Investigating the efficiency of Silicon Solar cells at different temperatures and wavelengths

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Abstract

In this project we develop and implement a data acquisition system to study the characteristics of silicon photovoltaic cells (solar cells). We vary the wavelength of light as well as the temperature of the solar cell to investigate how the open voltage across the cell varies with these parameters. This particular setup also allows fast data acquisition and is a stepping stone for further work that could investigate other parameters that affect the solar cell efficiency.

Introduction

There is a great need now to investigate the different forms of renewable energy and how to increase efficiency. We will soon find ourselves in an enormous energy crisis (after about 40 years) by that time we would need to depend on another source of energy. In order to maintain sustainable development as well as reduce environmental pollution we need to find a dependable 'clean energy' source that is cheap and easy to implement. Solar energy is very dependable but the cost of making the cells is too high for mass implementation at the moment. What we need to do is to increase solar cell efficiency and cheaper to make using new technologies. In this project my aim is to address the first issue. How can we make solar cells more efficient? In this work I look at the trend of the open source voltage at varying temperatures and wavelengths of light. This preliminary work will make a path for easy data acquisition and thereby opening the research to new parameters of study.

How does a solar cell work? A typical solar cell consists of a cover glass or other encapsulant, an anti-reflective layer, a front contact to allow the electrons to enter a circuit and a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their voyages [1].

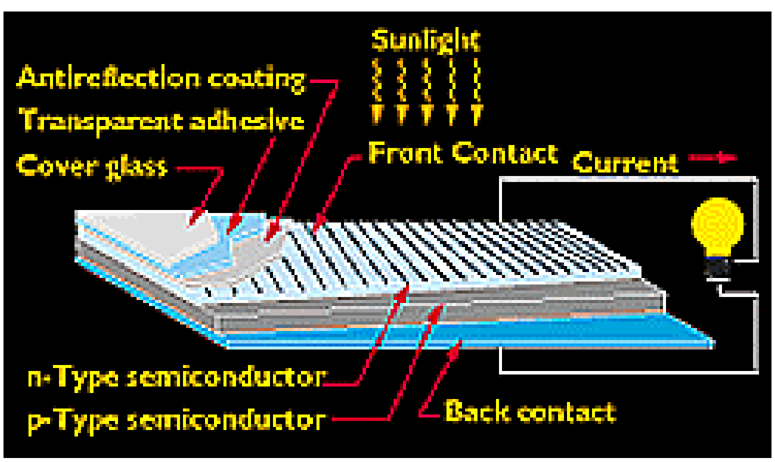


Figure 1. Schematics of a typical solar cell. The current flows from the p-type semiconductor to the n-type semiconductor and then through the circuit.

When the p-type and n-type semiconductors are placed on top of each other diffusion of a limited number of electrons and holes occurs, and a depletion region is formed. In this region, a small intrinsic voltage exists. Here if an electron moves into the conduction band it will be pushed away from the p-type and through the n-type material. A circuit is formed when leads are attached to the opposite sides of this p-n junction. In photovoltaic cells, the energy needed to boost an electron into the conduction band can be supplied by sunlight. In this manner solar energy is converted to electrical energy [2].

In this experiment we used a silicon solar cell (bought from radio shack no. 276-124). This solar cell was put onto a copper holder by first applying some thermally conduction, electrically insulating grease (thermal compound part no. 120-2, made by Wakefield Engineering INC.) A sheet of mica was placed between the copper and the solar cell to act as an electrical insulator. Two 25O power resistors were attached to the underside of the copper holder. This was done so that the temperature could be increased by the user. A small hole was drilled onto the side of the copper plate so that the temperature lead of the thermocouple could be in close proximity to the solar cell.

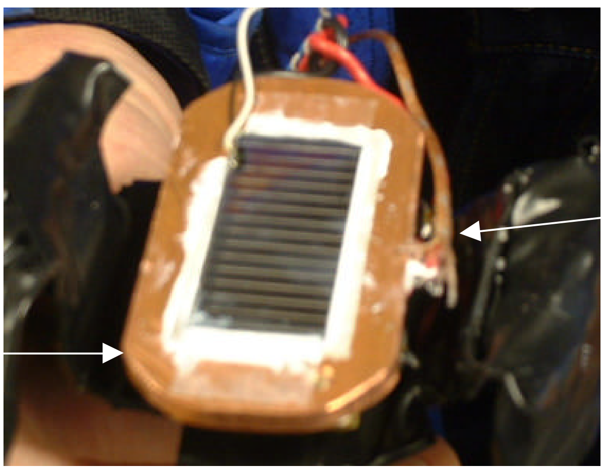


Figure 2. The solar cell is attached to the copper plate using the grease.

A hole was drilled into the copper block to have a brass rod screwed into the middle of the plate. This was done so that the brass rod could be immersed in liquid nitrogen thereby conducting the heat away from the cell. The copper plate was then placed into a metal hammock that was covered with insulating tape. This was done so that the plate would not touch the liquid nitrogen Dewar.

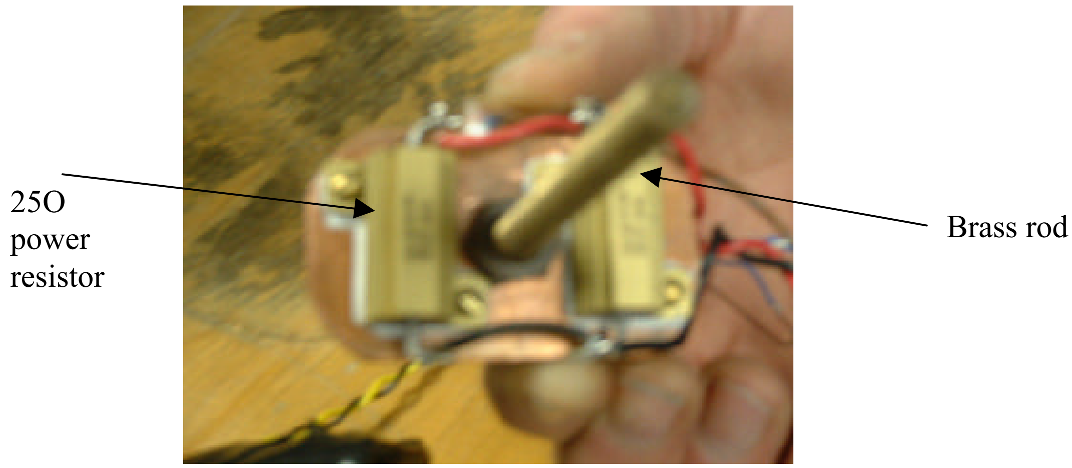


Figure 3. The underside of the copper plate showing the heating power resistors and the brass rod through the middle of the plate to conduct the heat away.

The entire setup was then placed into a liquid nitrogen Dewar:

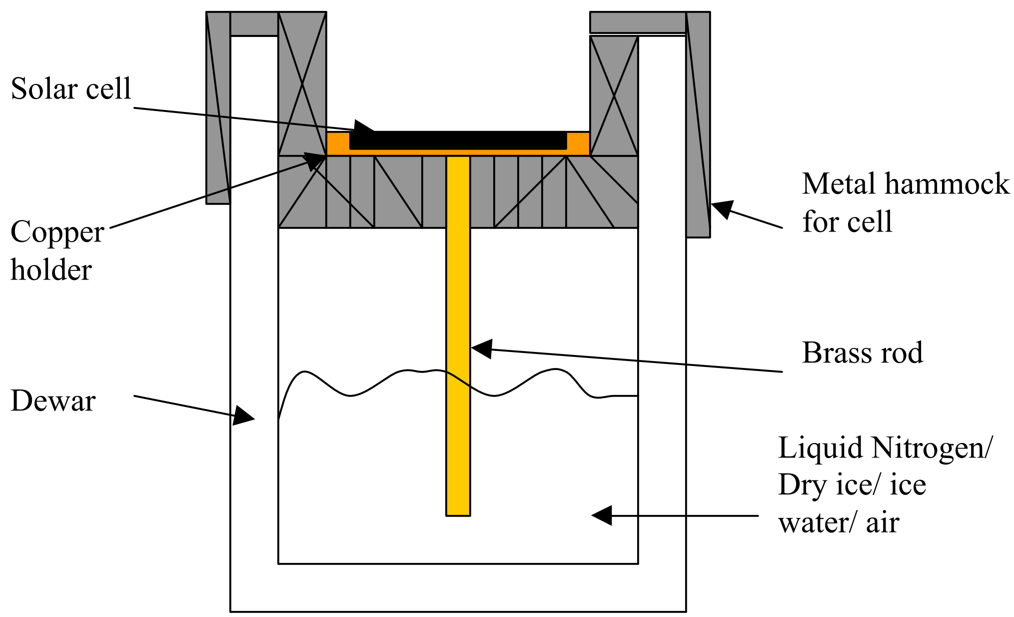


Figure 4. The setup of the solar cell in the liquid nitrogen Dewar. Inside the Dewar tried out a variety of coolers ranging from liquid nitrogen (-196ºC), dry ice (-78.5ºC), ice water (0ºC) and air (22ºC).

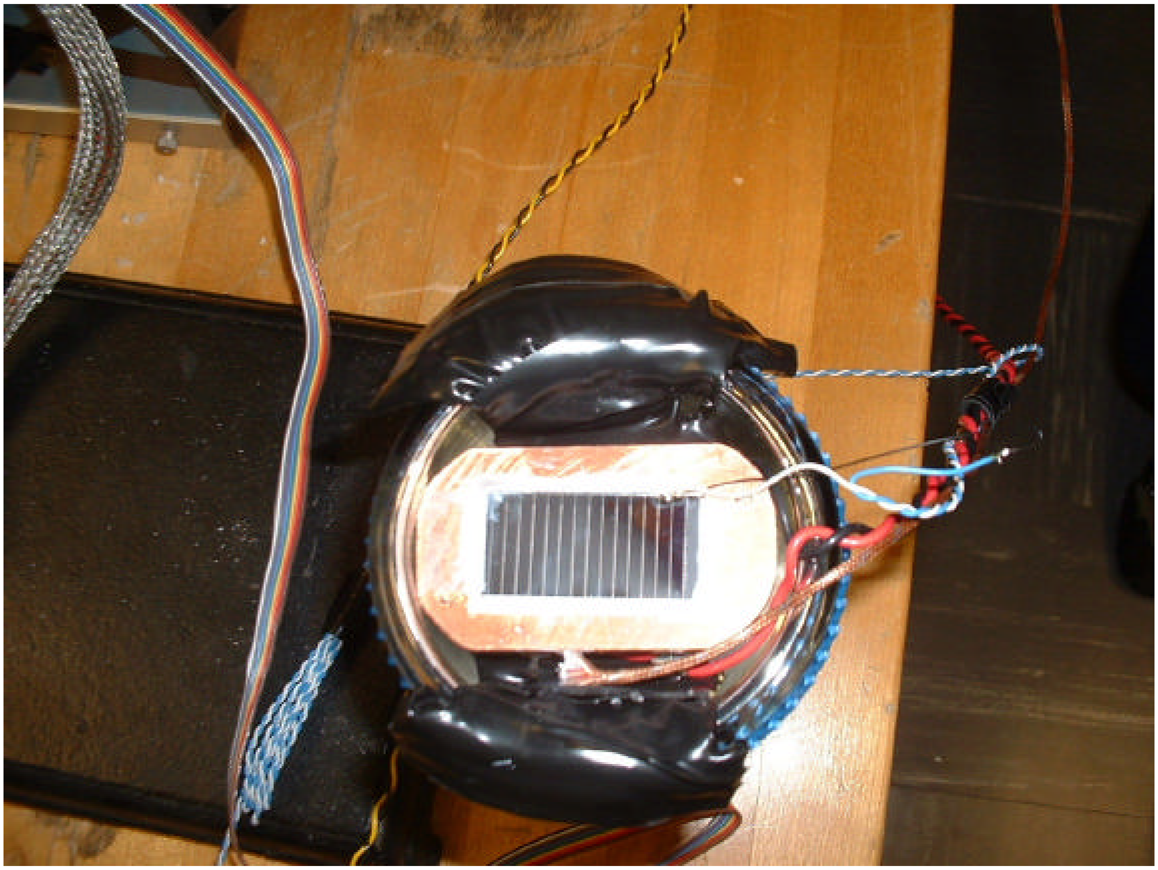


Figure 5. The top view of the solar cell setup. As you can see, the solar cell is not quite touching the Dewar. The leads coming out on the right of the picture are those belonging to the resistors, the solar cell and the thermocouple.

The thermocouple, as said earlier was used to measure the temperature of the copper block and thereby the temperature of the solar cell. We used copper and Constantine wires and exploited their different rates of thermal expansion to build our own thermocouple. The thermocouple was then connected to a 5B37 Analog devices thermocouple module. A variable power supply was used to supply power to the power resistors, this is user controlled.

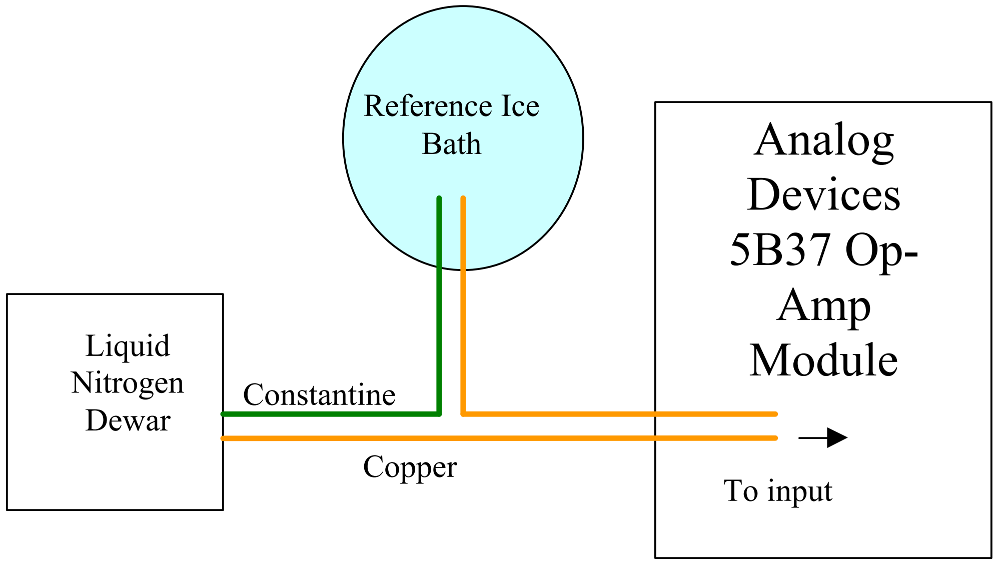


Figure 6. The schematics of the thermocouple used.

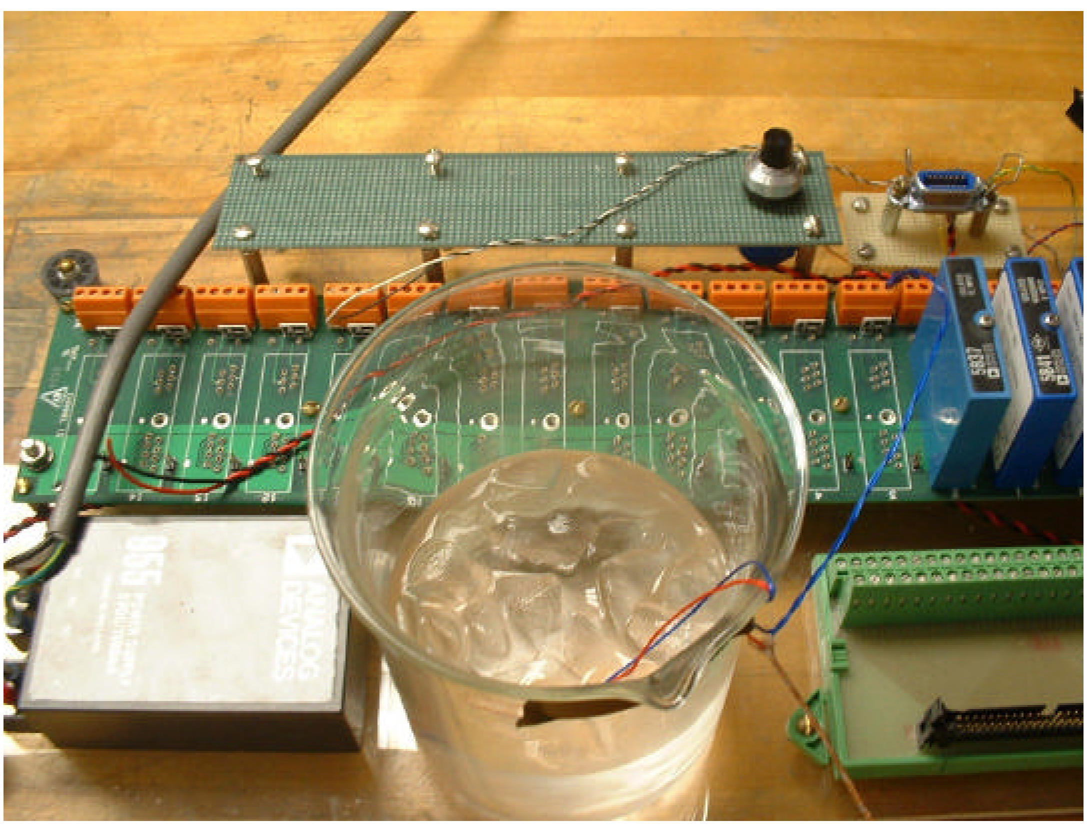


Figure 7. The ice bath used and the 5B37 Analog devices thermocouple module in the background.

A Chem Anal light source was used with a CM 3016 bulb, the light source is connected to a wavelength varying monochromator (also by Chem Anal). This device was then attached to a piece of Styrofoam that had a hole drilled through the center. This was done so that no water vapor could seep into the Dewar, and also to maintain constant temperature of the solar cell. All these leads were then hooked up to a circuit that had a feedback loop. The monochromator was hooked up to a stepper motor (SLO-SYN DC step motor M111) that would change the wavelength of light entering the solar cell. The Stepper motor was connected to a 12 volt power supply.

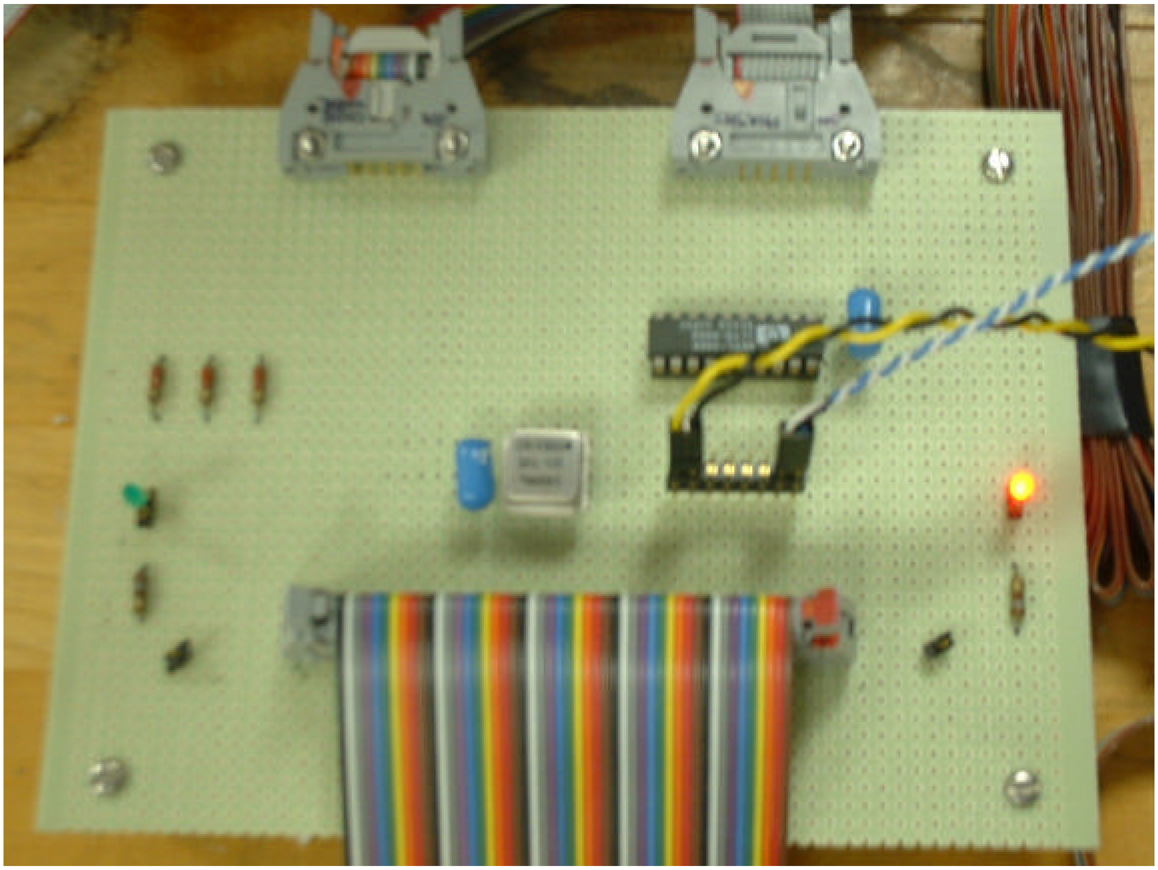


Figure 8. Circuit used to control the stepper motor as well as the phase on the 4 axis stepper motor control.

A power supply was used to provide 5v to the TTL components in the circuit. Please look at the attached circuit diagram for a better understanding of how the components are connected.

We used a DAQ Lab-PC+ which is a low-cost multifunction analog, digital, and timing I/O board for the PC [3].

Solar Cell DAQ system
National Instruments Lab PC + DAQ card Channel assignments:

Channel	**Pin #**	**Description**	**Read/Write**
ACH0	1	Solar cell voltage	
ACH1	2	Thermocouple voltage from AD 5B37 module	
ACH3	3		
ACH4	4		
ACH5	5		
ACH6	6		
ACH7	7		
ACH8	8		
AISNSE/AIGND	9	Tied analog together	
AGND	11	Tied analog together	
DGND	13	Digital ground	READ
PA0	14	D0 HP HCTL CODE WHEEL	READ
PA1	15	D1 HP HCTL CODE WHEEL	READ
PA2	16	D2 HP HCTL CODE WHEEL	READ
PA3	17	D3 HP HCTL CODE WHEEL	READ
PA4	18	D4 HP HCTL CODE WHEEL	READ
PA5	19	D5 HP HCTL CODE WHEEL	READ
PA6	20	D6 HP HCTL CODE WHEEL	READ
PA7	21	D7 HP HCTL CODE WHEEL	READ
PB0	22		READ
PB1	23		READ
PB2	24		READ
PB3	25		READ
PB4	26		READ
PB5	27		READ
PB6	28		READ
PB7	29		READ
PC0	30	SM TTL PHASE A	WRITE
PC1	31	SM TTL PHASE B	WRITE
PC2	32	SM TTL PHASE C	WRITE
PC3	33	SM TTL PHASE D	WRITE
PC4	34	SEL HP HCTL-2020	WRITE
PC5	35	!EO HP HCTL-2020	WRITE
PC6	36	!CLEAR HP HCTL-2020	WRITE
PC7	37	LED DAQ INDICATOR	WRITE

In building the circuit we used

1) 50 pin 3M wire wrap connector, screws and washers
2) HP HCTL – 2020 IC and a 20 pin wire socket
3) 1 MHZ quartz clock XTAL and a 14 pin wire wrap socket
4) 10-pin 3M 90º wire wrap connector and screws
5) 3 100µF @ 16 V dc capacitors
6) 1 green and 1 red mini LEDs and socket strip material
7) 180O resistors
8) Vector board material and standoff screws

This circuit is similar to the one used in the lab experiment entitled "A PC-Based Torsional oscillator experiment for the physics 301 undergraduate classical mechanics and E&M laboratory course" [4].

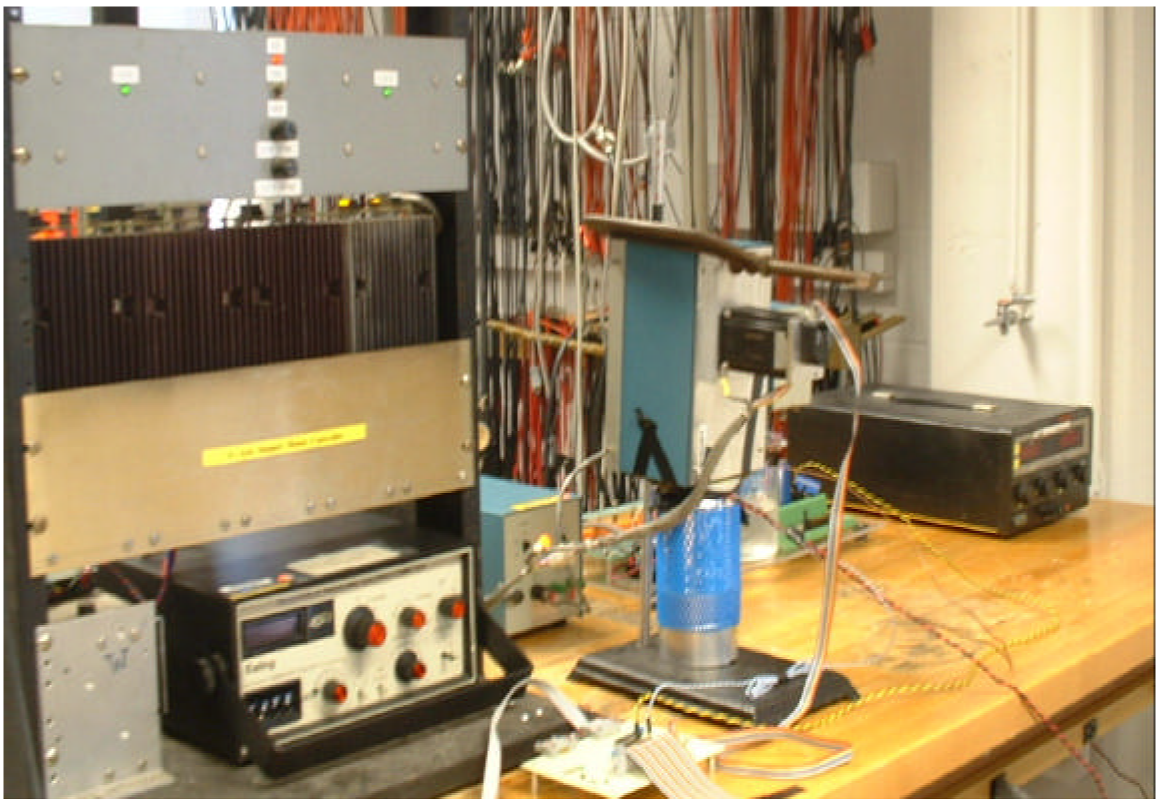


Figure 9. The entire experimental setup showing the various power supplies and 4 Axis step motor driver on the left and the Dewar, monochromator and light source in the center and the variable power supply on the right.

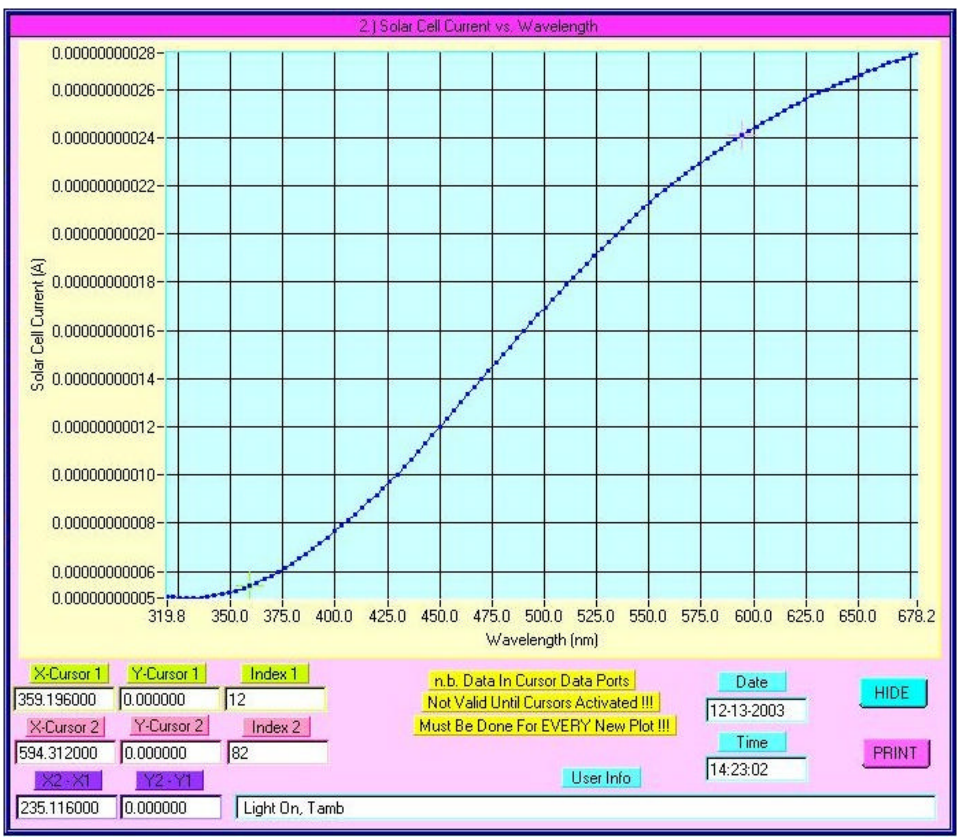
Professor Steven Errede wrote a computer program called Solar_Cell2.c that is an online DAQ program for the class. It uses National instruments Lab PC + I/O board and National instruments Lab Windows/CVI software

The Light source illumination the slit of the Chem Anal system diffraction grating spectrometer that is controlled by the 1.8 degree/step stepper motor is controlled by this program. It is directly coupled to the cam shift that changes the angle of the diffraction grating in the Chem Anal thereby scanning the visible wavelength spectrum (320 nm < ? < 680nm) by rotating the cam shaft.

The HP / Agilent HEDS-5540-A 06 code wheel encoder assembly is used to monitor the angular position of the stepper motor. The code wheel encoder has 500 counts / revolution readout. The HP / Agilent HCTL – 2020 16 bit up/down counter IC does a 4x sampling of the (90º) quadrature signals from the code-wheel assembly, therefore there are 2000 counts per revolution.

The stepper motor used in this experiment has 200 steps per revolution. The 4 phases (A, B, C, D) define the rotation. If you want a clockwise cycle, a sequence of 4 steps e.g. phase A, then phase B, then phase C and then D. Id you want a counter clockwise step, first move phase D, then C, then B and then A.

A 500 count / revolution optical code wheel is attached to the shaft of the Stepper motor to monitor the angular position of the stepper motor. The code wheel is read out by the HP HCTL -2020 16 bit up/down counter chip, that decodes the quadrature signals from the code wheel, using the 4x decoding. Thus, there are a total of 2000 (=4*500) decoder counts per revolution [5].



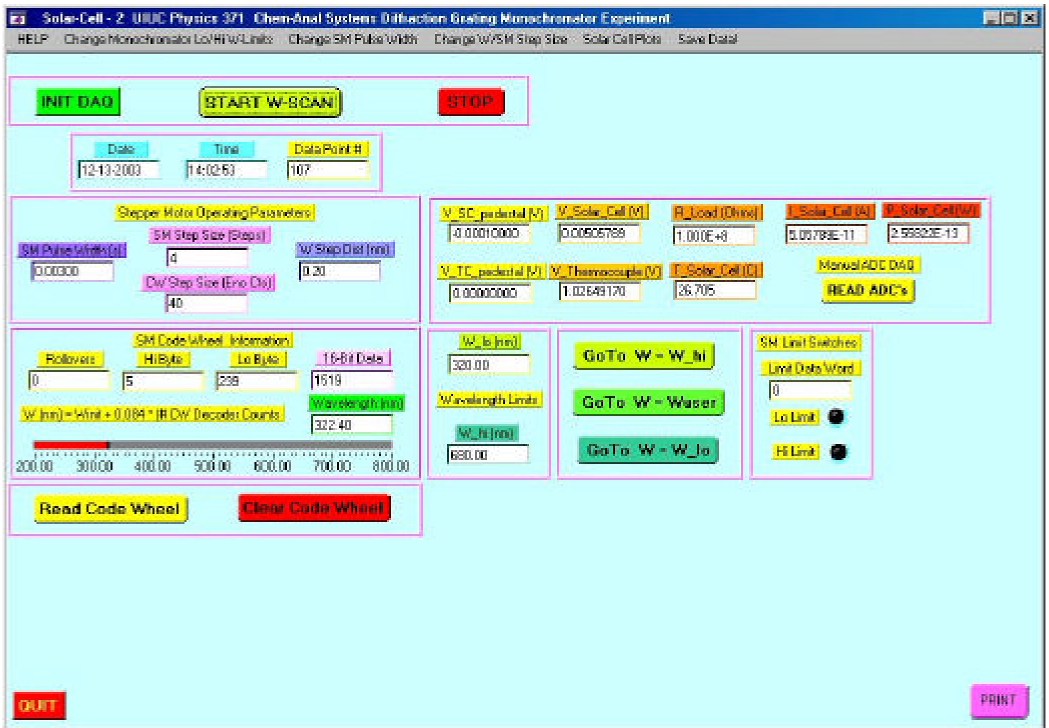


Figure 10. The computer program produces the above out put as well as text files that can be analyzed with MS Excel.

The user can input the wavelength they want to scan and the resistance load (in this case 1 x 10^8 O.

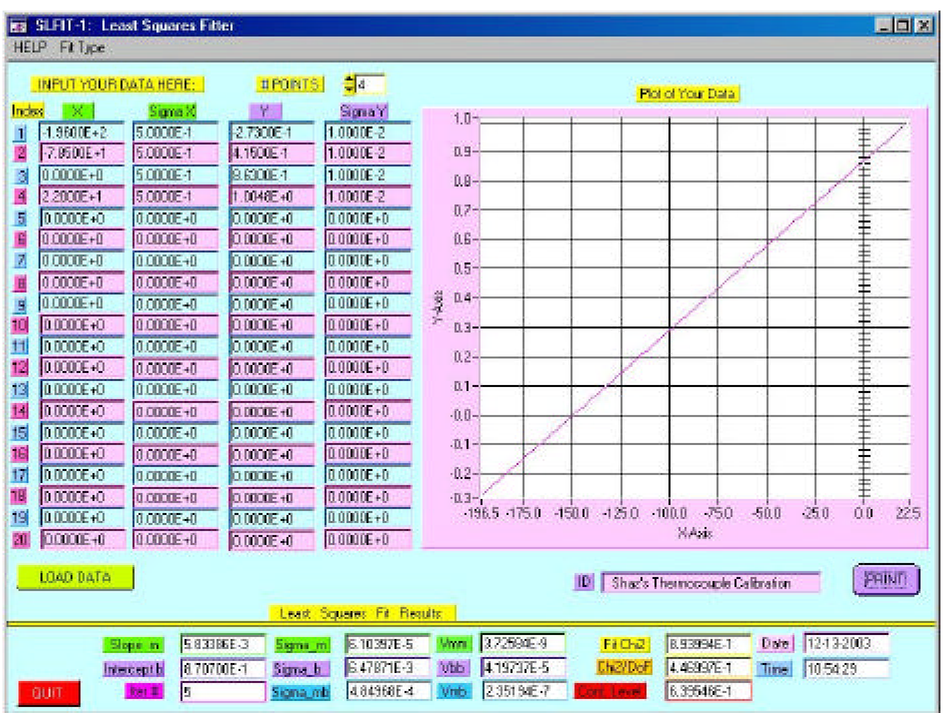


Figure 11. Least squares fit performed to configure the thermocouple instrument.

W (nm)	V_sc (mV)	T_sc (C)
319.748	1.560083	44.37156
321.932	1.569727	44.4041
325.46	1.584741	44.40902
328.82	1.612512	44.42932
332.18	1.649927	44.44334
335.372	1.69082	44.47755
338.732	1.762292	44.48979
342.176	1.836328	44.48226
345.788	1.92373	44.48843
349.064	2.029199	44.48864
352.34	2.148279	44.51605
355.7	2.276514	44.51542
358.976	2.400842	44.59441
362.42	2.561609	44.59326
365.696	2.704675	44.60738
369.224	2.873499	44.57945
372.5	3.026025	44.62433
375.776	3.188989	44.60686
379.136	3.362512	44.63312
382.496	3.536951	44.64808
385.94	3.716211	44.65122
389.216	3.902979	44.6371
392.66	4.087915	44.67162
396.02	4.267603	44.67246
399.38	4.455042	44.67612
402.656	4.663293	44.69516
405.932	4.869348	44.68041
409.376	5.086145	44.68292
412.736	5.298181	44.70573
416.18	5.51803	44.6983
419.456	5.757959	44.71368
422.732	6.007288	44.74726
426.176	6.247644	44.77541
429.62	6.509241	44.78859
432.98	6.759302	44.8657
436.256	7.018396	44.84331
439.7	7.248743	44.86842
443.06	7.506128	44.89018
446.336	7.757166	44.90127
449.696	8.002649	44.85314
452.972	8.249475	44.89792
456.5	8.505701	44.86455
459.692	8.75387	44.84038
463.22	8.996118	44.83358
466.328	9.238123	44.83818
469.772	9.504846	44.81391
473.132	9.744775	44.84801
476.576	9.980798	44.83933
480.02	10.22763	44.83107
483.212	10.46255	44.88767
486.656	10.69845	44.91748
490.016	10.9382	44.9134

493.292	11.16427	44.9201
496.736	11.38906	44.94061
500.096	11.62728	44.97544
503.456	11.85555	45.013
506.816	12.06625	45.05339
510.176	12.28732	45.07525
513.368	12.49978	45.05014
516.812	12.71255	45.08216
520.34	12.92752	45.06029
523.616	13.13931	45.02043
526.976	13.34451	45.07222
530.252	13.5386	45.07504
533.612	13.71945	45.09241
537.14	13.91659	45.10308
540.5	14.09628	45.10183
543.86	14.27578	45.10633
547.304	14.43826	45.11428
550.664	14.59286	45.13227
553.94	14.75619	45.11815
557.384	14.90243	45.15079
560.744	15.04476	45.11888
564.104	15.19711	45.11522
567.212	15.33566	45.12652
570.488	15.47543	45.11961
574.016	15.61325	45.09503
577.376	15.74002	45.13437
580.736	15.88192	45.16199
584.18	15.99801	45.19599
587.456	16.13088	45.21367
590.9	16.24764	45.19578
594.092	16.37576	45.21869
597.452	16.49294	45.23219
600.728	16.60507	45.28732
604.256	16.70712	45.23888
607.616	16.81991	45.26002
611.06	16.93032	45.30124
614.336	17.01199	45.32624
617.78	17.11025	45.30804
621.056	17.20437	45.31881
624.416	17.30429	45.32279
627.776	17.38821	45.34936
631.22	17.45254	45.36202
634.412	17.55874	45.34989
637.856	17.6481	45.37426
641.132	17.72213	45.37562
644.66	17.78933	45.3818
647.936	17.87179	45.39958
651.38	17.96481	45.43275
654.572	18.01376	45.43254
658.1	18.08993	45.44886
661.46	18.16531	45.45953
664.82	18.22085	45.47156
668.012	18.26254	45.47784

671.372	18.32546	45.45828
674.732	18.38711	45.44583

Figure 12. A sample data set from the program. At the head of the file the following data is also included:

c:\cvi\P344\Data\SC2_Light_On_Air_T44C_Gain10.txt
DAQ PROGRAM: Solar_Cell2.prj
Time:
16:52:33
Total Number of Data Points:
108
Stepper Motor Step Size (Cycles):
1
Stepper Motor Step Size (Steps):
40
Stepper Motor Step Size (nm):
0.2
Solar Cell Load Resistance (Ohms):
1E+08

The data can be imported into MS Excel and analyzed:

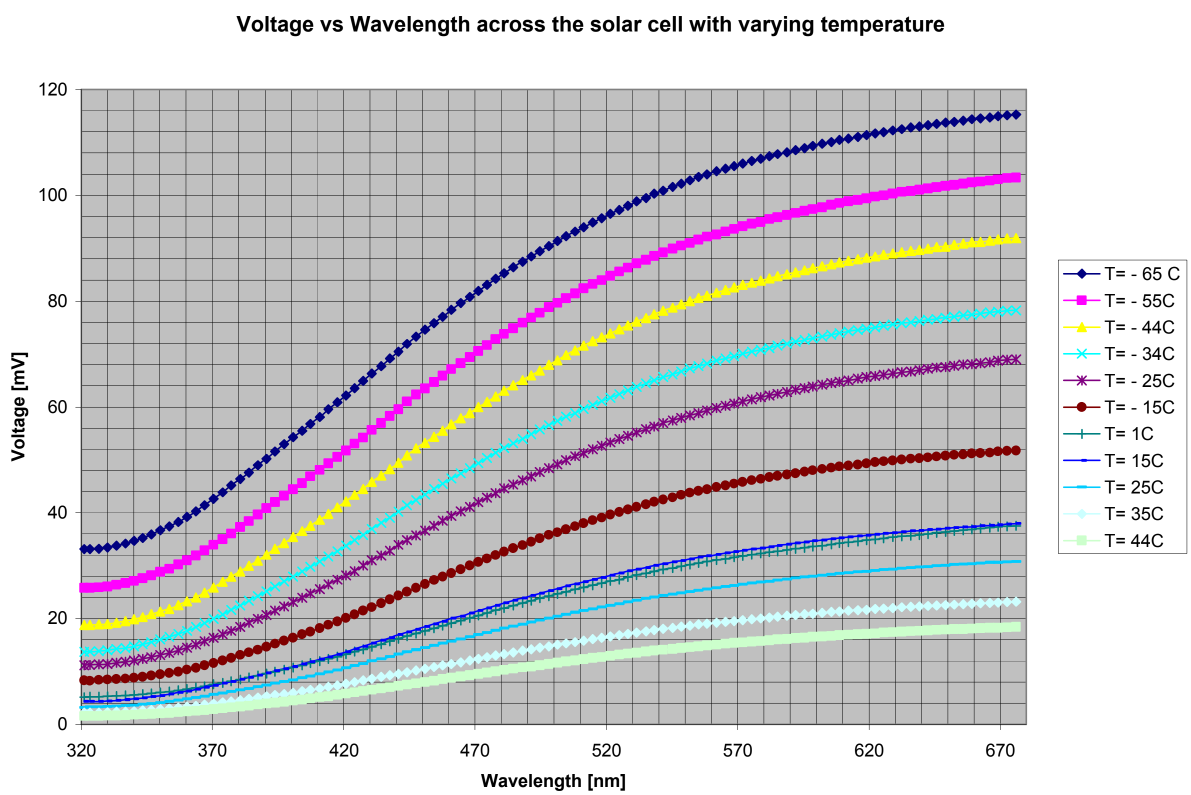


Figure 13. Data analyzed from the computer program

From this result we find that the voltage across the solar cell is very dependent on the wavelength. This is due to the fact that the light source does not have constant output intensity. We also find that the voltage increases with a decrease in temperature.

We then used an IL700 Radiometer/Photometer to calculate the light intensity of the bulb.

Here is some of that data:

W (nm)	V_sc (mV)	T_sc (C)	V_rp (mV)	I_rp(uW/cm^2)
321.02	141.3403	2.94869	107.69409	10.769409
323.204	140.89742	2.98949	108.11951	10.811951
326.816	139.92422	3.01564	108.83606	10.883606
329.924	140.32369	3.07999	110.53589	11.053589
333.284	139.67593	3.06346	112.71423	11.271423
336.812	139.25033	3.06231	115.63355	11.563354
340.172	139.9269	3.10761	119.62036	11.962036
343.448	141.06051	3.14171	124.57275	12.457275
346.724	136.4927	3.13261	130.19898	13.019897
350.168	139.22915	3.12445	137.56714	13.756714
353.444	137.2886	3.11493	146.37329	14.637329
357.056	139.4479	3.12299	156.1145	15.61145
360.584	139.42983	3.16986	168.8031	16.88031
363.776	138.51248	3.17938	182.09229	18.209229
367.304	137.31863	3.2273	199.03381	19.903381
370.412	140.82583	3.14381	215.23865	21.523865
373.856	141.93801	3.14423	234.85474	23.485474
377.3	142.47708	3.12142	256.3031	25.63031
380.492	143.04067	3.22604	277.72217	27.772217
383.684	142.21835	3.25628	301.01318	30.101318
387.296	126.01968	3.28578	324.51538	32.451538
390.572	101.93228	3.33003	347.25586	34.725586
394.016	102.42526	3.31256	372.72583	37.272583
397.292	114.03225	3.38078	396.51001	39.651001
400.82	115.67843	3.438	420.04334	42.004333
404.012	103.97647	3.46636	441.75659	44.175659
407.372	138.09664	3.48896	464.86572	46.486572
410.816	144.51553	3.44658	488.15552	48.815552
414.176	143.51455	3.41562	511.7926	51.17926
417.536	143.97048	3.42315	537.73315	53.773315
420.896	144.30978	3.40107	560.8783	56.08783
424.424	146.26937	3.37868	586.29395	58.629395
427.532	146.80154	3.36571	608.84155	60.884155
430.892	143.49465	3.32344	632.25464	63.225464
434.252	102.33529	3.27312	656.78467	65.678467
437.528	106.73745	3.33464	681.48987	68.148987
440.804	115.99673	3.40139	705.51514	70.551514
444.164	140.86373	3.42733	729.86023	72.986023

447.608	145.14956	3.40861	754.16565	75.416565
450.884	144.92605	3.4198	778.19519	77.819519
454.328	145.67074	3.41541	800.46021	80.046021
457.772	145.17098	3.42712	822.93091	82.293091
461.132	145.10214	3.46625	845.09705	84.509705
464.492	143.98007	3.42493	867.68982	86.768982
467.852	136.99148	3.431	891.33301	89.133301
471.296	145.81002	3.49502	915.25391	91.525391
474.404	146.60879	3.56878	938.43567	93.843567
477.848	147.03634	3.58427	961.80054	96.180054
481.292	148.04617	3.54754	986.4032	98.64032
484.484	148.67782	3.55623	1010.1984	101.019836
488.096	146.66543	3.47358	1034.1644	103.416443
491.288	146.67727	3.43372	1056.4789	105.647888
494.564	147.18917	3.32951	1078.7286	107.872864
498.008	142.28652	3.34604	1100.8838	110.088379
501.368	144.97958	3.30566	1121.8445	112.184448
504.812	142.94705	3.38245	1143.3557	114.335571
508.172	144.29904	3.39406	1161.778	116.177795
511.448	145.21554	3.49283	1181.7102	118.171021
514.808	144.91812	3.5557	1202.2742	120.227417
518.168	146.04714	3.56951	1223.1543	122.31543
521.612	146.72543	3.56167	1245.4327	124.543274
524.888	146.4111	3.53478	1268.7994	126.879944
528.08	146.17739	3.49597	1295.152	129.515198
531.44	146.94485	3.52034	1322.2614	132.226135
534.884	146.81381	3.54901	1353.2697	135.326965
538.244	146.76559	3.58584	1383.1976	138.319763
541.688	146.04238	3.61251	1411.1151	141.111511
545.132	145.69033	3.53384	1436.546	143.654602
548.492	145.7814	3.53666	1458.5992	145.859924
551.852	145.46115	3.57224	1477.7051	147.770508
555.128	145.79275	3.61168	1488.7952	148.879517
558.404	145.73373	3.58814	1496.7291	149.672913
561.764	144.89633	3.55393	1500.8649	150.086487
565.208	145.28005	3.49994	1501.5723	150.157227
568.568	144.68777	3.52243	1502.8638	150.286377
571.928	145.20071	3.52861	1504.0753	150.407532
575.288	144.61447	3.61314	1506.9928	150.69928
578.564	143.86056	3.64798	1511.228	151.122803
581.924	145.17037	3.65562	1516.5204	151.652039
585.368	144.21578	3.62538	1522.8473	152.284729
588.728	143.93014	3.62235	1529.4336	152.943359
592.172	143.78066	3.61074	1534.6149	153.461487
595.532	136.96188	3.60331	1538.1653	153.816528
598.808	139.41097	3.59201	1539.5264	153.952637
602.084	140.58895	3.54671	1539.1382	153.913818
605.444	136.9631	3.50978	1535.5139	153.551392

608.888	140.56747	3.53133	1529.7504	152.975037
612.332	144.27267	3.54388	1523.8586	152.385864
615.524	138.33731	3.55958	1515.2118	151.521179
618.968	138.83138	3.56512	1506.2689	150.626892
622.328	141.47866	3.6168	1498.4711	149.847107
625.688	137.10226	3.62381	1492.345	149.234497
629.132	135.60769	3.67382	1486.9574	148.69574
632.324	133.15499	3.74089	1483.7958	148.379578
635.768	136.36245	3.75784	1484.0448	148.40448
639.044	137.68362	3.77175	1487.0721	148.707214
642.404	123.49038	3.74329	1492.2351	149.223511
645.848	141.08486	3.71651	1500.8282	150.082825
649.124	143.30465	3.73712	1512.854	151.2854
652.652	144.49771	3.71368	1525.2026	152.520264
656.012	141.1777	3.65959	1536.3147	153.63147
659.288	144.12417	3.64599	1549.3982	154.939819
662.732	147.91799	3.64725	1563.0762	156.307617
665.924	148.99899	3.68795	1573.9587	157.395874
669.368	149.66079	3.71138	1582.135	158.213501
672.644	148.52377	3.75501	1590.9674	159.096741
676.172	142.43344	3.75846	1598.3026	159.830261
679.532	140.58627	3.78943	1600.8026	160.080261

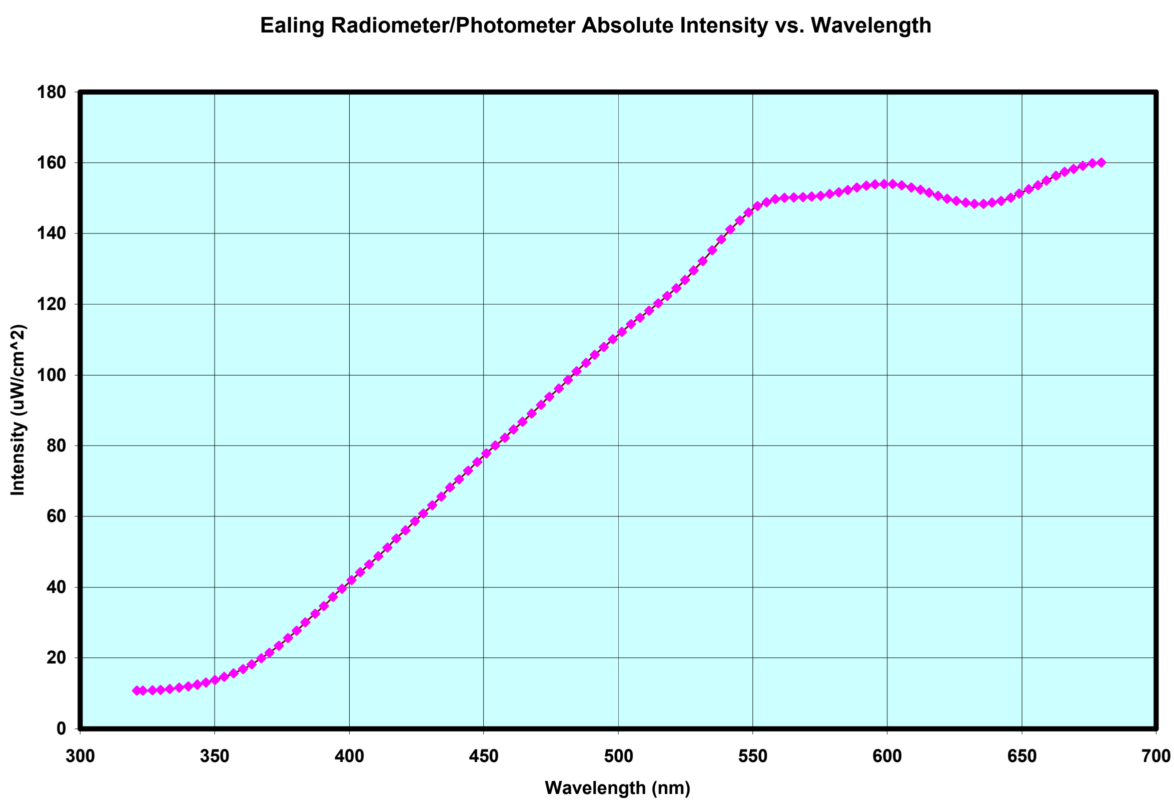


Figure 14. The graph showing the wavelength dependence of the intensity.

Note that since the solar cell was not hooked up for the calibration data-taking, nor was the thermocouple electronics powered on. The reason for this wavelength dependence could be the fact that the CM-1601 light gives off a black-body spectrum, and there are also some wiggles in the intensity curve at longer wavelengths, which may be due to e.g. wavelength-dependent reflection/transmission/absorption associated with the optics/lenses in the Chem Anal Diffraction Grating Spectrometer

In order to normalize the previous data from the solar cell we need to use this formula:

$$V\_solarcell(l\_normalised) = V\_solarcell(l) \times \frac{Intensity(l\_reference)}{Intensity(l)}$$

I am choosing the reference wavelength as 600 nm, the intensity at ? reference is 153.279602 uW/cm^2. Therefore we need to multiply the data by a new value:

Intensity/intensity_reference	W (nm)
14.30698112	320.936
14.26480433	323.204
14.15672873	326.396
13.96045923	329.84
13.67448643	333.704
13.29261033	336.896
12.87414117	340.592
12.39014124	343.784
11.82098579	346.808
11.17260317	350.336
10.50178146	353.948
9.837909747	357.14
9.141793534	360.5
8.4448333	363.776
7.7690117	366.968
7.168376136	370.244
6.574720793	374.024
6.02015792	377.3
5.529475612	380.408
5.104024131	384.272
4.766522568	387.044
4.445718486	390.32
4.136141862	394.268
3.893322237	397.376
3.673720037	400.988
3.48483101	404.18
3.311073006	407.456
3.156031272	410.9
3.014754832	414.008
2.878622136	417.2
2.745850589	420.728

2.63279159	424.676
2.534342296	427.448
2.438319945	430.724
2.346288067	434.084
2.259561358	437.612
2.181908464	441.224
2.110457862	444.752
2.041310951	447.86
1.981018337	451.052
1.927585064	454.496
1.877722004	457.604
1.826540893	460.964
1.778584602	464.324
1.730948652	467.6
1.684312161	471.548
1.64183408	474.656
1.605730112	477.68
1.563830183	481.292
1.526135021	484.484
1.492205726	487.76
1.457573175	491.372
1.427618098	494.816
1.399097034	498.176
1.374851708	501.2
1.348825134	504.728
1.326092631	508.088
1.303168282	511.868
1.280759132	515.228
1.259122155	518.252
1.236428289	521.948
1.215088611	524.72
1.187834608	528.248
1.163672919	531.86
1.13769957	535.22
1.114103988	538.58
1.092646389	541.52
1.071607243	545.384
1.056061393	548.408
1.042853909	552.02
1.034876607	555.632
1.028984338	558.488
1.025826068	562.016
1.025373717	565.04
1.024387051	568.652
1.024154357	571.844
1.022660052	575.12
1.019311589	578.48
1.014850987	582.008

1.010959261	585.2
1.006719793	588.896
1.003092357	592.508
1.000810582	595.448
0.9994846	598.724
1	602.168
1.00179669	605.948
1.005890347	608.972
1.009600178	612.08
1.015347876	615.944
1.021334975	619.052
1.026220525	622.16
1.030876631	625.436
1.034620798	628.88
1.036832179	632.24
1.036109251	636.104
1.033934154	639.38
1.030508613	642.656
1.025167355	645.68
1.017836732	648.956
1.009133232	652.568
1.001264269	656.18
0.993178	659.372
0.984741086	662.564
0.978014149	665.84
0.972519039	669.704
0.967393418	672.812
0.96283549	676.088
0.961814775	679.28

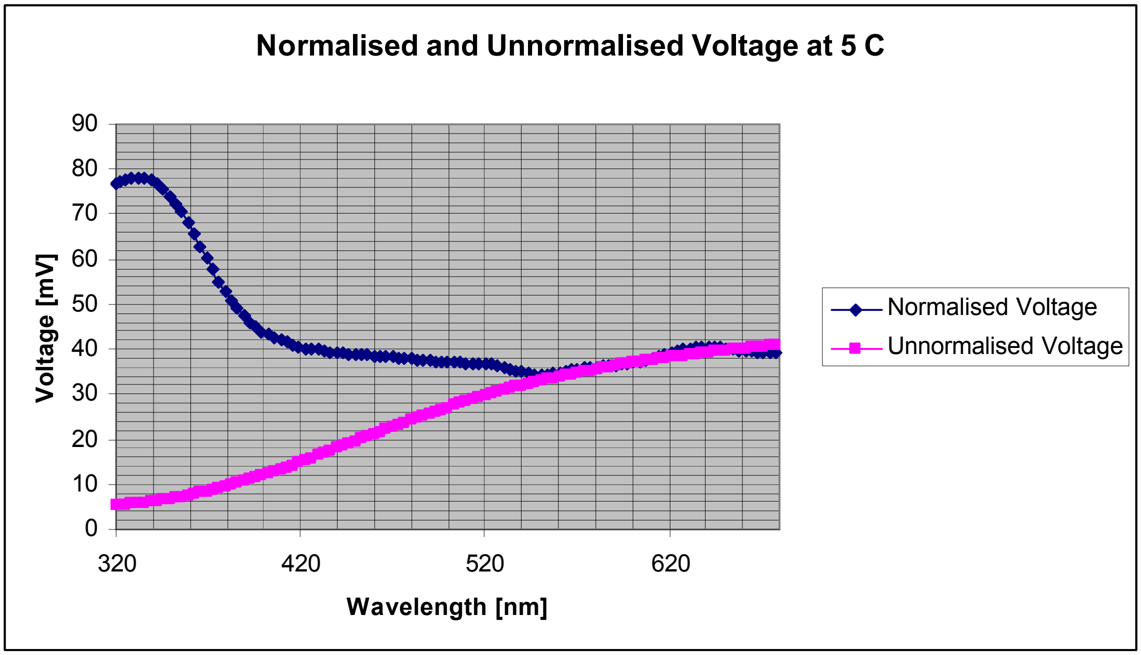


Figure 15. The normalized voltage and the unnormalised voltage vs. wavelength of light

The initial squiggles may be attributed to the fact that we simply chose 600 nm as our reference. But the normalized curve does flatten out. It is this value of voltage we are interested in.

In conclusion: primarily this semester was spent trying to build the system and making sure that it worked. The results obtained show explicitly that the amount of voltage produced across the solar cell is indeed increased by a temperature drop. In order to investigate the problem further we will need to understand some fundamentals about sunlight and experiment with varying the intensity of the light the solar cell is exposed to.

If the efficiency of solar cells are increased it would mean more energy for the same cost as before. This would make more people interested in the "clean energy option". The results of this experiment show that if we could some how reduce the temperature of the solar cell and keep it there, we could produce more energy. Further research has to be carried out to investigate different transparent insulators as well as other variables that could possibly affect the solar cell.

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