PHYSICS OF DC CARBON TRACKING OF PLASTIC MATERIALS

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ABSTRACT

Carbon Tracking is a phenomenon where an electric field across a normally insulating plastic can, in the presence of contamination, grow into an electrical short and cause a fire.

Underwriters Laboratories (UL) has long had a Carbon Tracking test (UL 746A, Section 23) for exposure to Alternating Current (AC), and have developed an index to classify materials as to their resistance to this phenomenon.

Recently, the United States Council for Automotive Research (USCAR) and MVFRI sponsored research at UL to develop such a test for Direct Current (DC) voltages which may be used in 42-volt (and higher) electrical systems for automobiles. For the DC test, we changed the electrodes to copper and we switched the electrolyte (used to simulate surface contamination – also sometimes called "reagent") from 0.1 % Ammonium Chloride to 5 % Sodium Chloride. The latter is representative of road salt and has a much higher electrical conductivity than Ammonium Chloride. Drops of a specified volume of electrolyte are applied to the plastic sample between the electrodes. A drop is made to fall approximately every 30 seconds, and if a sample survives 50 drops or more it is said to "pass" the test. The highest voltage that will result in 50 drops for a given material is the "Index" for that material.

UL performed this new DC test on 24 materials which are candidates for electrical system components (such as insulation and connectors) for 42-volt automotive electrical systems. Twelve tests were instrumented to capture electrode voltage and current at a sampling rate of 1000 Hertz. From these measurements, instantaneous power and cumulative energy were computed.

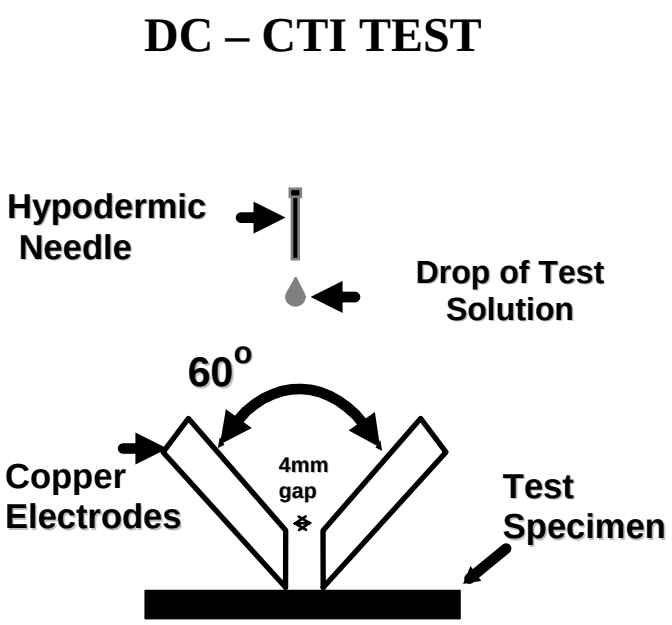
In this paper a simple model is presented which helps explain the effect of voltage, electrolyte conductivity, and electrolyte composition on the performance of several plastic materials. Several hypotheses for explaining this behavior are proposed and evaluated.

INTRODUCTION

Basic Results

The apparatus for the DC tests is shown in Figure 1.

Figure 1 – DC CTI Test Setup



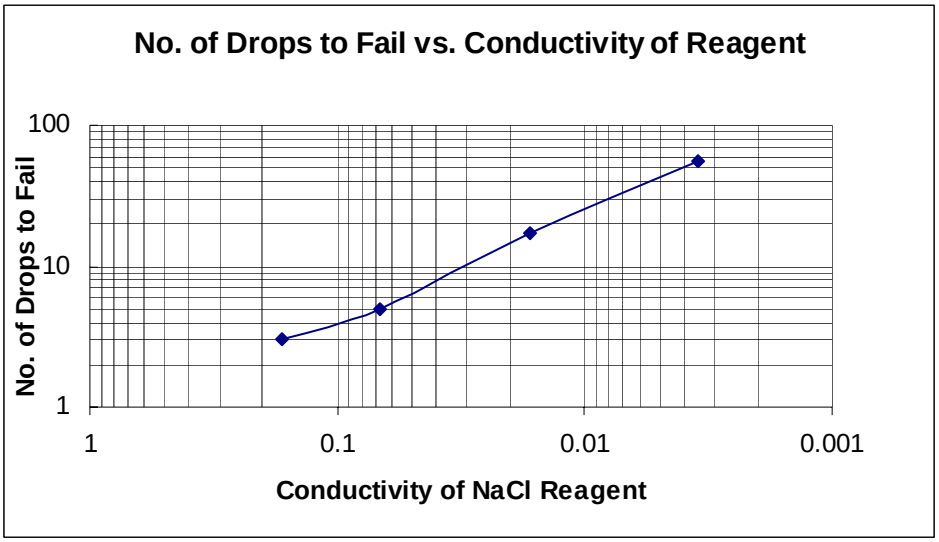
The UL basic test results [1, 2, 3] cover 24 materials subjected to DC voltages of 150, 100, 60, 50, 42, and 12. The highest voltage was tested first and some materials passed the test at that voltage. These are deemed "150-volt" materials. For those that failed, the voltage was reduced to 100 volts, and the test repeated. And so on, until the material passes. Out of the 24 materials, 5 passed at 150 V, 4 at 100 V, 10 at 60 V, 3 at 50 V, 1 at 42 volts, and 1 at 12 V. There certainly was a wide range of performance, which shows that the test can differentiate significant performance differences between these materials. The basic results are shown in Table 1 at the end of the paper. The designation "55+" means that the test was terminated at 55 drops and no failure had yet occurred. References [1, 3] are available at: www.mvfri.org

The basic report[1] contains a 32-citation literature search as Appendix A. Most of the academic research in this field was done by Professor William Middendorf [4, 5, 6, 7] of the University of Cincinnati during the 1980s. Prof. Middendorf has deceased, and that research has not been continued by the University. The tracking process is thought to work by "unzipping" the polymers and creating conductive carbon – a thermal degradation process. For the high conductivity electrolyte used here, there is a high thermal assault when each drop falls, and the presence of water can also help decompose the polymers.

Two materials, numbers 5 and 16, were subjected to 10 trials each to demonstrate repeatability. The standard deviation of the number of drops to failure is about 20-30%.

The effect of electrolyte conductivity was also examined by varying the concentration of the salt and Ammonium Chloride solutions. The resistivity values for the various electrolytes used are given in Table 2 of Reference [1]. The results[1] for material 16 at 100 V DC are shown in Figure 2. It is seen that there is a near straight line relationship on a log-log plot indicating a power relationship. The change from the 0.1% Ammonium Chloride (385 ohm-cm) used for the AC test, to the 5% NaCl (15 ohm-cm) for the DC test is a big change (factor of 26). Conductivity is the inverse of resistivity and is measured in Siemans/cm.

Figure 2 - No. of Drops to Fail vs. Conductivity of Electrolyte (Material 16)



One of the mysteries from these tests is that ceramic and glass substrates are also able to "track" (really result in a high-current arc), but at a high number of drops. For this situation, the physics and chemistry are clearly different because there is no source of carbon in the substrate. More will be said about this below.

Instrumented Tests

Additional testing was done on selected materials and reported in an Addendum [3.] These tests were video taped, and the voltage and current were measured at 1000 Hertz. Instantaneous power and cumulative energy were computed and plotted. The matrix of test conditions and results is shown in Table 2 at the end of the paper.

The plots from a typical short duration test, test # 4, are shown in Figures 3, 4, 5, and 6 at the end of the paper. This test is for material # 16, at 100 V DC, and using the 5% NaCl electrolyte.

On the current plot (Figure 4), you can see the spike each time a drop falls. This material failed just after the 7th drop. The voltage plot shows a voltage reduction with each electrolyte drop. This is due to the ballast resistor which is in series with the electrode circuit. The power curve shows the peak power of 75-100 watts after each drop. The cumulative energy plot shows the energy input of about 100 joules per drop. The end of the test, where an arc is stuck, is clearly identifiable in all the plots. The test is rapidly terminated when this happens. Also, the sample is always in flames at this point. During the test you can see some intermittent current activity between drops. This is called "scintillation" and appears to be small carbon micro-arcs which form and then extinguish.

A SIMPLE MODEL OF CARBON TRACKING

The tracking test is a thermally violent event at the high DC voltages and with the very conductive electrolyte. The event is initialized by the falling of the first drop of electrolyte between the electrodes. For a simple series circuit the power dissipated is given by Equation 1.

$$P = V^2 / R \quad (1)$$

The resistance, R, can be computed from the geometry of the electrodes. The electrodes are 5 mm wide and are spaced 4 mm apart. If you visualize imaginary "walls" one has a box with an area of 20 mm^2. The volume of the drop is specified by UL as 20 mm^3 (+5, and – 0). Thus a thickness of 1 mm of electrolyte will fill the box. The resistance can be computed from the resistivity, ρ (ohm-cm), by Equation 2.

$$R = \rho L/A \quad (2)$$

Where L is the spacing between the electrodes (0.4 cm), and A is the cross-sectional area (0.05 cm^2). Thus R = 8 ρ. For the 5% NaCl electrolyte, the resistivity is 15 ohm-cm which yields a resistance of 120 ohms.

For a 100 V test, the power from equation 1 is about 80 watts which is close to that shown in the 100 V example in Figure 5 (ca 75 - 100 watts). Note that this simple calculation assumes that there is no electrical conduction through the specimen under test. This is a good assumption until the very end of the drop sequence when arcing begins.

How much energy will be released by each drop? The 80 Watt power will quickly evaporate the water in the droplet and rapidly reduce the current flow to near zero.

The specific heat of water is 4.2 J/g – K. The water must be heated from room temperature (20C to 100 C – its boiling point) or a total of 80 K. The energy required to do this is 336 J/g.

The heat of vaporization of water is 2261 J/g. Thus the total energy to heat and evaporate the drop is ca 2600 J/g. The mass of water in the 20 mm^3 drop is 0.02 g, so the energy required to vaporize the drop is about 50 Joules. For the 100 V test this implies the drop should evaporate in ca 0.6 second. The predicted energy per drop of 50 Joules is about a factor of 2 less than observed.

Of course the real dynamics are time dependent, but a study of the plots shows that the drops disappear faster at higher voltage, and, at 100 V, the event lasts about 2 seconds – longer than predicted above. Also, as the drop boils away, the conductivity of the solution will increase thereby increasing the current and power delivered. The drop temperature will be limited to 100 C until most of the water is gone.

It should be noted that UL had considerable difficulty with their electrolyte pump and hypodermic needle used to deliver the 20 mm^3 drops. It is possible that drop-to-drop variability contributed to the range of values for the number of drops to failure.

HYPOTHESES FOR TRACKING BEHAVIOR AND RESULTS

Hypotheses and results

Prior to the testing, the author posited several hypotheses to test with the Addendum, instrumented, series of tests. They are:

1. Effect of Material.

Hypothesis: A low performing material should fail with considerably less cumulative energy than a high performing material. The amount of energy it takes to fail a material should be quite different for the various materials.

Material number 22 was chosen as a high performing material (100 V material), and material # 6 as a low performing one (42 V material). As seen in Table 2 it took more energy to fail the low performing material – so this hypothesis is *not* correct.

It can be shown from Table 2 that the average energy per drop is ca 120 Joules. There is a voltage dependence, but much less pronounced than V^2. The total energy released is thus pretty much directly proportional to the number of drops to failure.

It appears that most of the energy released with each drop is consumed in vaporizing the drop. The fraction that actually goes into the sample, and is available to form carbon, is unknown, but obviously much less.

A prediction was made that the background current between drops would gradually increase for the last few drops, and then lead to an exponential increase in current which would lead to arcing and ignition of the sample. While that shows up on a few tests, it is not evident on most tests. Each drop seems to be a more or less independent event. A study of several of the videos shows that the samples have brief flaming even after the first drop or two, and then the sample is able to absorb more and more drops. It is not clear what finally causes the sample to fail. Could it be the deposits on the surface? See the discussion about the test on glass, below.

2. Effect of Resistivity of the Electrolyte.

Hypothesis: The total energy should be about the same for the same material, electrolyte composition, and voltage. There may be a reduction of the total energy for the low resistivity (high conductivity) electrolytes because there is less time for material cooling before failure.

Tests 3, 4, and 5 test this hypothesis. The total energy is *not* about the same as shown in Table 2. The highest conductivity electrolyte has the lowest energy, and also the lowest number of drops. It is easily shown that the number of drops to failure is approximated by 0.5 ρ (ohm-cm).

It should be noted that battery acid has a resistivity of ca 3 ohm-cm (when fully charged) and thus is a factor of 2 more conductive than the 15% NaCl electrolyte. If tested with battery acid (sulfuric acid) the sample would be expected to fail in 1, or at most 2, drops.

It is well known that most crash-induced fires start under the hood. It is possible that various underhood fluids, including gasoline, could be electrically conducting, and could lead to Carbon Tracking. To test this, MVFRI contracted with Chilworth Technology[8] to measure the resistivity of 12 different underhood fluids. The results showed that the resistivity was at least 3 orders of magnitude higher than that required to be a concern for tracking.

3. Effect of Electrolyte Composition.

Hypothesis: The composition of the electrolyte should be a second order effect after the resistivity and voltage.

Tests 6 and 7 have different compositions but the same resistivity (15 ohm-cm). The total energy and the

number of drops are within 20% of the average – which is about the variance experienced in all these tests.

4. Effect of Voltage.

Hypothesis: The number of drops to failure (or total energy) should go as $1/V^{2.}$ There may be a reduction of total energy for the high voltage tests because there is less time for material cooling before failure.

The UL report[3] plots the energy versus V^2 and shows this hypothesis is supported. The number of drops to failure also follows this trend and can be approximated by $37{,}000/ V^2$.

5. Effect of Glass (non-carbon based substrates)

Hypothesis: An inorganic material such as a glass substrate should not exhibit Carbon Tracking.

In the original report[1] and the addendum report[3] samples of Pyrex glass were tested. Ceramic was also tested in the original report. Glass does not contain any carbon and thus would not be expected to become conductive. In the 3 tests on glass there was a failure between 54 and 61 drops – just over the "pass" criterion of 50 drops.

How could this happen? The DC test was derived from a long standing AC test at UL. In the AC test the electrolyte was 0.1 % Ammonium Chloride which has a resistivity 26 times higher than the 5% NaCl used for the DC test. So that AC test is much less energetic. Also the AC test uses Platinum electrodes while the DC uses copper. It is likely that conductive compounds are made in the vicinity of the electrodes. They are likely to be compounds made up of atoms from the water, sodium, chlorine, copper, and even oxygen and nitrogen from the air. UL did some preliminary chemical analysis of the deposits left on the glass after the test. They found Cu_2O, CuO, and Sodium Silicate. However, all three have very high resistivities and are not conductive. Salt deposits are also present and may be conductive and lead to tracking.

Never-the-less, the glass sample did fail. There is obviously another process occurring which probably is also present for polymer samples. It may be desirable to reduce the "pass" criterion from 50 drops to a lower number, say 35 drops, in order to avoid this other effect. A review of the UL original report[1] shows that changing the "Pass" criterion to 35 drops would raise 10 materials up one voltage Index category and leave the other 14 unchanged. It would also not have a major effect on the relative ranking of the materials. This is an area for further research.

OBSERVATIONS & CONCLUSIONS

A DC carbon tracking test has been developed by UL. The test procedure is in the process of becoming an ASTM standard.

The repeatability of the tests is pretty good – say 20-30% variation in the number of drops to failure.

The test is a thermally intense event. It is indicative of high concentration salt used on the roads in winter. It is not indicative of a slow, 15-year life test where the physics are not thermally driven until the very end. Thus a supplementary test may be needed to cover long-term carbon tracking.

The current test set-up limits the short circuit current to 20 A by a series ballast resistor. That resistor results in significant voltage droop as current is drawn with each drop. It also adds inductance to the circuit which contributes noise and possibly negative currents. It is recommended that a "stiff" power supply be used and that the current be limited by a current-limiting power supply. That may help reduce

the variability of the tests. It is also recommended that the drop size be monitored. It may be possible that the electrolyte drop mechanism is contributing to the variability of results.

In the future, it is also desirable to automate the test as much as possible. This will reduce lab-to-lab and technician-to-technician variance.

There is still some question about what finally causes the material to fail – that is, to cause a high current arc between the electrodes and for the plastic to burst into flame. Which comes first, the flame or the electrical arc? Once an arc starts between the electrodes it will sustain itself – especially at the higher DC voltages. The resulting energy release is enormous, and any plastic will soon flame. There are several mechanisms going on simultaneously: (1) The thermal assault (as emphasized in this paper) which can cause thermal degradation of the sample; (2) the build up of deposits of salt, copper, and many associated compounds formed from the atoms present (including air); and (3) the build-up of carbon "tracks" from either thermal degradation or from the small scintillation arcs. Also, as the polymers "unzip" they revert back to the monomers from which they are made. Many of these are flammable gases - for example, ethylene. It is also likely that hydrogen and oxygen are formed at the electrodes due to electrolysis. Could these flammable gases be the source of the little flames frequently seen even in the early part of the drop sequence? What is necessary to start an arc? We all assume that carbon is involved – after all, the test is called "Carbon Tracking." Is it possible to track without carbon? Maybe so – we showed it on glass and ceramic.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Consider changing the "pass" criterion to 35 drops.

2. Do more extensive chemical analysis of the deposits on the glass and on the plastic samples (which lasted 50 drops or longer and did not fail). Try to determine the phenomenon which allows glass and ceramic to track, and examine the extent it also affects the plastic samples. It would be informative to repeat the glass tests (up to 500 drops) with platinum electrodes. If it fails to track with Platinum, then we will know for sure that copper is the culprit. It would also be interesting to test the watch glass at 100 V in addition to 150 V.

3. Take steps to improve repeatability through better drop size control, fixed voltage from the power supply (no ballast resistor), and test automation.

4. Develop a separate test to stimulate a slow, non-thermal, tracking process taking place over the 15-year life usually assumed for an automobile. Of course it will have to be accelerated, but not by a factor of 300,000 as is the current DC tracking test.

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CONTACT

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Table 1 – Test Summary

Material Designation	Average No. of Drops to Track Voltage 150	100	60	50	42	12	DC CTI
1	49+	55+	55+	---	---	---	100
2	3	5	37	55	55+	---	50
3	3	38	55+	55+	55+	---	60
4	14	39	55+	---	---	---	60
5	1	5	21	---	47	*	12
6	1	4	18	35	55+	---	42
7	55+	55+	55+	---	---	---	150
8	1	3	43+	55+	55+	---	50
9	4	21	55+	---	---	---	60
10	3	17	55+	---	---	---	60
11	55+	55+	55+	---	---	---	150
12	55+	55+	55+	---	---	---	150
13	55+	55+	55+	---	---	---	150
14	3	9	55+	---	---	---	60
15	52+	55+	55+	---	---	---	100
16	1	5	53+	55+	---	---	50
17	42+	55+	55+	---	---	---	100
18	55+	55+	55+	---	---	---	150
19	3	15	55+	---	---	---	60
20	4	8	55+	---	---	---	60
21	2	10	51+	55+	55+	---	60
22	12	55+	55+	---	---	---	100
23	55+	55+	55+	---	---	---	150
24	4	40	55+	---	---	---	60
25	1	5	55+	---	---	---	60

Note: * No scintillations were observed. Test aborted.

Table 2 – Addendum Test Results

Test #	Hypothesis	Material ID #	Reagent / Concentration	Voltage (VDC)	Addendum Tests No. of Drops to Failure				December 15, 2003 Report Results No. of Drops to Failure											Energy (Joules)
					Trial				Trial											
					1	2	3	4	1	2	3	4	5	6	7	8	9	10	11	
1	1 - Material	22	NaCl / 5%	150	33	33	**7**		15	9	11									850
2	"	6	NaCl / 5%	60	**16**				26	17	10									1450
3	2 - Resistivity	16	NaCl / 1%	100	**38**	33			21	20	11									4375
4	"	16	NaCl / 5%	100	**6**				6	5	4	5	3	6	7	3	6	3		740
5	"	16	NaCl / 15%	100	**3**				3	3	3									300
6	3 - Electrolyte	5	NaCl / 5%	42	**33**	32	78		54	48	37	52	55+	33	51	55+	55+	26	77	3700
7	"	5	NH_4Cl / 35%	42	**48**	15	>65	19	32											5700
8	4 - Voltage	5	NaCl / 5%	150	**1**				2	1	1									200
9	"	5	NaCl / 5%	100	**3**				7	4	4									375
10	"	5	NaCl / 5%	60	11	**16**			17	25	20									1510
11	5 - Glass Substrate	glass	NaCl / 5%	150	**54**				61	61										7500
12	vs. Carbon Material	25	NaCl / 5%	60	**66**				70	55+	55+	55+								7620

Note: The No. of Drops to Failure indicated in **BOLD FACE** under the Addendum Tests reflects the trial used to calculate the Energy and the Energy/Drop at the point of arc tracking failure.

Figure 3. Voltage (Volts)

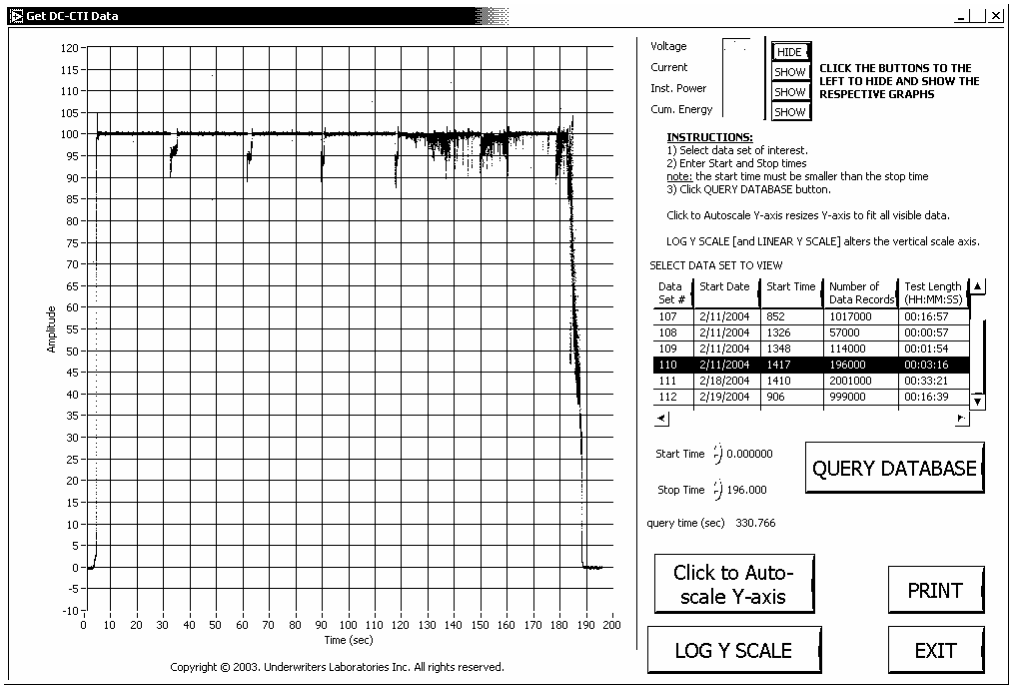

Figure 4. Current (Amps)

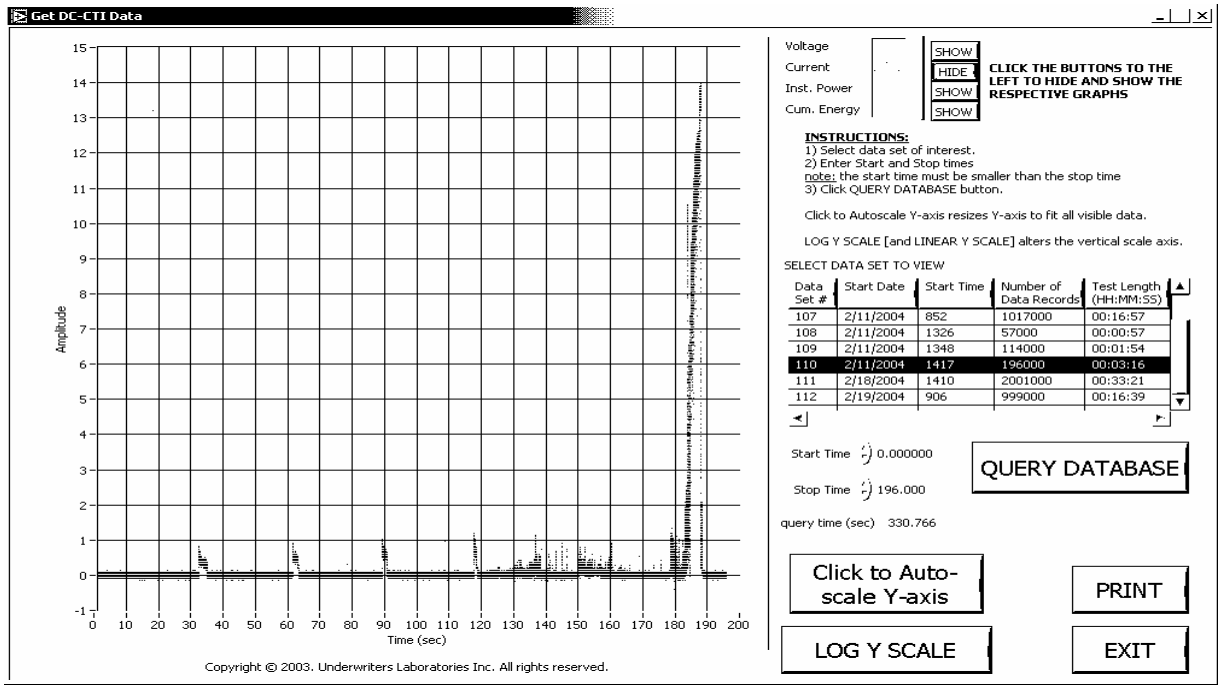

Figure 5. Power (Watts)

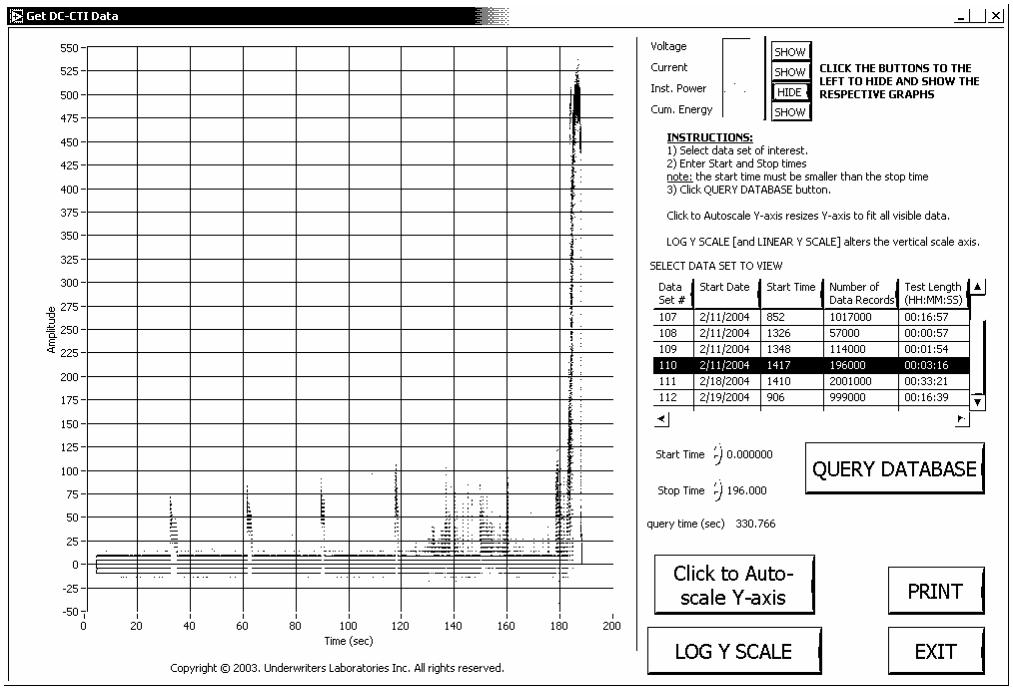

Figure 6. Cumulative Energy (Joules)