Final Report for the Design of a Reliable Spark Gap

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Abstract:

The design of a reliable spark gap was explored for its use in discharging a large transient current. A spark gap consists of two electrodes placed a certain distance apart and that are at a potential difference. When the voltage is raised to the breakdown voltage of air, a spark will bridge the gap due to the ionization of the air in the gap, thus completing the circuit and allowing a current to flow from one electrode to the other. In this project, three designs were chosen along with three different electrodes. The designs were tested for adjustability and the ability to have an accurate gap distance. The electrodes were tested for reliable sparking and lower voltage requirements for sparking. The electrodes were made of galvanized steel, stainless steel, and brass. The major goal was to be able to predict the voltage required to spark a gap given certain conditions in humidity while at the room temperature and standard air pressure. This was done through fitting a line to the data taken using Paschen's Law as the equation and solving for the constants. The best electrode material was the brass, while the second design was chosen as superior. The Chi-Squared value from the fit was so high that reliable data could not be extracted from the data. The bad fit is due to the lack of data at a distance below 0.038 mm.

Introduction:

The purpose of this experiment was to find the best spark gap design. The criteria for the best spark gap design includes the adjustability for accommodating different electrode distances for allowing different voltages for sparking. Another criteria to find is the electrode that requires lowest possible voltage to spark over a given distance. Three different designs were created to test the gap adjustability. Two were created similar in that the electrodes could be adjusted only towards one another. The other design rotated on an axis to making larger adjustments quicker. To test the lower voltage required to spark, three different apparatuses were used as the electrode portion of the design. A stainless steel carriage bolt, a galvanized steel carriage bolt and a threaded brass sphere threaded on a threaded rod were chosen. These were the only chosen due to cost constraints. The brass spheres were the most expensive in this test. From the designs, it is expected that the angular design of the spark gap will allow for the best adjustability and the brass sphere will allow for the lowest voltage required for a spark. The design is expected to be the best because it allows for a greater range of spark gaps and a way to make the fine adjustments. The electrode can be expected to be the best for lower voltages because the brass is more conductive than the steel.

Theory:

A spark gap is a device that consists of two electrodes (anode and cathode) separated by an air gap. When the potential difference between the electrodes reaches the breakdown voltage of air, a spark connects the two electrodes, thus completing the circuit for a short period of time. A spark gap is essential in creating a large transient current due to the electric discharge that can be accomplished by spacing the electrodes and increasing the voltage. The current is large due to the low resistance of the wire and is transient due to the short period of time the circuit is completed.

The spark gap is possible due to Paschen's Law detailed in equation 1. The law states that the pressure (p) and separation of the gap (d) directly influence the breakdown voltage of air (V_B). All other values are constants involving the gas composition and electrode material. When the voltage difference of the spark gap reaches the breakdown voltage of air, a spark will connect the electrodes, completing the circuit. The simplified version, equation 3, is then used for calculating the minimum voltage conditions, while equation 2 shows what was used for the simplification. To simplify the constant C is defined and the laws of logarithms is used to remove the logarithm. To get the minimum voltage, the derivative of the breakdown voltage in Paschen's Law is taken and set equal to zero. Equation 4 shows the derivative and equation 5 shows the root that is found for the derivative.

Paschen's Law

$$V_B = \frac{Bpd}{ln\left(Apd/ln(1/\gamma)\right)} \tag{1}$$

$$C = \ln\left(\frac{A}{\ln\left(\frac{1}{\gamma}\right)}\right) \tag{2}$$

$$V_B = \frac{Bpd}{ln(pd)+C} \tag{3}$$

$$\frac{\partial V_B}{\partial (pd)} = \frac{B(ln(pd)+C-1)}{(\ln(pd)+C)^2} \tag{4}$$

$$pd = e^{1-C} \tag{5}$$

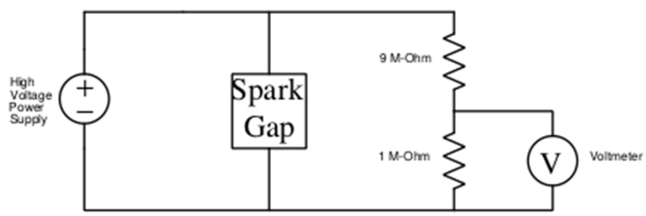
Since the multimeter is restricted in the amount of current it can handle, a separate circuit is set up to measure the voltage. Because the voltage across circuits in parallel are the same, the separate measuring circuit is connected in parallel to the spark gap. The separate circuit consists of two different resistors with a high resistance in series which limits the current and also effectively reduces the voltage. The equivalent resistance formulation, equation 6, is used for calculating the voltage to be measured in the circuit and how the reduction factor is calculated. Measured voltage (V_m) is given by the actual voltage from the multimeter (V), the resistance of resistor being measured across, and the equivalent resistance of the circuit.

Equivalent Resistance Voltage

$$V_m = V\left(\frac{R_1}{R_1+R_9}\right) \quad (6)$$

Methods:

To analyze the data, a thermometer/barometer/hygrometer was used to gather the temperature, pressure and humidity during each test. Feeler gauges were used to measure the gap distance before each test. A separate circuit used as a voltage divider was connected in parallel with the spark gap circuit. A 9 MΩ and a 1 MΩ resistor are connected in series and the voltmeter connected in parallel with the 1 MΩ resistor. This effectively reduces the voltage by a factor of 10 when reading from the multimeter, while simultaneously reducing the current going through this section of the circuit. The multimeter was used to check the breakdown voltage required for the tested distance and air composition.



Circuit Diagram for Testing

The design of the circuit centers on safety along with functionality. Safety is a concern because of the high voltages required by the spark gap and high currents that are created. The desired functionality is to produce a working spark gap that is reliable in different atmospheric conditions, 10 gauge wire was used to prevent the burning of a smaller gauge wire.

Three spark gaps were built for use in the circuit described above. The first design consisted of two 3/8" threaded holders bolted into a piece of wood with copper wire running from the bolts. Both bolts were screwed into the top portion of each angle bracket facing one another. The bolts were then screwed in and out to adjust the distance between the two. The wire for the circuit was attached on the end of the bolt and secured with nuts.

Image of Spark Gap 1

The second spark gap was built with two pieces of wood connected to each end of a hinge. A friction lid support for a chest was re-purposed to allow for the large adjustments of angle. A hole was then drilled through the wood on the each side. 3/8" brad tee nuts were placed into each side and screwed in. The electrode was then screwed into the nuts on both sides facing one another. The wire for the circuit was connected on the far end of the electrodes.

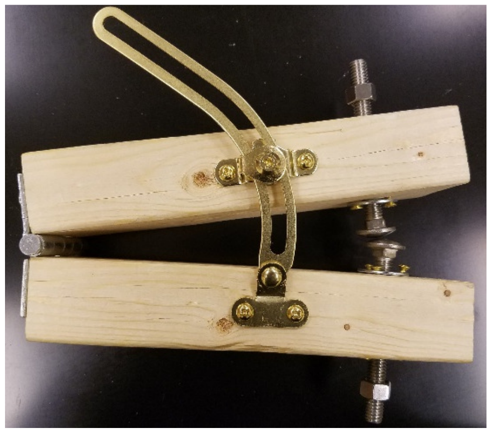


Image of Spark Gap 2

The third spark gap had a bottom of wood with wood attached on both ends. A hole was drilled into the wood to put a threaded rod through with a brass sphere head. 3/8" brad tee nuts were used again in this situation to allow for the adjustments. The spheres faced one another and copper wire was connected on the other side of the wood directly to the bolt. The bolt could be moved in and out to get the desired distance.

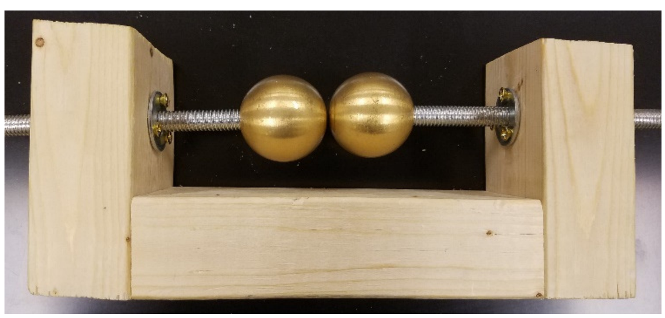


Image of Spark Gap 3

In the experiment, a DC high voltage source, with a max of 5 kV, was connected across the spark gap. Each day where there was a different condition in the humidity, a new test was ran. The tests consisted of increasing the voltage until a spark was observed for the three different designs. The test consisted of thirteen different spark gap separations of the electrodes over a range of distances from 0.038 mm to 0.635 mm.

The programming language ROOT was used to find a fit to Paschen's Law. The constants of the law were the fit parameters to be solved for. To verify that the experiment has worked, the line of best fit will have to have a Chi-Square value less than 15 when fitting. To have a successful design, the Chi-Squared value must be good and the design must fire consistently.

Data:

To calculate the error in the measurement of the voltage, the equivalent resistance voltage equation 7 is used. Below shows the formulation of the error in formula 8. The error for the voltage and resistance measured is found from the error on the Keysight 34401A 6 ½ Digit Multimeter. The error calculation for the pressure and distance is shown below. The error in the gap size is given by 0.038 mm, because it is the size difference that is certain the gap is not above. The pressures error is given by plus or minus 50 Pa.

Error Formulation

$$\Delta V = V\sqrt{(\frac{\Delta V_m}{V_m})^2 + (\frac{\Delta R_1}{R_1})^2 + (\frac{\Delta (R_1+R_9)}{R_1+R_9})^2} \tag{8}$$

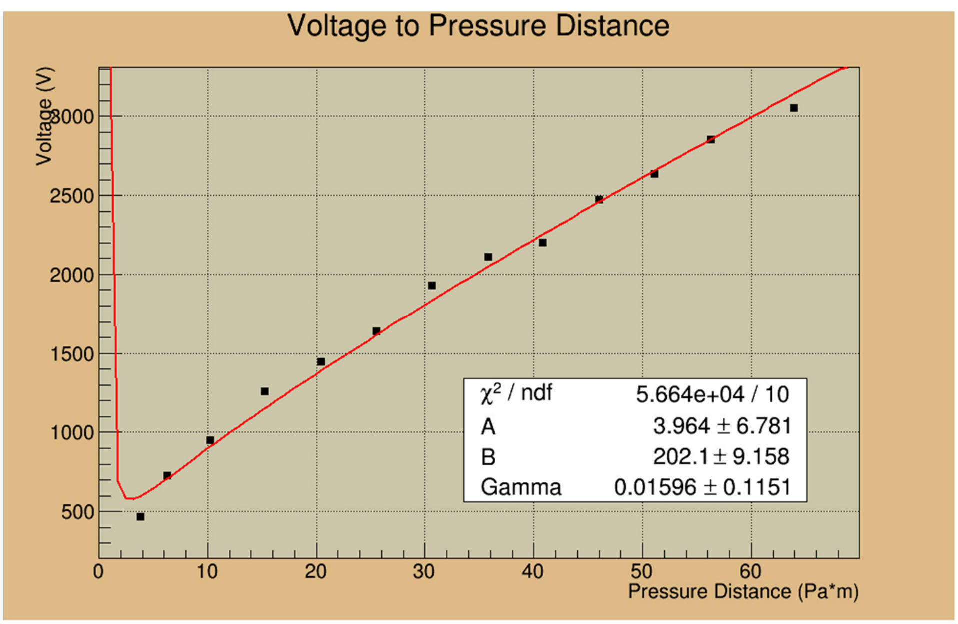
$$\Delta(R_1 + R_9) = \sqrt{\Delta R_1 + \Delta R_9} \tag{9}$$

$$\Delta(pd) = \sqrt{(\frac{\Delta p}{p})^2 + (\frac{\Delta d}{d})^2} \tag{10}$$

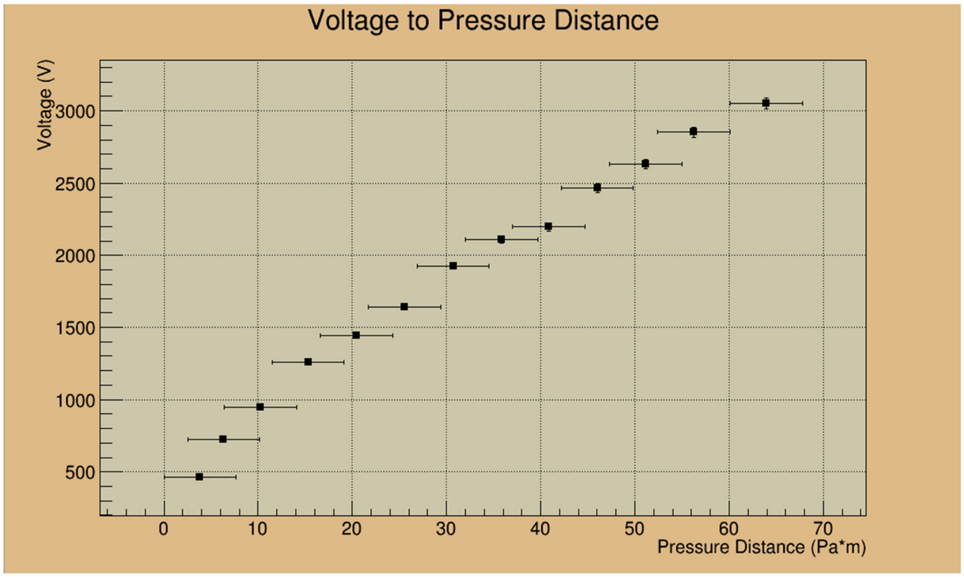
Data from Sparks Including Errors

All data is included in the appendices because of the bulky size of the tables containing the data.

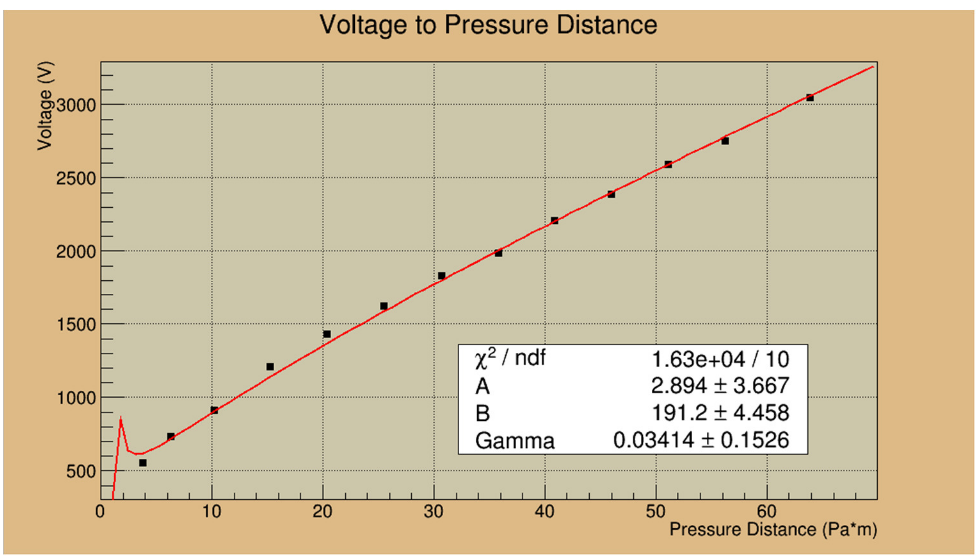
Graphs



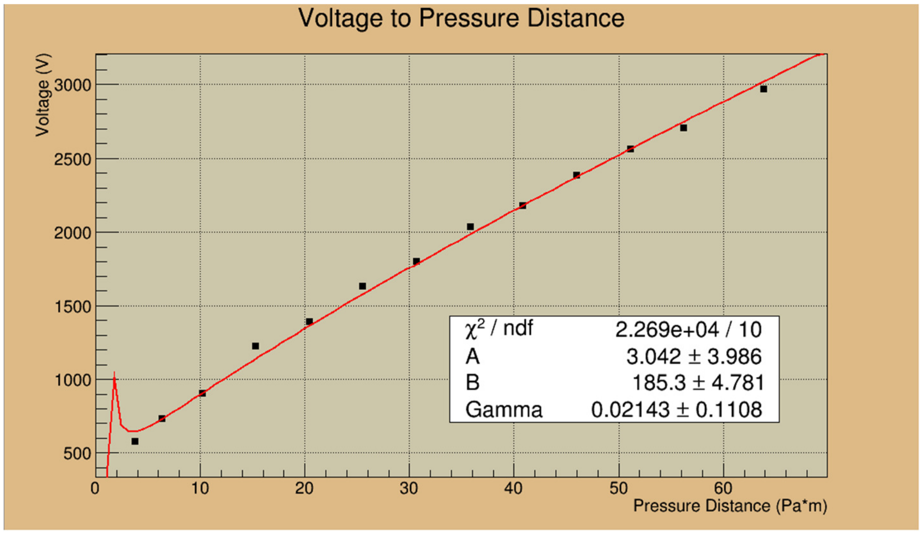
Averaged Data for Brass Sphere design at 19.5 % Humidity



Averaged Data and Error for Brass Sphere design at 19.5 % Humidity



Averaged Data for Brass Sphere design at 28 % Humidity



Averaged Data for Brass Sphere design at 49 % Humidity

Discussion:

The best design was chosen on adjustability and gap accuracy. The first design was thrown out because of the wide threading on the rod hanger which did not allow enough tightness to lock the electrode into a solid position. The slack caused an added time in setting the gap. The other two designs used the same ways for tightening so they had the same accuracy. The deciding factor for those two designs was the adjustability and since the second design had a minimal time for large gap changes and fine tuning, it was chosen as the best design. The electrode that showed the best results for the majority of the gap sizes was the bass spheres so it was chosen for the best. The others were all relatively close at high gap sizes so they could be used as an alternative when facing a cost constraint.

The chi-square value when fitting Paschen's Law to the data taken was on the order of thousands for all configurations so it was inconclusive on what the constant values were. For 19.5 % humidity and brass sphere configuration, the minimum distance is found to be somewhere between 5 and 28 μm if assuming standard pressure. For 28 % humidity and brass sphere configuration, the minimum distance is found to be somewhere between 7 and 31 μm if assuming standard pressure. For 49 % humidity and brass sphere configuration, the minimum distance is found to be somewhere between 8 and 34 μm if assuming standard pressure. Because of the high uncertainty, the minimum gap distance is not reliable to be used even through a range is found from the fit parameters by plugging them into formula 5.

The high chi-square value can be attributed to the lack of data taken at extremely low gap distances so the upward curve seen from Pashcen's Law is not accounted for. The data was not taken at this low of a distance due to the lack of feeler gauges small enough to accurately measure the gap at that size.

Conclusion:

To improve on this experiment, smaller feeler gauges on the order of single digit micrometers would be necessary. A finer threading would benefit the accuracy of the spark gap. In this experiment, 16 threads per inch was used, which is considered a coarse threading. To improve the spark voltage reading, graphing the voltage through a data acquisition machine would allow analyzing the graph for the instantaneous drops in voltage at the sparks. If attempting to only recreate Paschen's Law, thought should be put to changing the pressure instead of the gap size to allow for a more efficient way to get data from the entire curve including the lower end.

The experiment showed how essential it is to automate tasks when taking data so that the error can be minimized and more data can be taken rapidly. A day of taking data in this experiment would take from an hour to two hours, which with automation, would have been reduced greatly. Safety and sturdiness influenced a bigger design, although the designs could have been made at a smaller scale when only using for smaller gaps and the melting of the threading on the electrode is not an issue.

Appendices:

For the following table (1, 2, 3 signifies test number):

- Pressure: 1006.7 hPa
- Resistor 1: 1.000 MΩ
- Resistor 9: 9.000 MΩ
- Temperature: 21.4 ^{o}C
- Humidity: 49 %

	pd (Pa*m)	*Δpd* (Pa*m)	*V1* (V)	*ΔV1* (V)	*V2* (V)	*ΔV2* (V)	*V3* (V)	*ΔV3* (V)
Design 1	3.82546	3.825460472	604	7.3236051	601	7.28722958	608	7.3721058
	6.34221	3.825461297	795	9.6395133	805	9.76076507	805	9.7607651
	10.26834	3.8254634	947	11.48254	943	11.4340391	950	11.518915
	15.30184	3.825467549	1369	16.599363	1371	16.6236136	1373	16.647864
	20.43601	3.825473465	1505	18.248387	1505	18.2483869	1503	18.224137
	25.57018	3.825481081	1622	19.667032	1627	19.7276581	1628	19.739783
	30.70435	3.825490397	1901	23.049956	1900	23.0378306	1903	23.074206
	35.83852	3.825501412	2102	25.487116	2102	25.4871158	2104	25.511366
	40.87202	3.825513861	2215	26.85726	2214	26.8451352	2216	26.869386
	46.00619	3.825528242	2418	29.318671	2406	29.1731687	2405	29.161043
	51.14036	3.825544324	2630	31.889208	2632	31.913458	2636	31.961959
	56.27453	3.825562104	2759	33.453355	2759	33.4533551	2762	33.489731
	63.92545	3.825591755	3056	37.054532	3060	37.1030324	3059	37.090907
Design 2	3.82546	3.825460472	581	7.0447261	586	7.10535197	582	7.0568513
	6.34221	3.825461297	708	8.5846232	706	8.56037285	704	8.5361225
	10.26834	3.8254634	875	10.609527	871	10.5610266	878	10.645903
	15.30184	3.825467549	1142	13.846949	1141	13.8348235	1143	13.859074
	20.43601	3.825473465	1415	17.157121	1413	17.1328709	1413	17.132871
	25.57018	3.825481081	1592	19.303277	1594	19.3275274	1595	19.339653
	30.70435	3.825490397	1763	21.376682	1760	21.3403062	1758	21.316056
	35.83852	3.825501412	1948	23.619839	1943	23.5592131	1941	23.534963
	40.87202	3.825513861	2279	27.633272	2276	27.596896	2278	27.621146
	46.00619	3.825528242	2361	28.627536	2358	28.5911603	2354	28.54266
	51.14036	3.825544324	2574	31.210198	2573	31.1980727	2573	31.198073
	56.27453	3.825562104	2767	33.550356	2763	33.5018558	2765	33.526106
	63.92545	3.825591755	3024	36.666526	3026	36.6907765	3025	36.678651
Design 3	3.82546	3.825460472	572	6.9355995	579	7.02047575	580	7.0326009
	6.34221	3.825461297	727	8.8150015	734	8.89987772	734	8.8998777
	10.26834	3.8254634	901	10.924782	902	10.936907	905	10.973282
	15.30184	3.825467549	1224	14.841213	1217	14.7563368	1228	14.889714
	20.43601	3.825473465	1394	16.902493	1386	16.8054912	1391	16.866117
	25.57018	3.825481081	1614	19.570031	1642	19.9095357	1635	19.824659
	30.70435	3.825490397	1798	21.801063	1805	21.8859391	1808	21.922315
	35.83852	3.825501412	2031	24.626228	2036	24.6868543	2035	24.674729
	40.87202	3.825513861	2173	26.348003	2176	26.3843786	2179	26.420754
	46.00619	3.825528242	2386	28.930665	2386	28.9306652	2384	28.906415
	51.14036	3.825544324	2567	31.125322	2566	31.1131965	2560	31.040445
	56.27453	3.825562104	2701	32.750095	2703	32.7743453	2706	32.810721
	63.92545	3.825591755	2968	35.987516	2966	35.9632661	2969	35.999642

For the following table (1, 2, 3 signifies test number):

- Pressure: 1007.1 hPa
- Resistor 1: 1.000 MΩ
- Resistor 9: 9.000 MΩ
- Temperature: 21.3 ^{o}C
- Humidity: 28 %

	pd (Pa*m)	Δpd (Pa*m)	V1 (V)	ΔV1 (V)	V2 (V)	ΔV2 (V)	V3 (V)	ΔV3 (V)
Design 1	38.2698	38.2698047	606	7.34786	600	7.2751	604	7.32361
	63.4473	38.269813	768	9.31213	783	9.49401	784	9.50614
	102.7242	38.269834	1039	12.5981	1036	12.5617	1038	12.5859
	153.0792	38.2698755	1260	15.2777	1258	15.2535	1257	15.2413
	204.4413	38.2699346	1456	17.6543	1452	17.6058	1453	17.6179
	255.8034	38.2700107	1646	19.958	1648	19.9823	1647	19.9702
	307.1655	38.2701038	1839	22.2982	1839	22.2982	1837	22.2739
	358.5276	38.270214	2132	25.8509	2131	25.8387	2130	25.8266
	408.8826	38.2703384	2245	27.221	2243	27.1968	2246	27.2331
	460.2447	38.2704822	2428	29.4399	2429	29.452	2428	29.4399
	511.6068	38.2706429	2651	32.1438	2645	32.0711	2647	32.0953
	562.9689	38.2708206	2743	33.2594	2742	33.2472	2741	33.2351
	639.5085	38.271117	3044	36.909	3047	36.9454	3047	36.9454
Design 2	38.2698	38.2698047	579	7.02048	578	7.00835	580	7.0326
	63.4473	38.269813	764	9.26363	767	9.30001	765	9.27576
	102.7242	38.269834	957	11.6038	958	11.6159	957	11.6038
	153.0792	38.2698755	1250	15.1565	1248	15.1322	1249	15.1443
	204.4413	38.2699346	1438	17.436	1436	17.4117	1438	17.436
	255.8034	38.2700107	1702	20.637	1699	20.6007	1700	20.6128
	307.1655	38.2701038	1831	22.2012	1828	22.1648	1832	22.2133
	358.5276	38.270214	2064	25.0264	2065	25.0385	2066	25.0506
	408.8826	38.2703384	2188	26.5299	2189	26.542	2191	26.5663
	460.2447	38.2704822	2400	29.1004	2398	29.0762	2398	29.0762
	511.6068	38.2706429	2643	32.0468	2642	32.0347	2644	32.059
	562.9689	38.2708206	2768	33.5625	2769	33.5746	2770	33.5867
	639.5085	38.271117	3036	36.812	3037	36.8242	3037	36.8242
Design 3	38.2698	38.2698047	553	6.70522	552	6.6931	556	6.7416
	63.4473	38.269813	731	8.8635	732	8.87563	732	8.87563
	102.7242	38.269834	912	11.0582	912	11.0582	911	11.046
	153.0792	38.2698755	1207	14.6351	1199	14.5381	1208	14.6472
	204.4413	38.2699346	1426	17.2905	1429	17.3269	1427	17.3026
	255.8034	38.2700107	1621	19.6549	1624	19.6913	1622	19.667
	307.1655	38.2701038	1831	22.2012	1829	22.1769	1828	22.1648
	358.5276	38.270214	1986	24.0806	1978	23.9836	1982	24.0321
	408.8826	38.2703384	2209	26.7845	2211	26.8088	2208	26.7724
	460.2447	38.2704822	2386	28.9307	2388	28.9549	2387	28.9428
	511.6068	38.2706429	2591	31.4163	2588	31.38	2589	31.3921
	562.9689	38.2708206	2750	33.3442	2749	33.3321	2748	33.32
	639.5085	38.271117	3042	36.8848	3045	36.9212	3045	36.9212

For the following table (1, 2, 3 signifies test number):

- Pressure: 1013.9 hPa
- Resistor 1: 1.000 MΩ
- Resistor 9: 9.000 MΩ
- Temperature: 21.3 ^{o}C
- Humidity: 19.5 %

	*pd (Pa*m)*	*Δpd (Pa*m)*	*V1 (V)*	*ΔV1 (V)*	*V2 (V)*	*ΔV2 (V)*	*V3 (V)*	*ΔV3 (V)*
Design 1	38.5282	38.52820468	578	7.008351	575	6.97197505	574	6.9598499
	63.8757	38.52821288	741	8.984754	738	8.94837841	736	8.9241281
	103.4178	38.52823375	1000	12.12517	1009	12.2343006	1008	12.222175
	154.1128	38.52827496	1352	16.39324	1355	16.4296108	1353	16.40536
	205.8217	38.5283337	1586	19.23053	1584	19.2062756	1584	19.206276
	257.5306	38.52840931	1896	22.98933	1894	22.9650796	1893	22.952954
	309.2395	38.52850181	1998	24.2261	1996	24.2018473	1994	24.177597
	360.9484	38.52861118	2215	26.85726	2212	26.8208849	2213	26.83301
	411.6434	38.52873479	2296	27.8394	2295	27.8272743	2297	27.851525
	463.3523	38.52887758	2491	30.20381	2490	30.1916833	2487	30.155308
	515.0612	38.52903725	2634	31.93771	2635	31.9498335	2636	31.961959
	566.7701	38.52921379	2827	34.27787	2828	34.2899921	2827	34.277867
	643.8265	38.52950819	3184	38.60655	3183	38.5944289	3183	38.594429
Design 2	38.5282	38.52820468	538	6.523344	543	6.58396948	541	6.5597191
	63.8757	38.52821288	724	8.778626	726	8.80287633	727	8.8150015
	103.4178	38.52823375	1055	12.79206	1053	12.7678082	1052	12.755683
	154.1128	38.52827496	1241	15.04734	1243	15.0715913	1242	15.059466
	205.8217	38.5283337	1523	18.46664	1524	18.4787652	1521	18.44239
	257.5306	38.52840931	1761	21.35243	1763	21.3766818	1759	21.328181
	309.2395	38.52850181	1883	22.8317	1887	22.8802033	1887	22.880203
	360.9484	38.52861118	2121	25.71749	2119	25.6932437	2120	25.705369
	411.6434	38.52873479	2215	26.85726	2216	26.8693856	2214	26.845135
	463.3523	38.52887758	2451	29.7188	2453	29.7430518	2455	29.767302
	515.0612	38.52903725	2621	31.78008	2624	31.8164566	2623	31.804331
	566.7701	38.52921379	2853	34.59312	2854	34.6052466	2853	34.593121
	643.8265	38.52950819	3102	37.61229	3102	37.6122898	3105	37.648665
Design 3	38.5282	38.52820468	461	5.589705	464	5.62608074	463	5.6139556
	63.8757	38.52821288	724	8.778626	719	8.71800011	724	8.778626
	103.4178	38.52823375	948	11.49466	947	11.4825398	952	11.543166
	154.1128	38.52827496	1254	15.20497	1257	15.2413437	1256	15.229219
	205.8217	38.5283337	1442	17.4845	1441	17.4723757	1442	17.484501
	257.5306	38.52840931	1644	19.93379	1633	19.8004091	1639	19.87316
	309.2395	38.52850181	1921	23.29246	1929	23.3894607	1926	23.353085
	360.9484	38.52861118	2108	25.55987	2111	25.5962423	2111	25.596242
	411.6434	38.52873479	2195	26.61476	2198	26.6511325	2198	26.651132
	463.3523	38.52887758	2467	29.9128	2468	29.9249294	2469	29.937055
	515.0612	38.52903725	2633	31.92558	2634	31.9377083	2635	31.949833
	566.7701	38.52921379	2851	34.56887	2853	34.5931214	2854	34.605247
	643.8265	38.52950819	3054	37.03028	3052	37.0060311	3053	37.018156