will last 40 minutes. A blanket will be placed over the glass, and no samples will be taken. The second stage will last approximately twenty minutes (5 minutes per sample) , and a total of 8 samples will be taken. Four samples will come from the inlet sampling chamber, and 4 samples will come from the outlet sampling chamber. During the second stage the blanket will remain on top of the reactor. The third stage will last 30 minutes, and 12 samples will be taken. The blanket will be taken off during the third stage. Six samples will come from before the reactor, and 6 will be taken after the reactor.

Expected Results

The expected formaldehyde destruction will be near 100% if our results are similar to the reference below. Using a maximum residence time of 5 seconds, a formaldehyde concentration ranging from 2 to 1,500 ppbv, and for UVA intensities ranging from 0.1 mW/cm² to 3.8 mW/cm², nearly 100% of the formaldehyde was destroyed by Stevens and Jacoby in 1998.

Materials and Expenses

Table 2 provides a list of all the material expenses, which total \$3747.19. Future material expenses should be less than \$2500 for sample testing, and unexpected system modifications. David Stump has provided 104 hours of professional services valued at \$3,640. This brings the total expenses to \$7,387.19. Future labor requirements should be less than 60 hours to run the experiment and write a final report.

Table 2 – Material Receipts

Description	Cost	Vendor
Aluminum cannister, 76 cf Zero Air, Dual Stage 200 Series Regulator, + tax, shipping	\$1,085.00	Mesa International Tech., Inc
Swagelok Components - plug valves, bulkhead fittings, plumbing parts	\$430.80	Swagelok Austin
Fabrication of reactor and off gassing chamber	\$867.08	Custom Sheet Metal Inc.
Flow regulator, tubing, tubing adapters	\$220.37	Cole Parmer
PID VOC detector	\$379.75	TRS
Residential Ventilation Handbook by Paul H. Raymer	\$50.89	Amazon.com
CRL UV Transmission and Power Meter	\$297.30	Amazon.com
Lennox Healthy Climate #X8791 Filters	\$209.00	Filter Outlet

Indoor Air Quality Conference	\$207.00	UT Center for Lifelong Education
Material Costs	\$3,747.19	

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Appendix A: Process Design Calculations

Author: David Stump
Formaldehyde Design
Design Parameters

5 seconds. Ref. pg 981 of Investigation of
Photo., by Lisa Stevens and John A.
Lanning.

Also ref. Pg 892 of Heterogeneous
Photocatalysis by William A. Jacoby.

Residence Time 1 to 5

Reactor Volume 40 inches³
655.48256 cm³
655.48256 mL
0.65548256 L

Cross Sectional Area of Reactor
5 in²
32.258 cm²

Cross Sectional Area of tubing
0.04908739 in²
0.00034088 ft²

Flow Rate, RT = V/Q
0.13 L/s
7.87 L/min
131.10 cm³/s
0.00463 ft³/s

Velocity inside chamber = Q (flow rate)/ Cross Sectional Area
4.06 cm/s
1.60 in/s
0.13 ft/s

Velocity inside tube
13.58 ft/s

Reynolds Number = $\rho * U * L / \mu$, see pg 491, Ch. 9.1 of Fundamentals of Fluid Mechanics

For $Re \gg 1$, flow is turbulent

rho = density 2.380E-03 slugs/ft³
mu = dynamic
viscosity 3.740E-07 lb*s/ft²
U = velocity
L pipe 0.25 in
0.02 ft

L chamber = $2*a*b/(a+b)$, ref. pg 448 of Ch. 8 in Fundamentals of Fluid Mechanics

a= 8.00

b = 0.63

L chamber = 1.16 inches

0.10 ft

Re tube

= 1799.79 Might be laminar, could be mildly turbulent

Re Chamber = 81.98 Definitely laminar

Area of Holes into chamber = area of tubing

Total area of holes 0.049087 in²

# of holes 4.00

Area/ inlet hole 0.012272 in²

Diameter = $\sqrt{(4*A/\pi)}$

0.125 inches

Total Time for Experiment

40 minutes to stabilize

Sample Stream % of total flow rate 5.085312

Sample pump flow rate = 0.2 L/min

Min. volume per sample = 1 L

Min. Sample Time 5 min

Control Sampling Time

8 samples

2 sampling ports

20 minutes, at Min. Sampling time

Performance Sampling Time

12 samples

30 minutes, at Min. Sampling time

System Setup and testing

30 min

Total 120

Total volume of gas at 1.05 atm

991.089631 liters

34.985464 cubic feet

Gas Matrix

Ref. Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes, by Thomas J. Kelly and Deborah Smith

Environmental Science Technologies, 1999, 33, 81-88

$$E = C \cdot N / L \rightarrow E \cdot L / N = C$$

E = Emission rate of target compound, in $\mu\text{g}/(\text{m}^2 \cdot \text{h})$

C = concentration of target compound in steady state conditions, in $(\mu\text{g}/\text{m}^3)$

N = air exchange rate, in h^{-1}

L = product loading rate in chamber in m^2/m^3

Diameter of offgassing chamber

D = 6 inches

15.24 cm

0.1524 m

Area = 0.018241 m^2

Length 1 m

Volume 0.018241 m^3

18241.47 cm^3

Residence time in offgassing chamber = V/Q

139.1453 seconds

Air exchanges per hour = $(60 \text{ min/ hour} \cdot 60 \text{ seconds/ min}) / \text{residence time}$

N = 25.87223 h^{-1}

Product

Bare 5/8" particle board underlayment

Elevated formaldehyde emission 393 $\mu\text{g}/(\text{m}^2 \cdot \text{h})$

Product Loading Rate

0.46 m^2/m^3

since our volume is 0.018241 m^3

We need loading rate * V = area

Area = 0.008391 m^2

Assume 15.24 cm wide, for size of tubing

Assume both sides are open

3048 cm^2 available

0.3048 m^2

Our loading rate is 16.70918 m^2/m^3

Steady State Concentration

C = 253.813 $\mu\text{g}/\text{m}^3$, this is based on my calculated loading rate, which might not be a correct use of the loading rate factor
0.253813 mg/m^3

Convert steady state to ppbv: 1 ppm = 1.23 mg/m^3 , from California EPA Formaldehyde Data sheet

Cal EPA Reference # = CAS Registry Number: 50-00-0, Ref.
(http://oehha.ca.gov/air/chronic_rels/pdf/50000.pdf)

0.206352 ppmv
206.352 ppbv

Lennox PCO filter Dimensions

length 8 inches
width 8 inches
depth 1.5 inches

Distance between filter and bottom of glass
0.625 inches

ID of tubing 0.25 inches
0.635 cm

Sampling Zone Volume

length 8.25 inches
width 2.8125 inches
depth 1.875 inches

Volume 43.50586 inches³
712.9333 cm³
0.712933 L

Residence Time inside sampling area

0.090637 min
5.438232 seconds