Underwriters Laboratories Inc.®

PROPERTIES OF PLASTIC MATERIALS FOR USE IN AUTOMOTIVE APPLICATIONS

Study of Arc Track Properties of Plastic Materials when Subjected to DC Voltages Ranging from 12 V DC - 150 V DC

Addendum Report

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Prepared for the:
United States Council for Automotive Research

and the:
Motor Vehicle Fire Research Institute

Prepared by:
Rich Wagner
Senior Research Engineer
Research & Development

Reviewed by:
John Stimitz
Principal Engineer
Primary Designated Engineers

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EXECUTIVE SUMMARY

The automotive industry is evolving automobile designs using greater electrification of systems and components previously mechanically operated. e.g. – air conditioning, water pumps, oil pumps, heating, and solenoid operated engine valves. The resulting demands on electrical systems require upgrading from the traditional 12 V DC battery supply to a 36 V DC battery supply with a nominal 42 V DC charging circuit. Automobiles utilizing electric traction motors generally operate at even higher DC voltages.

A concern when operating in an automotive environment at increased DC voltage levels, is the DC arc track properties of thermoplastic materials used for automotive switches, electrical connectors, etc. A DC electrical arc, once struck may be more readily sustained than an AC arc due to the inherent stability of its uni-polarity. In an AC arc, the arc voltage and current become zero each half cycle allowing the conductive gas to cool. If the plasma cools to the extent that the gas becomes de-ionized, the arc will extinguish and will require that the arc be repeatedly re-struck each half-cycle in order to sustain itself. In a DC arc, the arc voltage and arc current do not experience a zero crossover, and once DC arcing is established, the arc tends to be self-sustaining.

The appropriate selection of thermoplastic materials for use at the higher DC voltages will mitigate the possibility of an arc tracking event occurring. In order to develop a suitable test that would evaluate the arc tracking properties of thermoplastic materials and assist in identifying suitable materials, a UL Research Project was conducted titled:

Study of Arc Track Properties of Plastics Materials when Subjected to DC Voltages Ranging from 12 V DC - 150 V DC

The DC-CTI test design was optimized through experimentation on a variety of materials. Following development of an acceptable test design, a series of evaluation trials were conducted using 24 different polymeric materials supplied by Daimler-Chrysler, Ford and General Motors. A report of our findings was issued on December 15, 2003 [1].

Following issuance of this report, additional testing was performed as described in this Addendum Report.

ADDENDUM TESTING

A. Introduction:

On December 15, 2003, Underwriters laboratories released a report describing the development of a DC Comparative Tracking Index (DC-CTI) Test to be used as a pre-selection criteria for choosing polymeric materials for use in 42 V DC automotive applications. Twenty-four (24) materials supplied by USCAR were evaluated using the developed test criteria.

Additional testing was planned (but not included in the 12-15-03 report) to conduct repeat DC-CTI testing with the DC-CTI test equipment instrumented to record electrode voltage (V) and current (I). These values could then be used to calculate and plot instantaneous power (V x I). Integrating the area under the power curve produced a cumulative energy plot.

B. Instrumentation:

For each test run, the voltage at the test electrodes and the current were recorded at the rate of 1 kHz utilizing a National Instruments SCXI-1000 data acquisition system. The instrumentation was calibrated and zeroed prior to its use. The test voltage was measured directly across the copper electrodes. The test current was measured using a coaxial shunt in order to capture both the steady state DC as well as time varying DC characteristic associated with DC electrical arcing. This shunt has an internal impedance of 0.01018 ohms. At a DC current of 20 A (the maximum permitted by the ballast resistor) the calculated shunt output is 204 mV. At test failure, an arcing fault current approaching 20 A was expected and the selected shunt satisfactorily recorded the current flow at failure of the test specimen.

A problem was encountered, however, when attempting to record the currents observed prior to the tracking failure during the periods of visible scintillation. At these much lower levels of current, background “noise” can introduce an error in the measurements. Sources of noise in the lab include the fluorescent lights as well as line noise produced by other pieces of test equipment in use in the lab. Shielded leads were used and a snap-on RF choke added to the lead between the current transducer and the data acquisition system in order to minimize noise pickup, however some noise is still visible on each of the current plots with the DC power supply turned on before the first droplet of reagent has fallen.

C. Data:

The voltage and current data were plotted and used to calculate and plot the instantaneous power. Energy was calculated and plotted by integrating the area under the instantaneous power curve.

Before each test, a reference signal to both channels was recorded with the DC power supply turned on and before the first droplet of reagent had fallen. This was later used to establish a zero reference and correct the raw data using LabView software but did not entirely eliminate the “noise” associated with the scintillation current measurements.

When the recorded scintillation current data is multiplied times the recorded voltage data to calculate the instantaneous power, the “noise” is exaggerated. For a given level of “noise”, the greater the applied voltage, the greater the error magnification will be.

The plots labeled as Power show what appears to be “negative power”. This “negative power” is simply the noise multiplied out and is cancelled out during the integration of the Power plot to get the Energy plot. In our opinion, the affect of the "noise" is relative to each plot, and therefore, the curves are comparative. If the "noise" were eliminated, each curve would be slightly adjusted by that offset. All of the data recorded used the same instrumentation and laboratory procedures and conditions. Any hypotheses to explain the behavior of the test specimens may be based on this relative data.

Plots of voltage, current, power and energy from each test (selected trials as identified in Table 1) are shown in Appendix A.

D. Video Record:

Each test was videotaped for further study.

Table 1 – Addendum Test Results

Test #	Hypothesis	Material ID #	Reagent / Concentration	Voltage (VDC)	Addendum Tests No. of Drops to Failure – Trial 1	Addendum Tests – Trial 2	Addendum Tests – Trial 3	Addendum Tests – Trial 4	December 15, 2003 Report Results No. of Drops to Failure – Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11	Energy (Joules)
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 reflect the trial used to calculate the Energy and the Energy/Drop at the point of arc tracking failure.

E. Observations:

Tests 2, 4, 5, 8, 9 and 12 produced test results consistent with the range of test results previously obtained and reported in the 12-15-03 report. The previous results are also summarized in Table 1. Only one instrumented test trial was deemed necessary for each of these tests. The plots of Voltage, Current, Instantaneous Power and Energy for each of these tests are shown in the attached Appendix.

Test 1 - Three trials were performed with the numbers of drops to failure recorded as 33, 33 and 7 respectively. Three trials were previously performed as noted in the 12-15-03 report with results of 15, 9 and 11 drops to failure. A plot of Test 1, Trial 3 (7 drops to failure) is included in the Appendix since this result is closest to the results previously obtained.

Test 3 - Two trials were performed with the numbers of drops to failure recorded as 38 and 33 respectively. In reviewing the 12-15-03 report, three trials were previously performed with results of 21, 20 and 11 drops. A plot of Test 3, Trial 1 is included in the Appendix even though consistency in test results appears to be lacking. One possible reason for this inconsistency is discussed below.

Test 6 – Three trials were performed with the numbers of drops to failure recorded as 33, 32 and 78 respectively. In reviewing the 12-15-03 report, it was noted that a wide range of test results (26 – 77 drops to failure) were previously observed. The instrumented test results obtained were within this range and a plot of Test 6, Trial 1 is included in the Appendix.

Test 7 - Four trials were performed with the numbers of drops to failure recorded as 48, 15, >65 and 19 respectively. In reviewing the 12-15-03 report, it was noted that only one trial was performed previously with 32 drops to failure recorded. A plot of Test 7, Trial 1 is included in the Appendix.

Test 10 - Two trials were performed with the numbers of drops to failure recorded as 11 and 16 respectively. As reported in the 12-15-03 report, three trials had been performed with results ranging from 17 – 25 drops to failure. The results from Test 10, Trial 2 are plotted in the Appendix.

Test 11 – In one trial a low impedance path was established between electrodes after 54 drops compared to 61 drops for the two earlier tests described in the 12-15-03 report. An examination of the video recording and a rudimentary infrared analysis of the deposits formed between the electrodes on the glass substrate tested provided some insight into possible cause and effect relationships for the observed phenomenon. The exact cause(s) of this phenomenon however is an area for further and much more detailed investigation. Such study could include an analysis of the gases produced at the positive and negative electrodes as well

as a more detailed analysis of the resulting deposits formed between electrodes across the surfaces of the inorganic materials. At the present time, polymeric materials for use in 42 V applications may be qualified at a maximum DC voltage of 60 VDC.

F. Hypotheses:

It takes 4 parameters to define a DC-CTI Test:

- Material
- Reagent (Electrolyte chemistry)
- Reagent Concentration (Resistivity)
- Voltage.

In order to better understand the relationship of these parameters on test outcome, MVFRI suggested 12 specific tests to explore 5 hypotheses and one prediction:

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.

Test 1: High Performing Material: The 150-volt materials are all 55+ by definition. A material which passes at 100 volts and fails at 150 is needed and material number 22 was selected.

Test 2: Low Performing Material: In this case a material that passes at 42 V and fails at 60 V is needed. Material number 6 was selected.

Observations:

Test 1 - Failure occurred after 7 drops at a cumulative energy of 850 Joules.

Test 2 - Failure occurred after 16 drops and a cumulative energy of 1450 Joules.

Since the low performing material (number 6) exhibited a higher cumulative energy to fail than the high performing material (number 22), Hypothesis 1 is not supported by the collected data. Changing both the material and the applied voltage may have confounded the results.

2. Effect of Resistivity of the Reagent.

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

The NaCl reagent at 1%, 5% and 15% concentrations was selected and testing performed at 100 VDC.

Test 3: Material 16, NaCl, 1%

Test 4: Material 16, NaCl, 5%

Test 5: Material 16, NaCl, 15%

Observations:

Test 3 - Failure occurred after 38 drops and a cumulative energy of 4375 Joules.

Test 4 - Failure occurred after 6 drops and a cumulative energy of 740 Joules.

Test 5 - Failure occurred after 3 drops and a cumulative energy of 300 Joules.

Hypothesis 2 is not supported by the collected data due to the wide variation in cumulative energies at failure.

3. Effect of Electrolyte Composition.

Hypothesis: The composition of the reagent should be a second order effect after the resistivity.

Material 5 was tested at 42 volts:

Test 6: Material 5, NaCl, 5%

Test 7: Material 5, NH_4Cl, 35%

Observations:

Test 6 - Failure occurred after 33 drops and a cumulative energy of 3700 Joules.

Test 7 - Failure occurred after 48 drops and a cumulative energy of 5700 Joules.

The resistivity of a 5% NaCl reagent solution and a 35% NH_4Cl solution are identical (15 ohm-cm.). However when the same material (No. 5) was tested at an applied voltage of 42 V DC, a difference in the number of drops to failure and the cumulative energy differed and this hypothesis is not supported by the collected data. It should be noted that in the previous testing material no. 5 exhibited a test failure after 33 drops with the 5% NaCl solution (one of 11 trials) and 32 drops with the NH_4Cl solution (one trial). The cumulative energy was not recorded during these earlier trials.

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.

Test 8: Material 5, NaCl at 5%, 150 V

Test 9: Same at 100 V

Test 10: Same at 60 V

Observations:

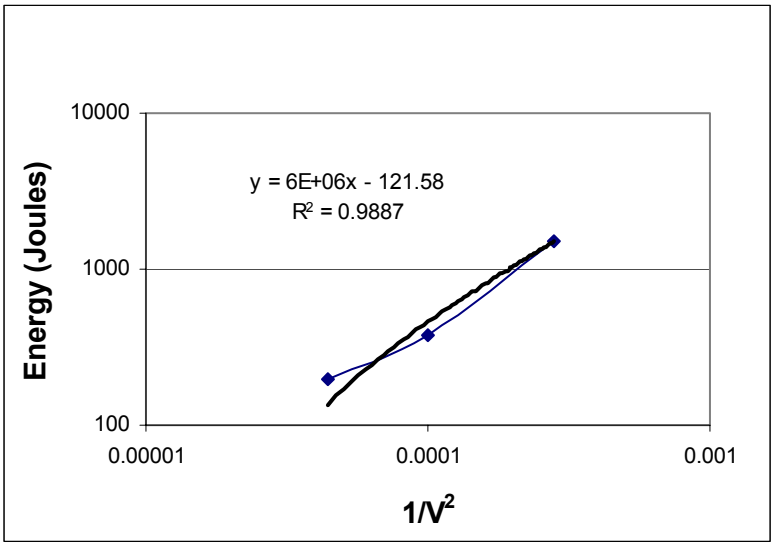
Test 8 - Failure occurred after 1 drop and a cumulative energy of 200 Joules.

Test 9 - Failure occurred after 3 drops and a cumulative energy of 375 Joules.

Test 10 - Failure occurred after 16 drops and a cumulative energy of 1510 Joules.

The reciprocal of the voltage was calculated and the energy vs. $1/V^2$ plotted as shown in Figure 1 using a log – log scale. A linear trend line was added and a correlation of $R^2 = 0.9887$ obtained. Given the limited number of data points collected, this hypothesis appears reasonable over the range of voltages tested.

Figure 1 - Energy vs. 1/V²



5. Effect of Glass (non-Carbon based substrates) (including 500-drop tests)

Hypothesis: An inorganic material such as a glass substrate should not exhibit Carbon Tracking. As reported in the 12-15-03 report, two tests were performed using a glass substrate and a 5% NaCl reagent at 150 VDC. In both cases, a low impedance path was created between the copper electrodes after the testing continued beyond the normal 55 drop maximum. In each case, this low impedance path was established between electrodes after 61 drops of reagent had fallen. The establishment of the low impedance path may be due to a salt residue from the reagent, deposits from the copper electrodes or a combination of both. Two tests were performed to compare failure modes.

Test 11: Glass substrate; 5% NaCl, 150 Volts, up to 500-drops.

Test 12: Material 25, 5% NaCl. 60 volts.

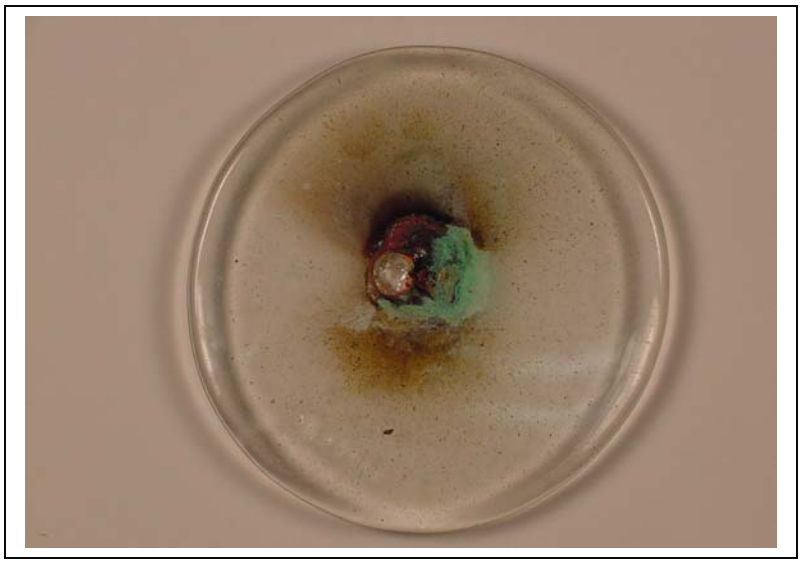
Observations:

Test 11 - Failure occurred after 54 drops and a cumulative energy of 7500 Joules.

Test 12 - Failure occurred after 66 drops and a cumulative energy of 7620 Joules.

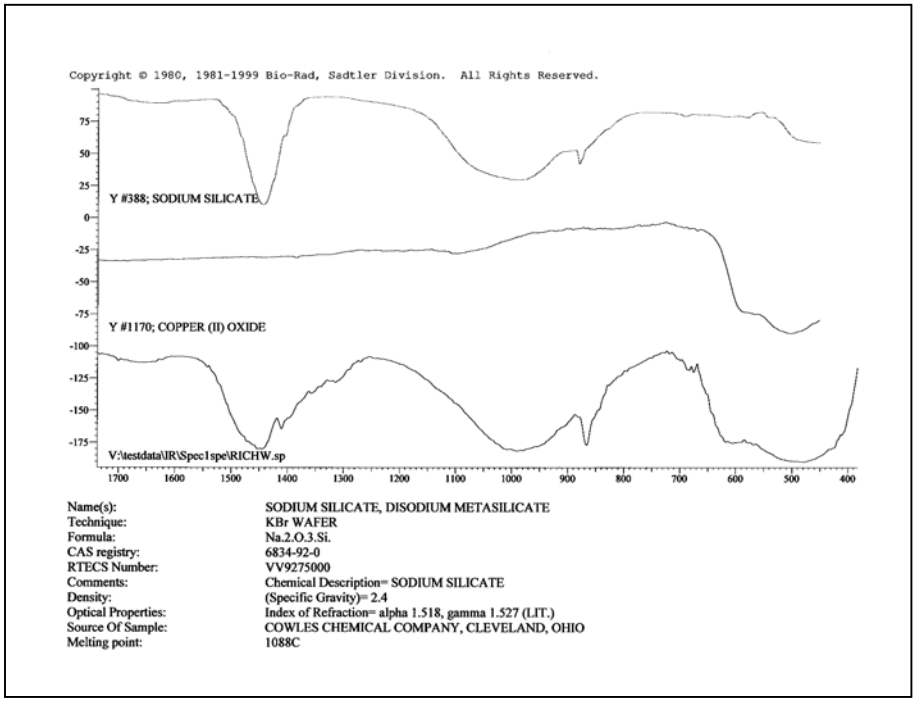
A typical deposit formation on the glass substrate is shown in Figure 2.

Figure 2- Deposits on Glass Substrate



These deposits were identified by means of an infrared (IR) scan. The results of this scan are shown in Figure 3.

Figure 3- IR Scan of Glass Substrate Deposits



The IR Scan identified copper oxide deposits as well as sodium silicate. When the videotape of this testing was reviewed, significant heating of the copper electrodes was noted with the electrode glowing red. This intense heating may have caused some decomposition of the glass and this would account for the sodium silicate in the IR scan. Since no carbon was observed when the testing was performed on the glass substrate, this hypothesis was validated by the collected data.

6. Background Current Increase as specimen approaches failure

Prediction: The background current in-between drops should gradually increase as more and more of the plastic is pyrolyzed into Carbon. This should be most evident during the last 5-10 drops before failure. No additional testing beyond the testing described above was performed to evaluate this prediction.

Observations:

In the testing performed, an increase in the current magnitude was noted associated with each fallen droplet of reagent. An avalanche increase in current was observed at the point of test failure. The test data does not support this prediction.

According to Babrauskas [2] *Arc tracking is a progressive creation by electrical means of a carbonized path along the surface of in insulator that separates two current-carrying conductors. Moisture and contaminants are generally responsible for causing arc tracking, although dry tracking also can occur. The electric conductivity of pure water is very low, but when ionic contaminants are dissolved in water, its conductivity increases and it becomes possible to create current flow if the layer of moisture has access to circuit conductors somewhere. The flow of current then has a drying effect on the moisture layer. The drying is non-uniform, and eventually dry patches start to be formed along the current path. The first overt electrical discharges occur as faint, purple-colored corona discharges across the dry patches. With buildup of carbonization along the path, small electrical discharges, called scintillations, can then occur. These are red or orange-colored. Since part of the current flow is through an electrolyte of significant resistance, these scintillations represent a very small current flow (less than 50 - 100 mA in one series of tests) and would not trip any overcurrent devices. Surprisingly, temperatures up to 1000°C can be generated by such surface leakage discharges. These elevated temperatures then continue the process of polymer carbonization. Thus, in the tracking process, a carbon track is laid down along the surface, and that track has a low enough resistivity that current can subsequently start to flow along the carbonized track, which, in turn, causes more carbonization and more heating. A runaway situation can then develop.*

G. General Discussion of Variations in Test Results.

Arcing is a chaotic event and some inherent variability in the test outcome may be anticipated.

A different operator performed the addendum testing than the technician who performed the testing reported in the 12-15-03 report. This raises the question of whether some variation in observed test performance may be a result of operator dependency. In order to validate the repeatability of the DC-CTI test procedure when different technicians perform the test, it is suggested that a series of round robin tests be performed on a larger sampling of materials. Identical materials will be tested at a number of selected test locations and by different laboratory technicians and the test results obtained compared.

Performance of the round-robin testing would necessitate the acquisition of a minimum of three DC-CTI testers from a test equipment manufacturer. It is suggested that one of these testers be located at each of three different UL domestic test locations. Sites that may be considered are Melville, NY; Northbrook, IL and Novi, MI.

It would be the intent that the DC-CTI testers used for round-robin testing would incorporate all necessary modifications and safety upgrades to permit DC-CTI testing of thermoplastic materials on a production basis.

Two of the suggested upgrades include an optical ignition detector to sense continuous flaming of the material and the addition of a DC voltage rated circuit breaker to automatically terminate the test once arc tracking occurs without the need for human monitoring. Based on empirical testing performed with a variety of circuit breaker trip levels, it appears that a thermal magnetic circuit breaker having a 1 A handle rating may be used.

H. References

1. Wagner, R. & Stimitz, J., *Study of Arc Track Properties of Plastic Materials when Subjected to DC Voltages Ranging from 12 V DC - 150 V DC*, UL Report to USCAR & MVFRI, December 2003.

2. Babrauskas, Vytenis, *Ignition Handbook*, Fire Science Publishers, 2003.

TEST # 1, Trial 3

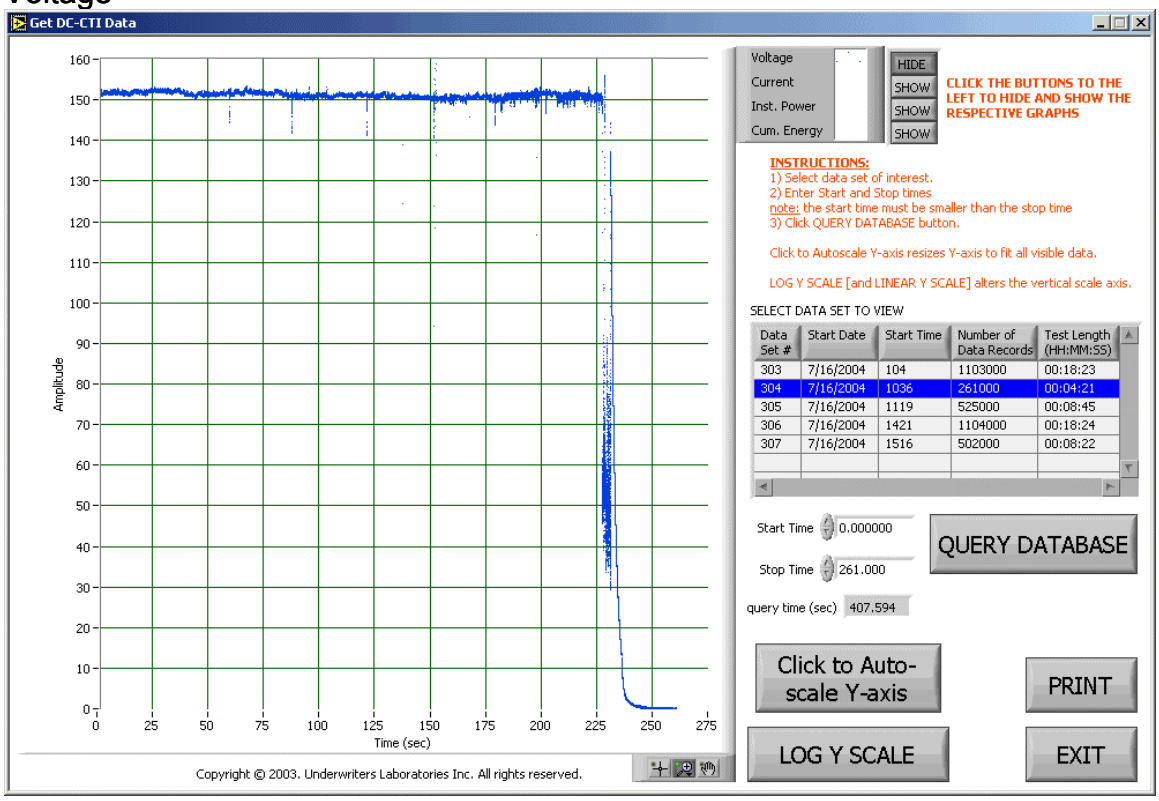
(Material # 22, 150 V DC, 5% NaCl)

APPENDIX A – ADDENDUM TESTING

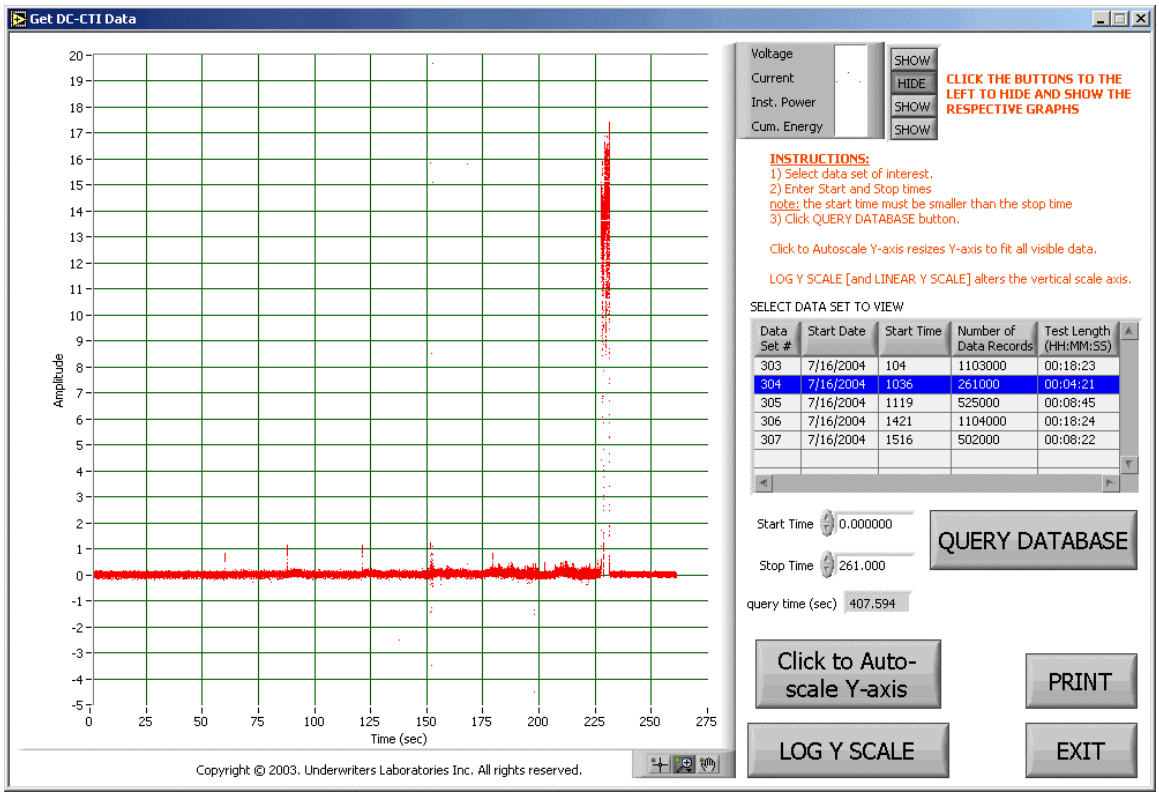
For each test, the voltage at the test electrodes and the current were recorded at the rate of 1 kHz. The voltage and current data were used to calculate the instantaneous power expressed in Watts. Energy (expressed in Joules) was calculated by integrating the area under the instantaneous power curve.

TEST # 1, Trial 3
(Material # 22, 150 V DC, 5% NaCl)

Voltage

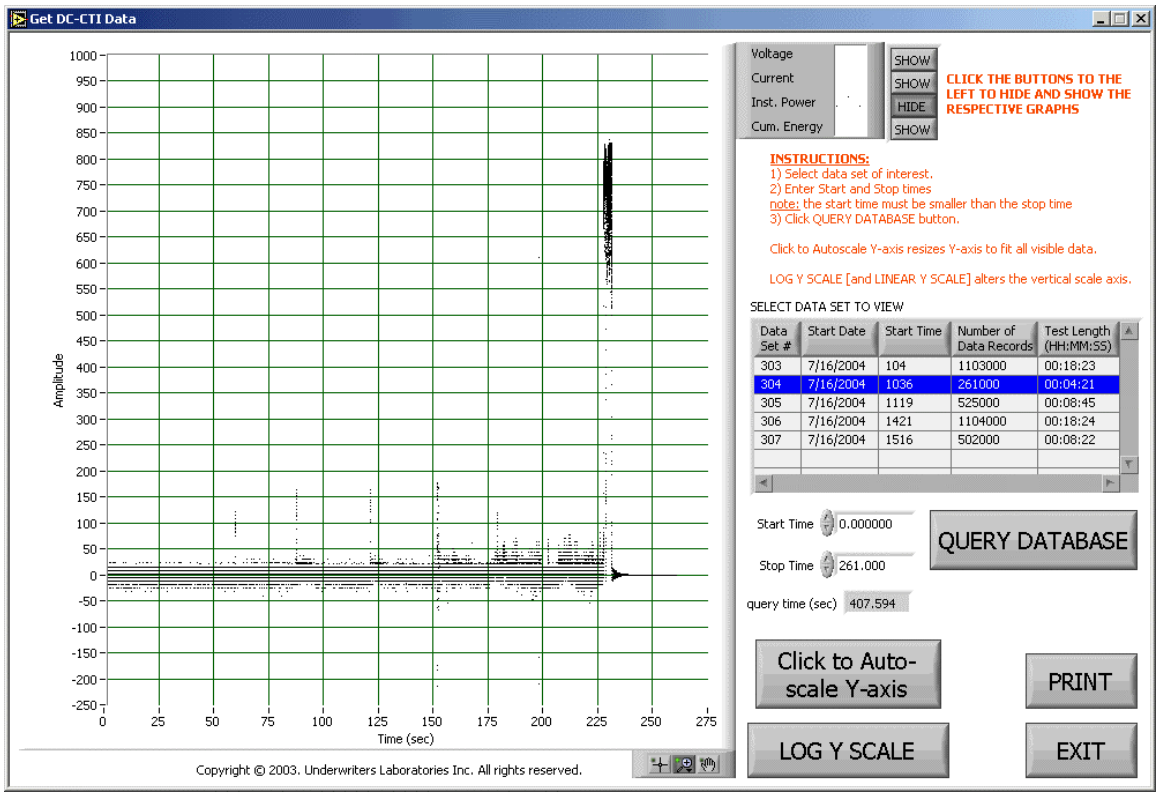


Current

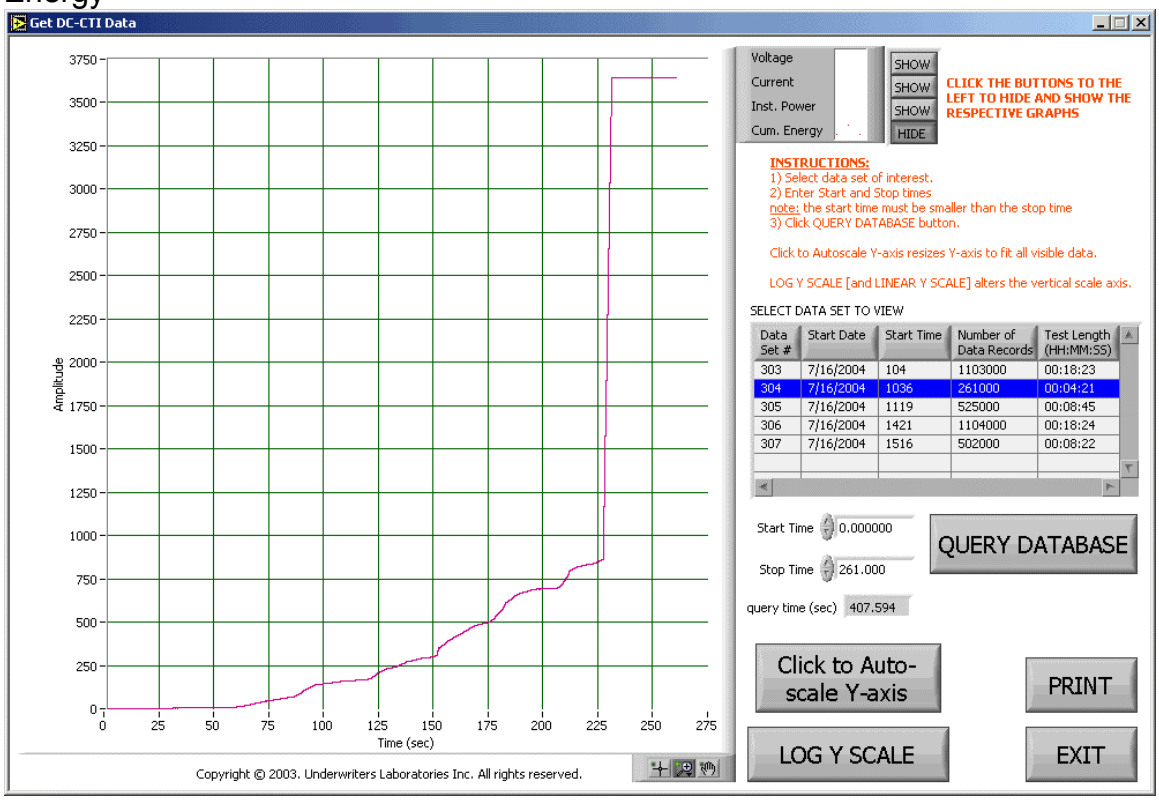


TEST # 1, Trial 3
(Material # 22, 150 V DC, 5% NaCl)

Power

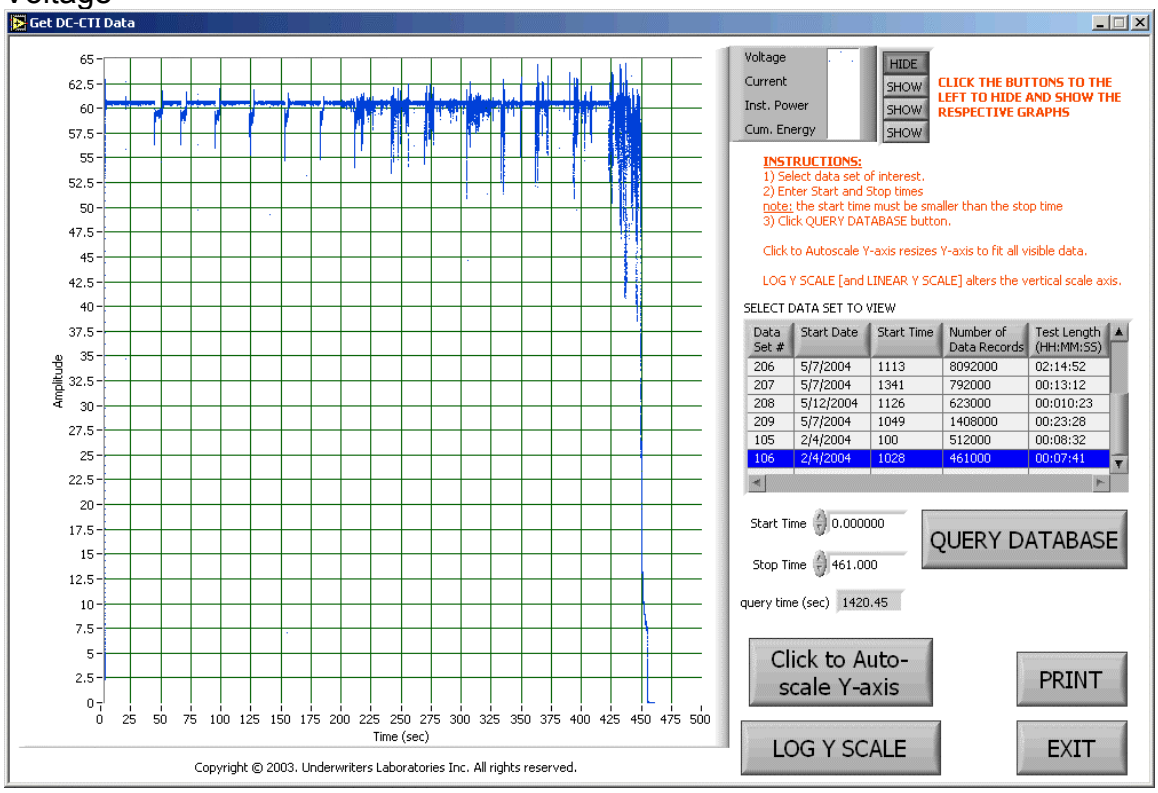


Energy



Test # 2, Trial 1
(Material # 6, 60 V DC, 5% NaCl)

Voltage



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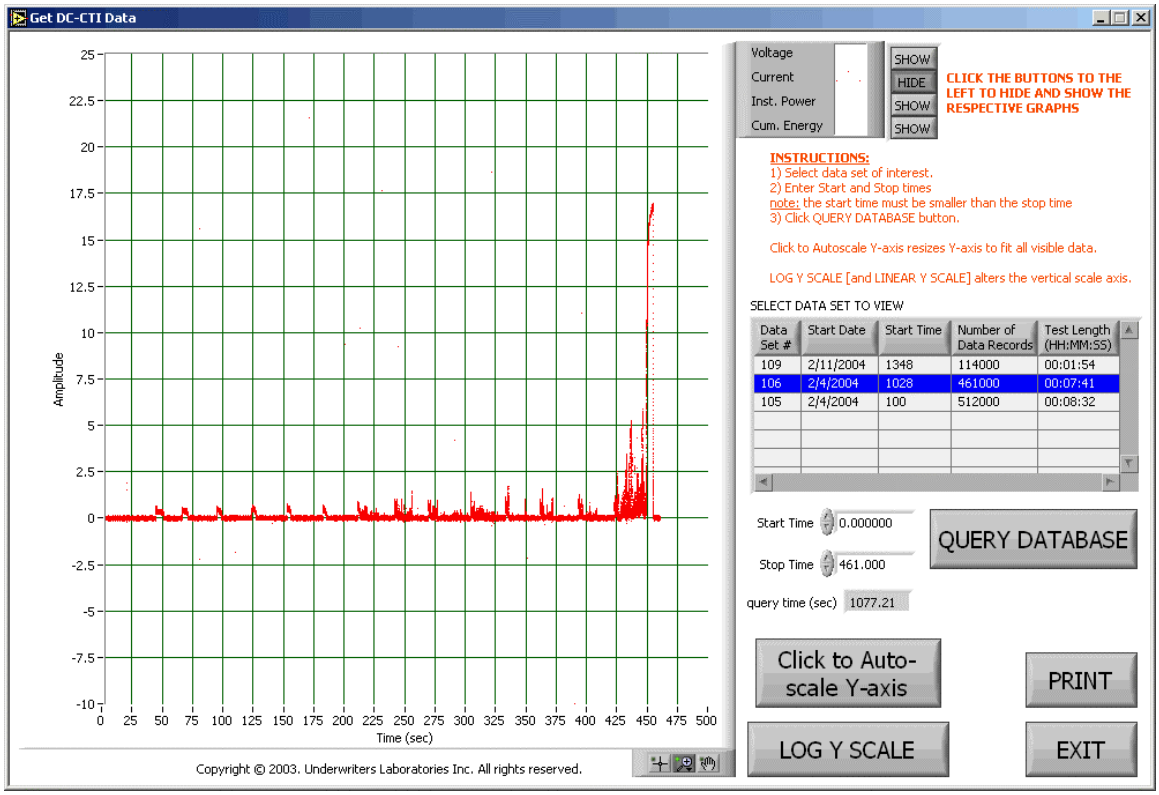
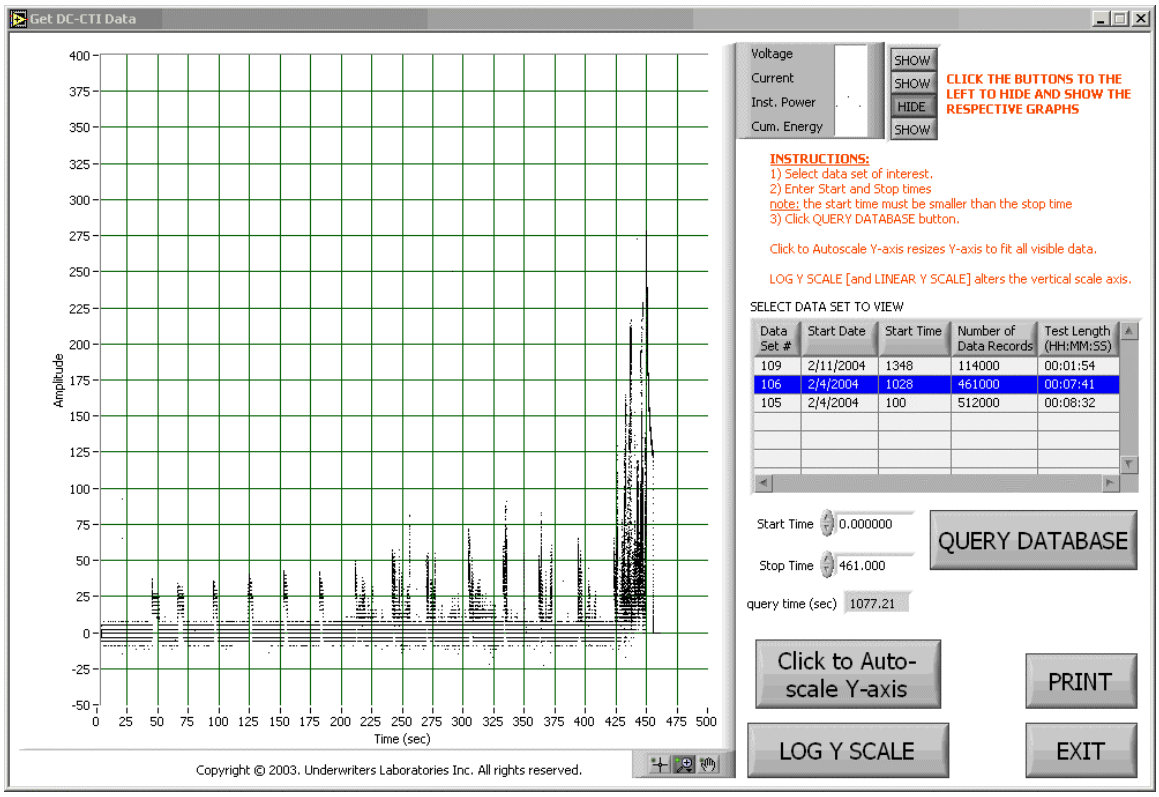


Test # 2, Trial 1
(Material # 6, 60 V DC, 5% NaCl)

Power



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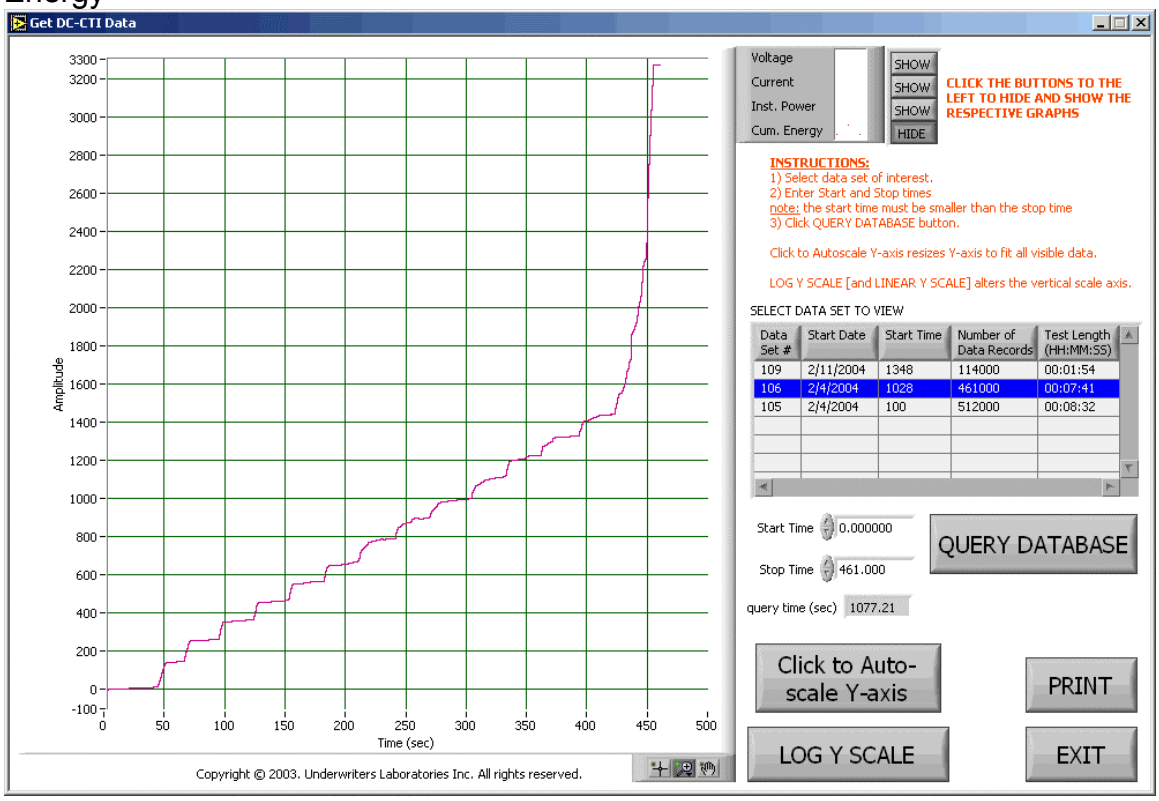
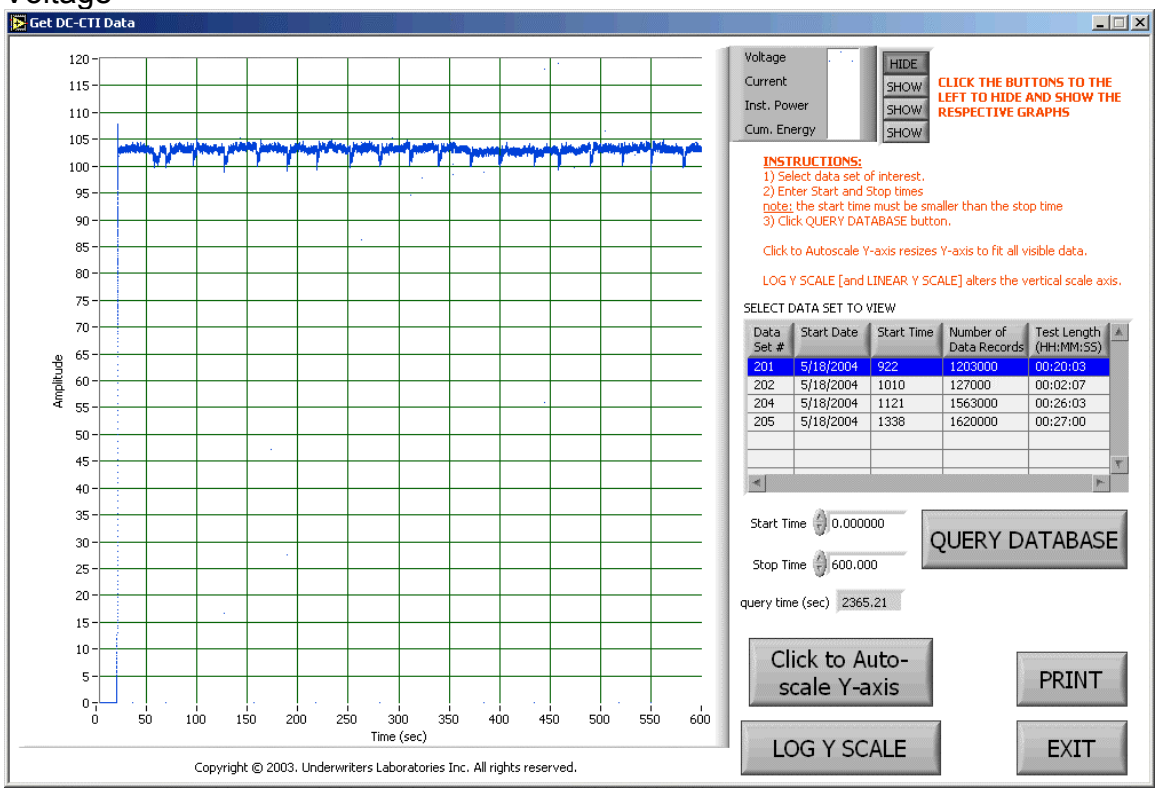


Voltage



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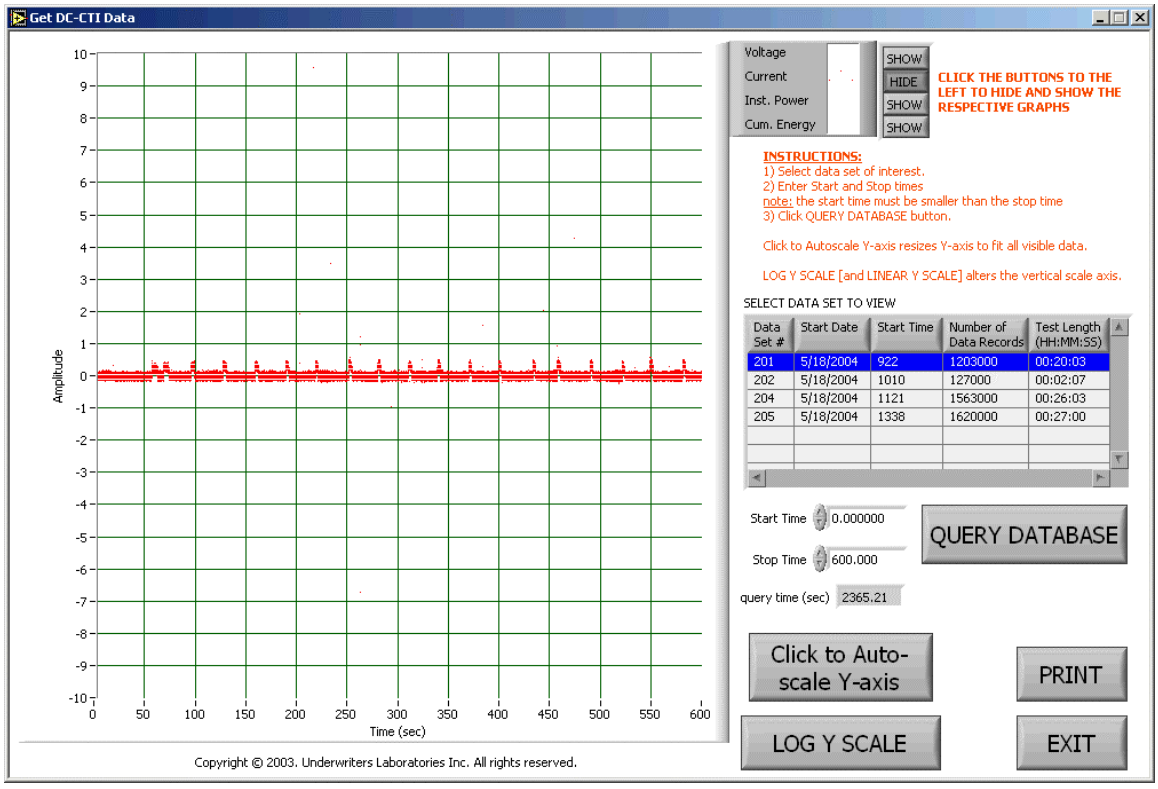

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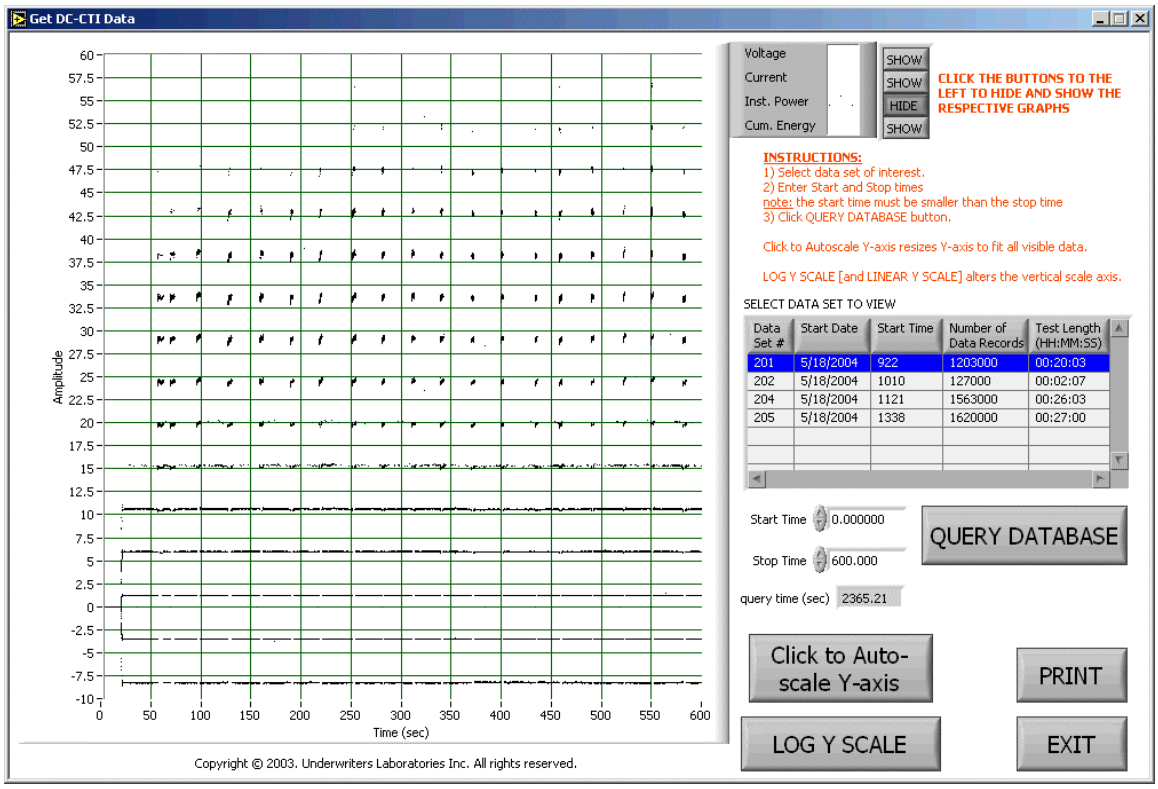
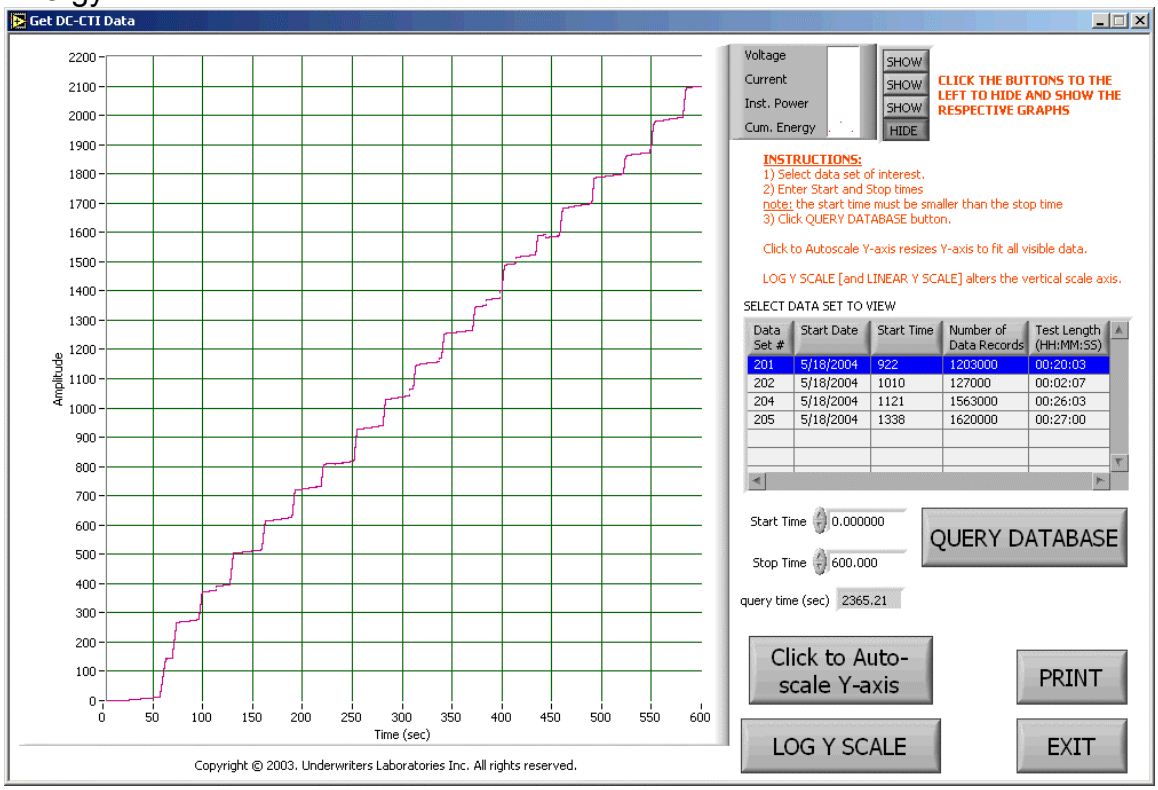
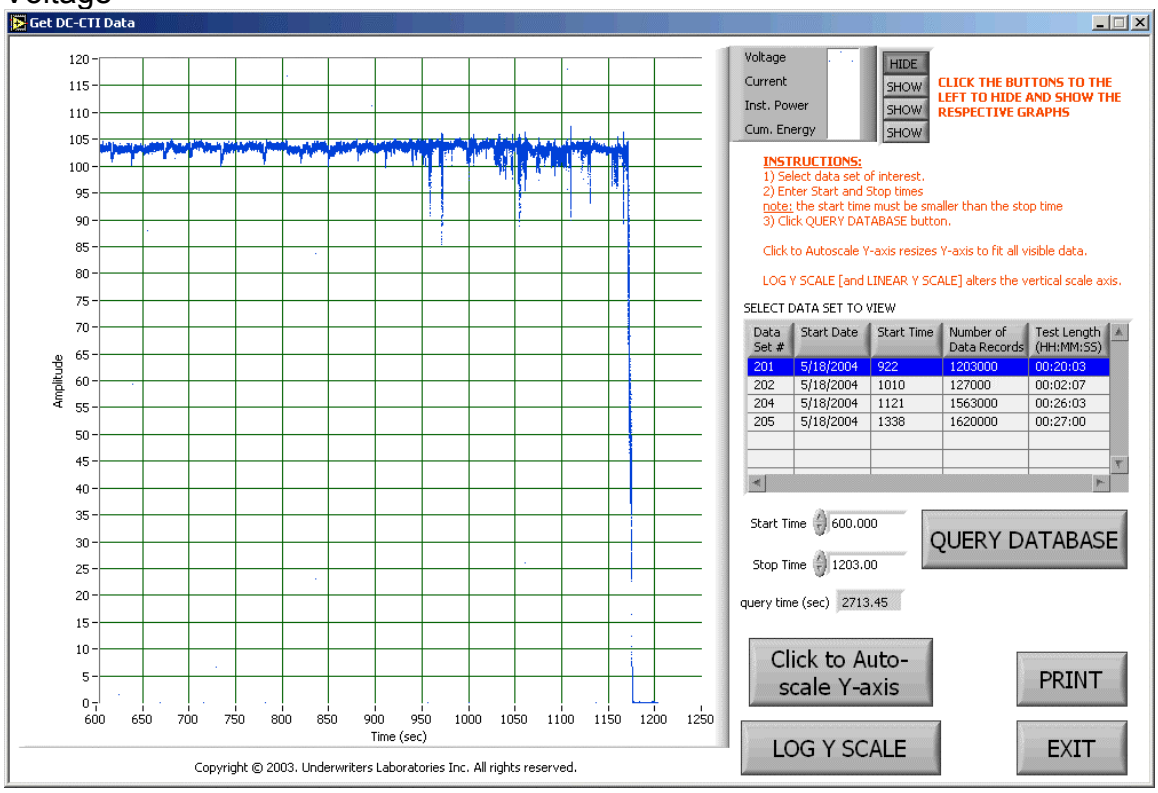


Energy



Voltage



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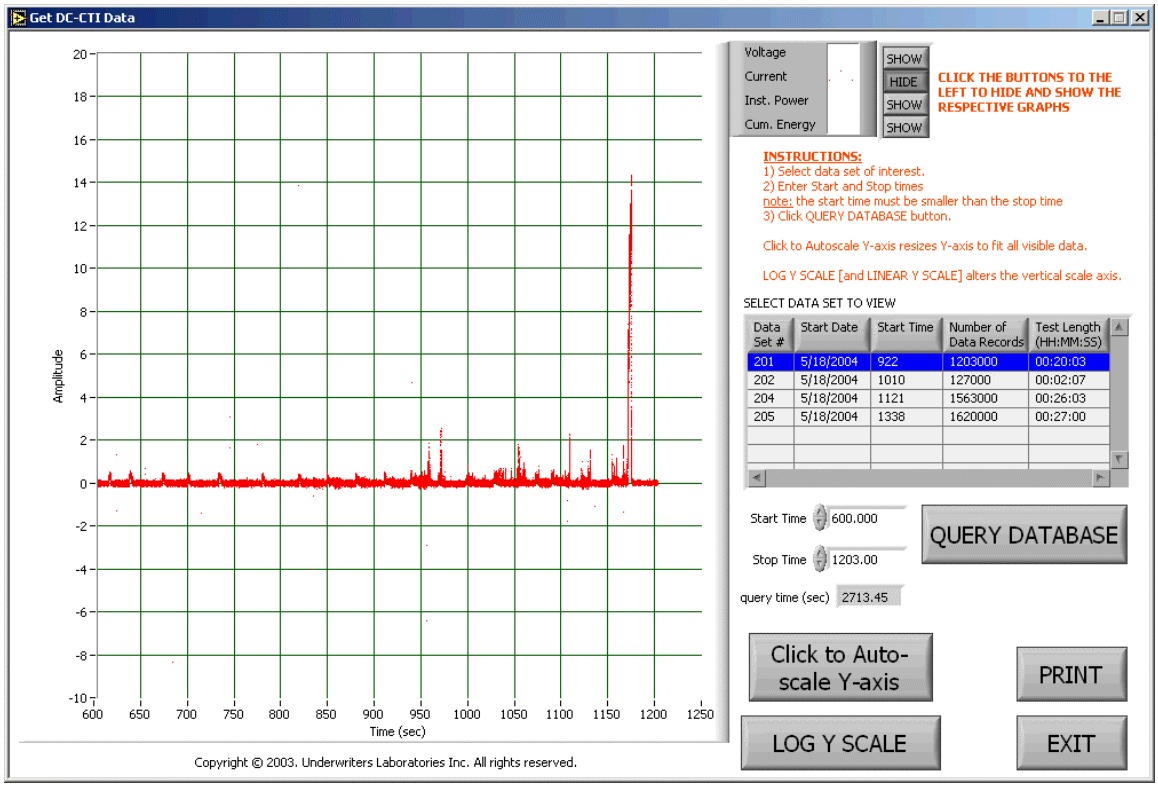

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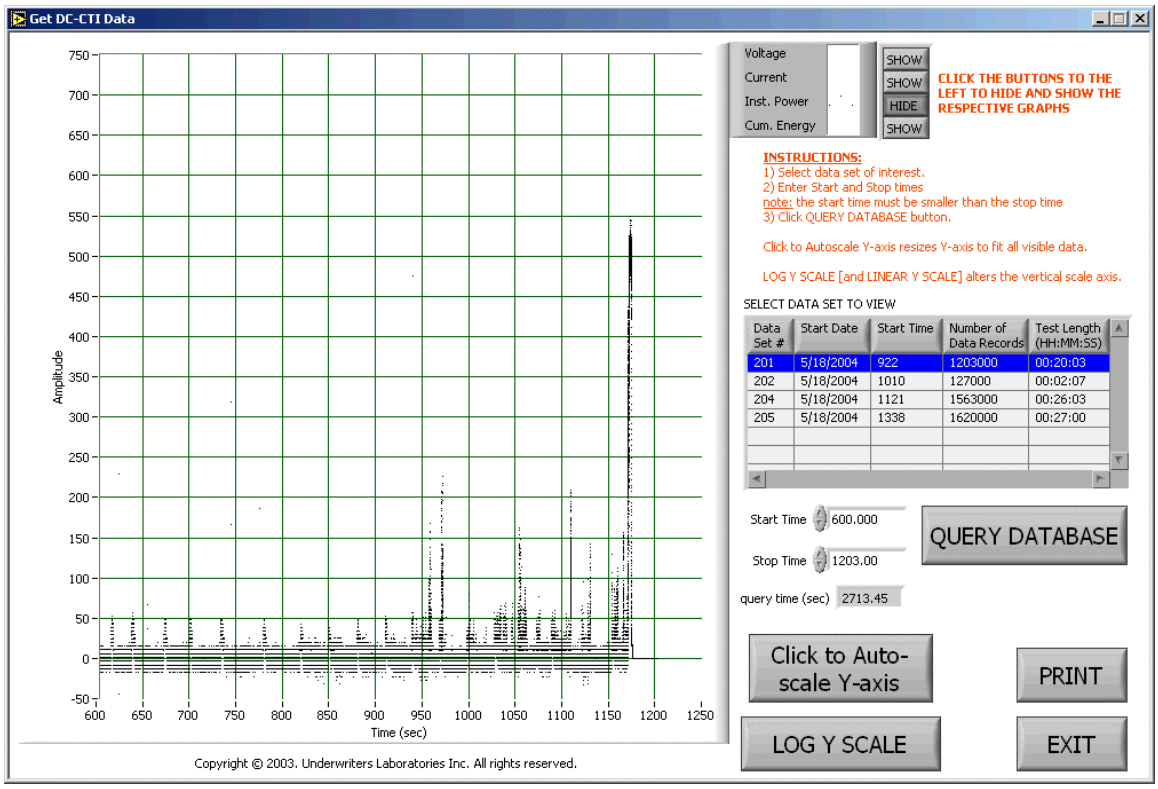

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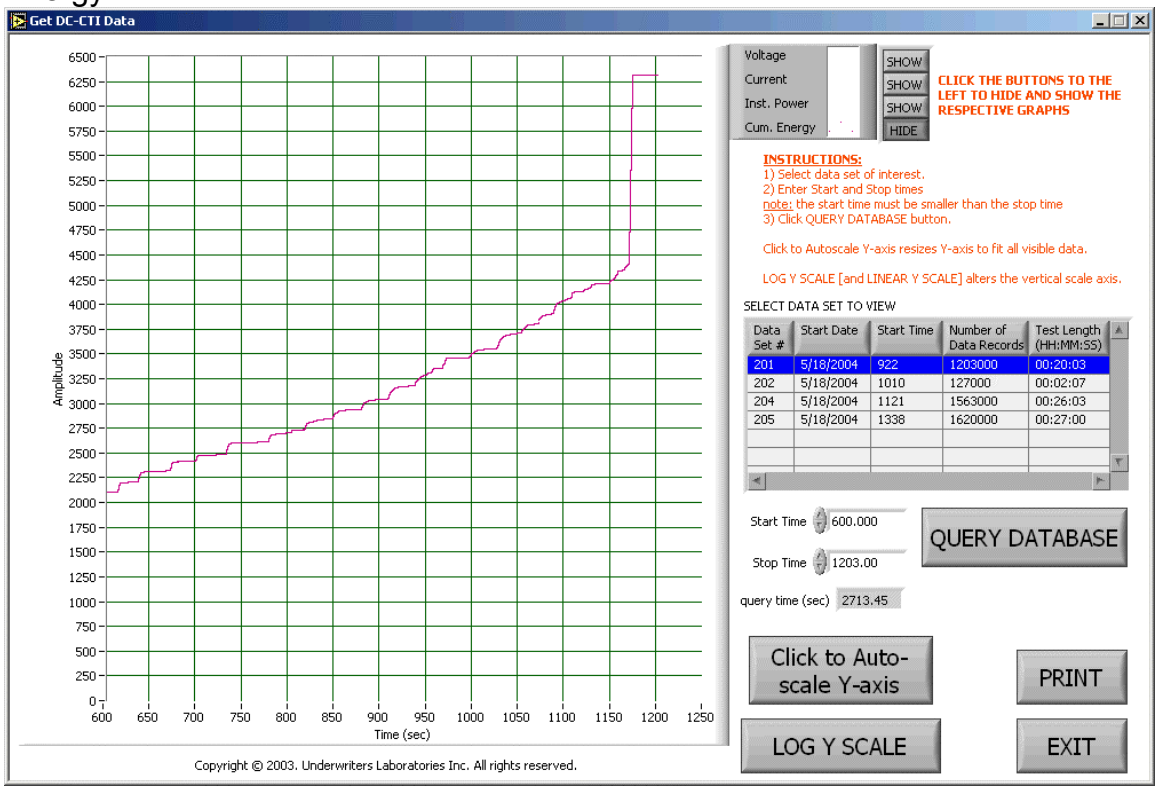
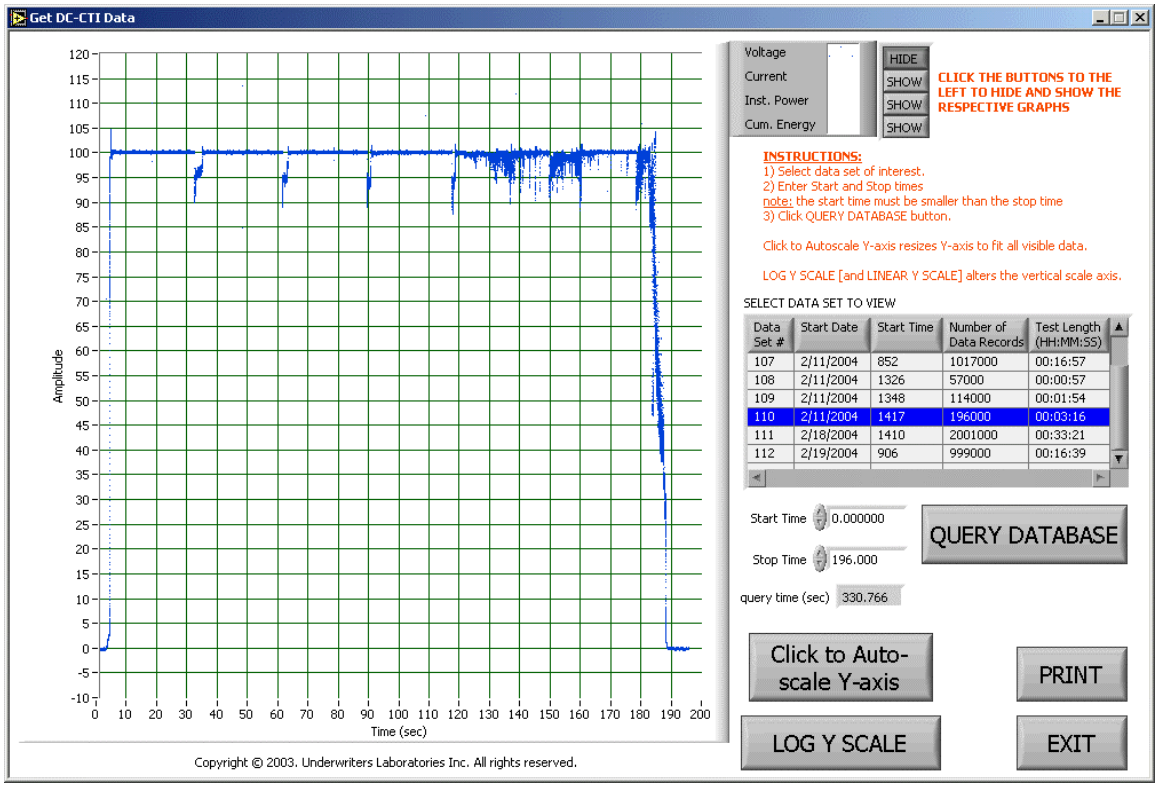
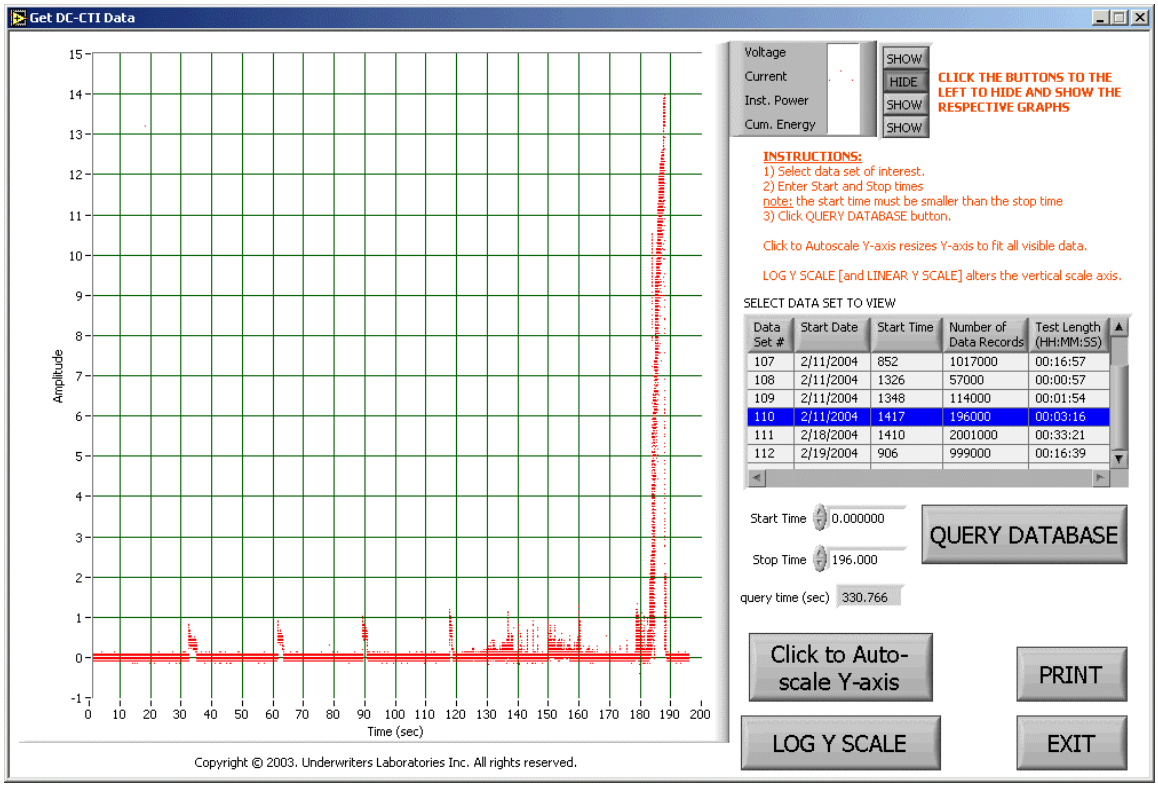


Test # 4, Trial1
(Material # 16, 100 V DC, 5% NaCl)

Voltage

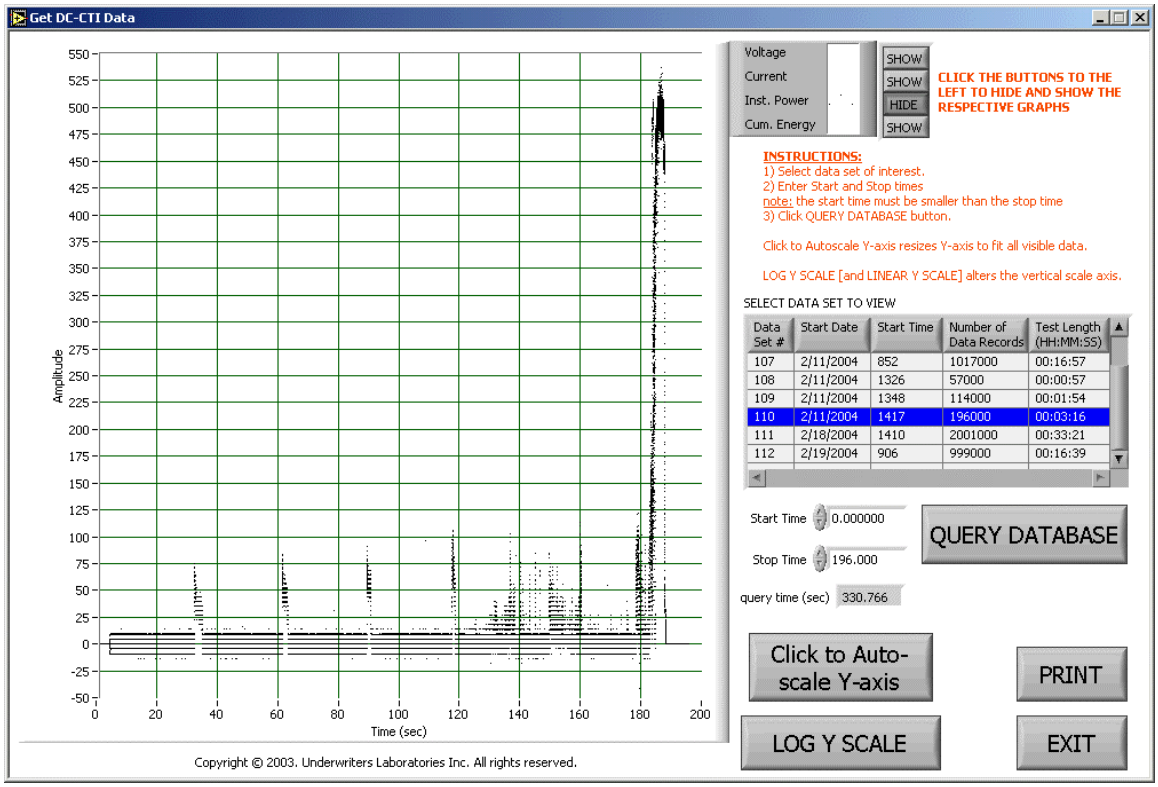


Current

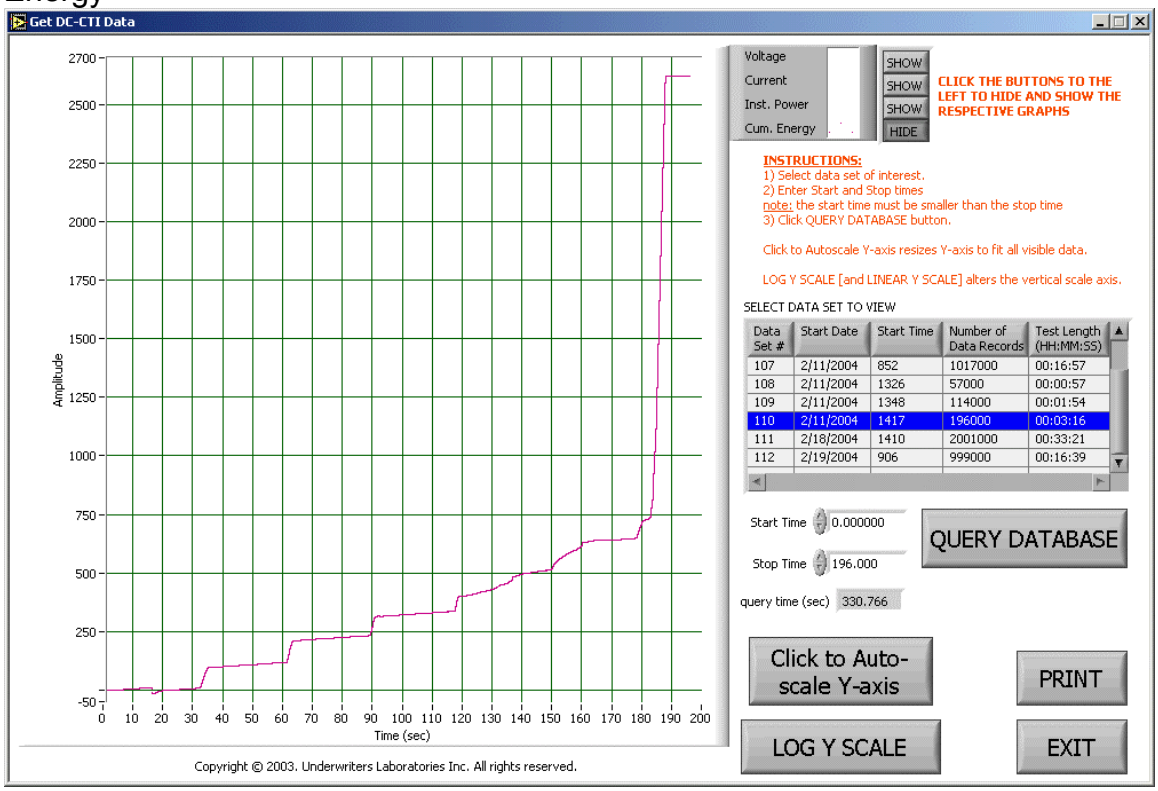


Test # 4, Trial1
(Material # 16, 100 V DC, 5% NaCl)

Power

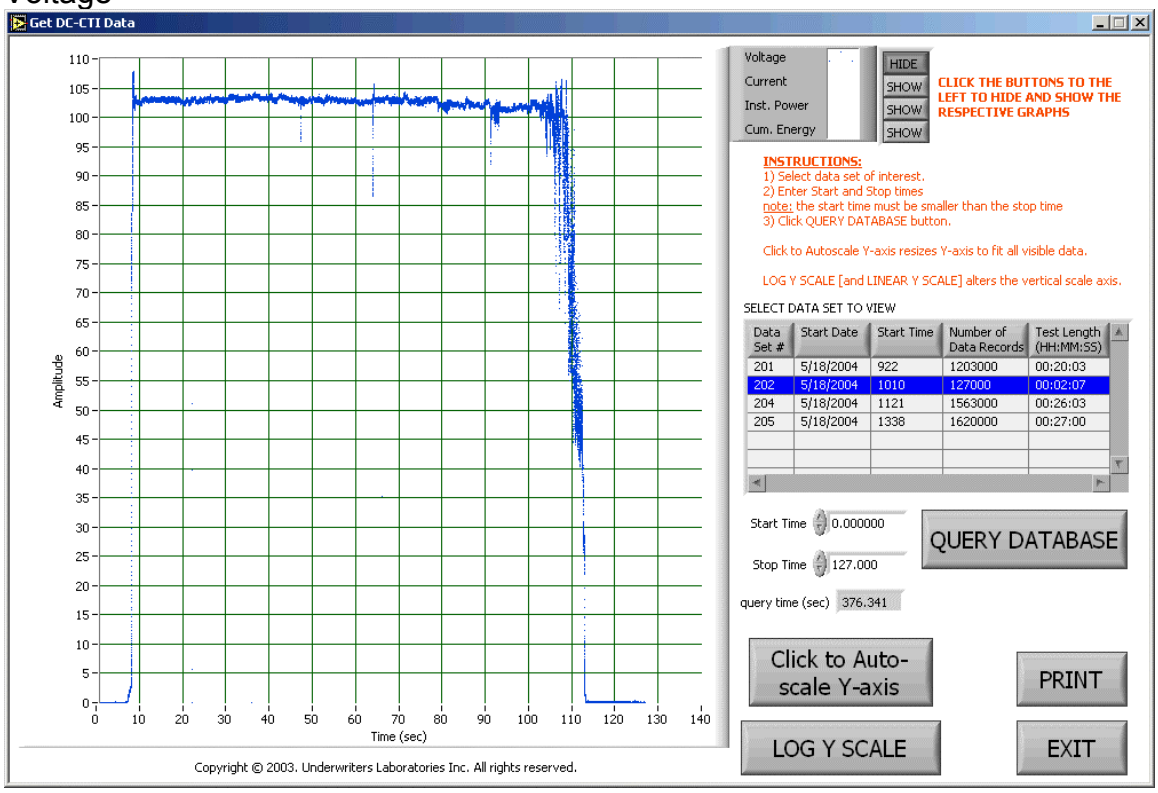


Energy

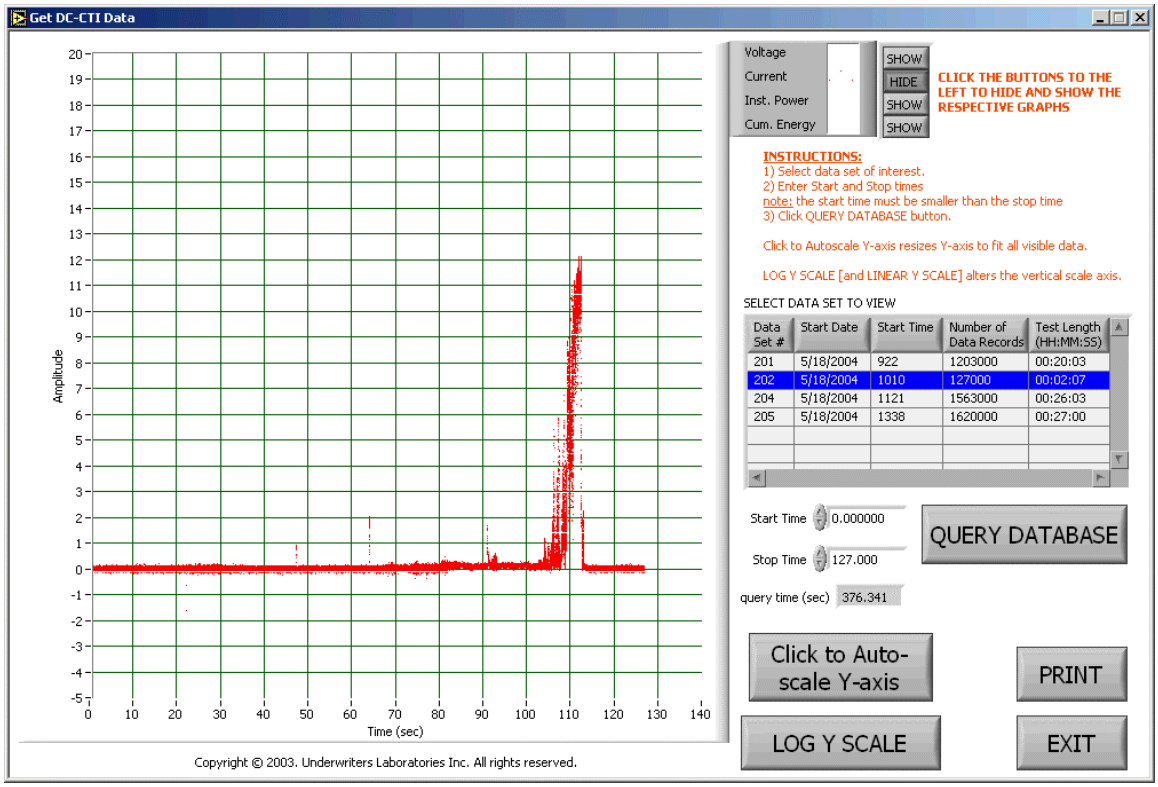


Test # 5, Trial 1
(Material # 16, 100 V DC, 15% NaCl)

Voltage

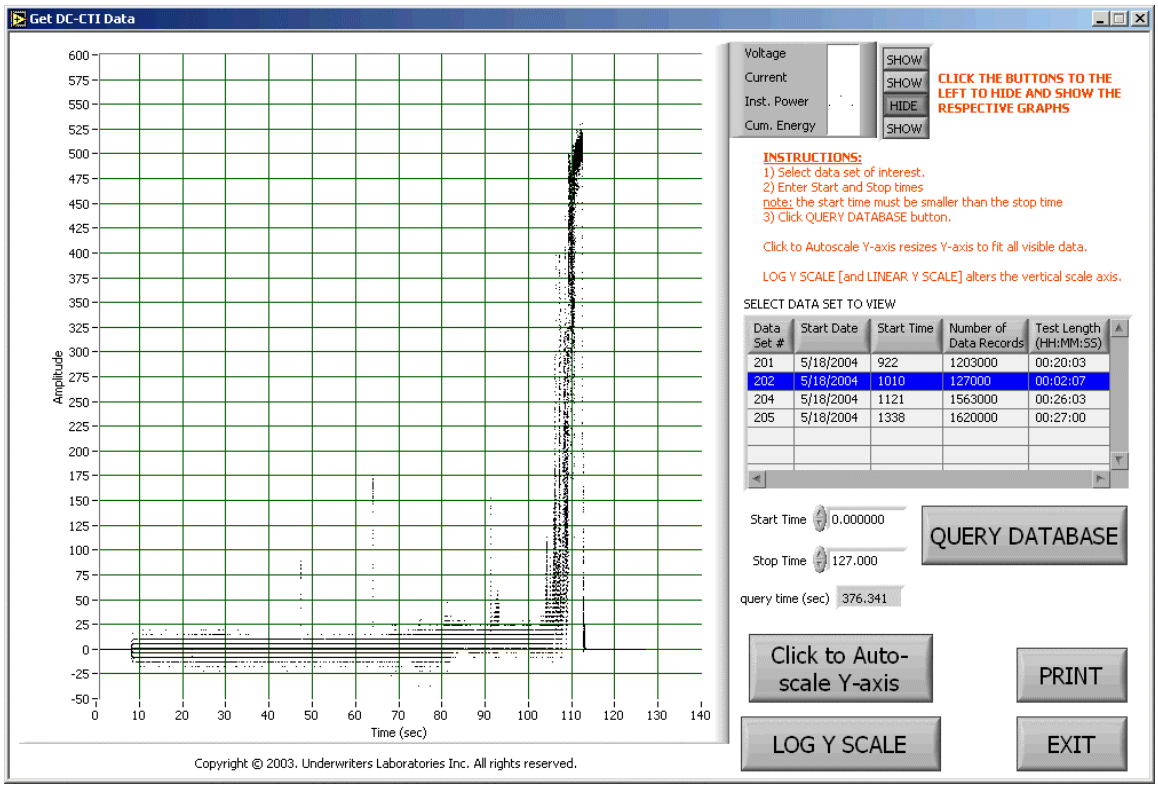


Current

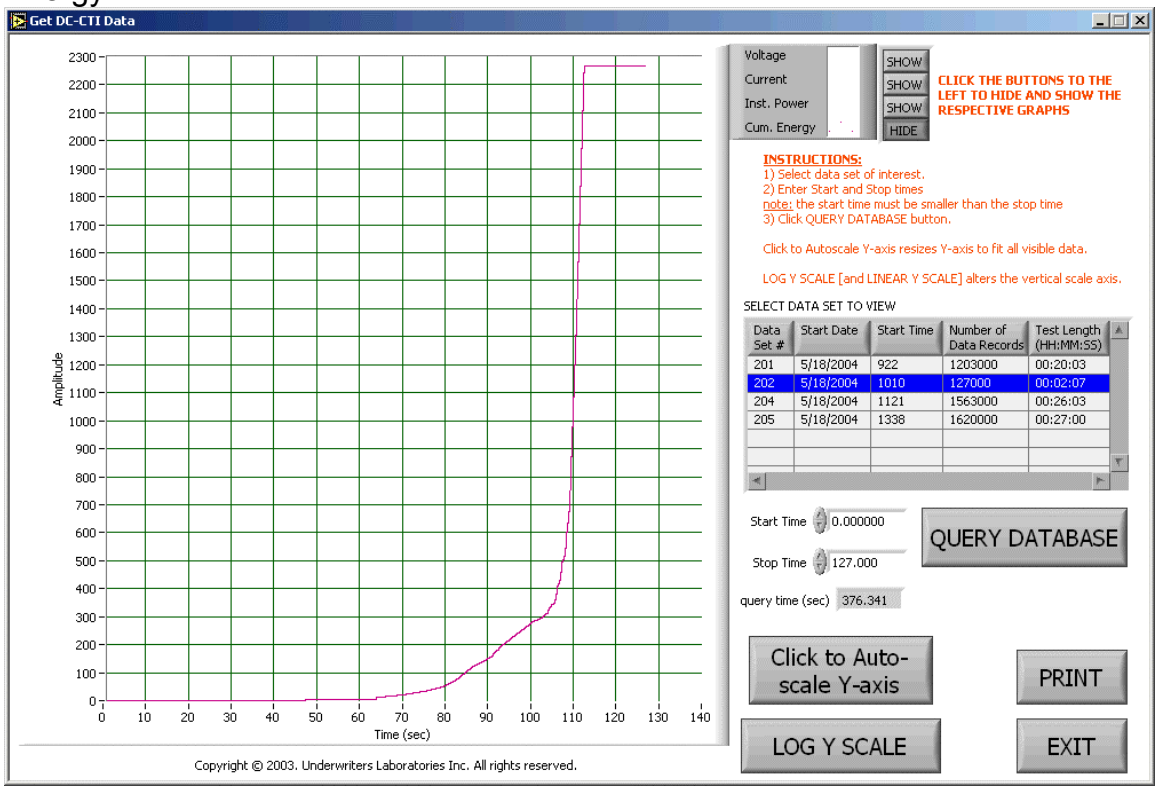


Test # 5, Trial 1
(Material # 16, 100 V DC, 15% NaCl)

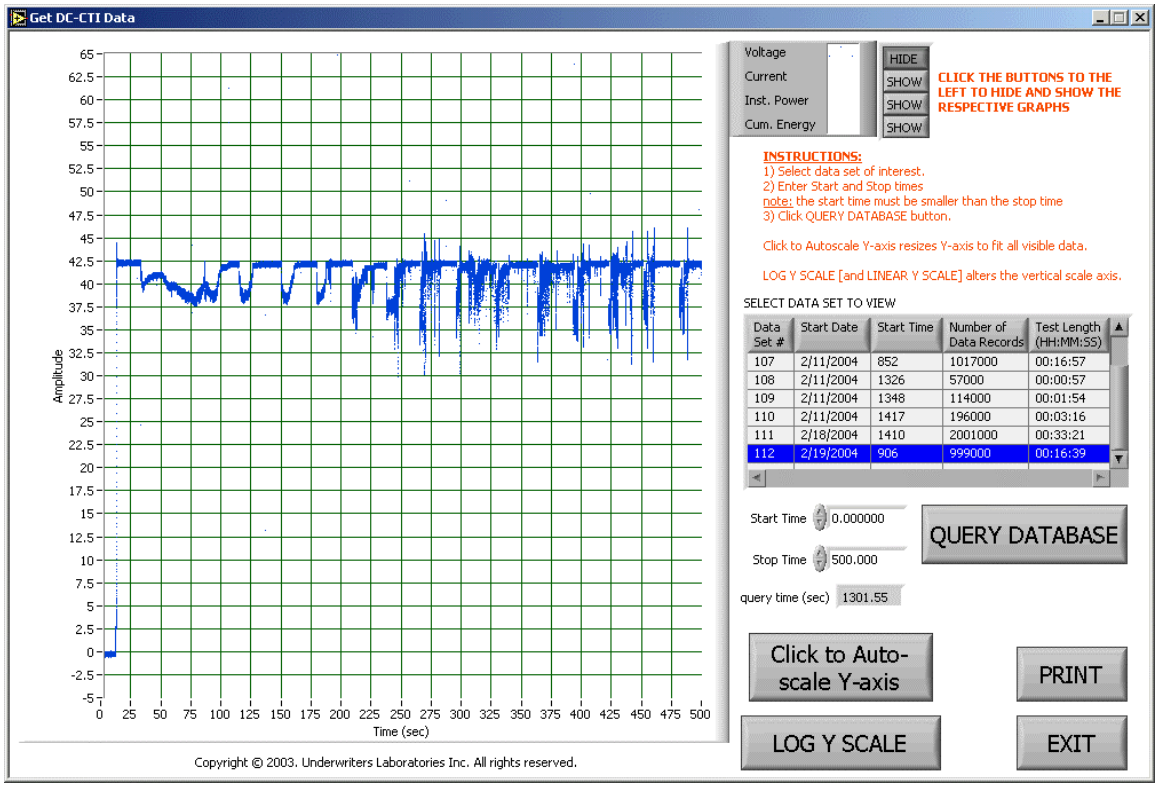
Power



Energy



Voltage



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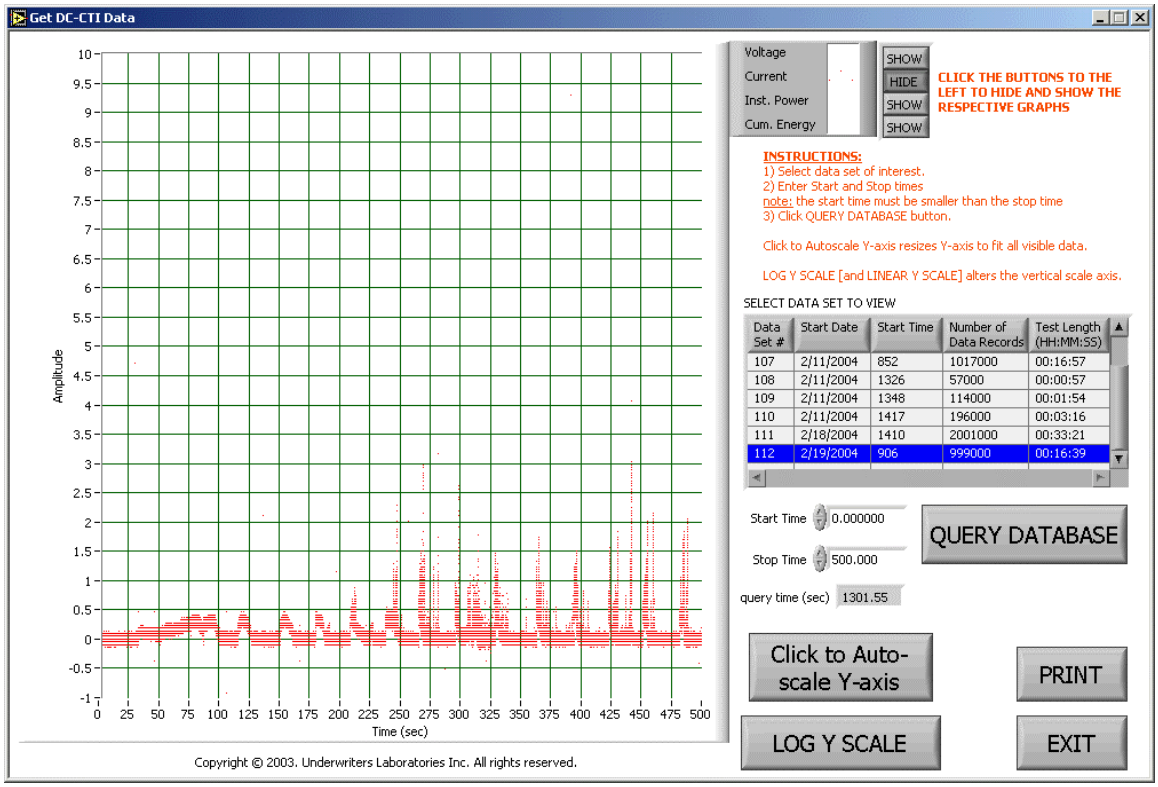

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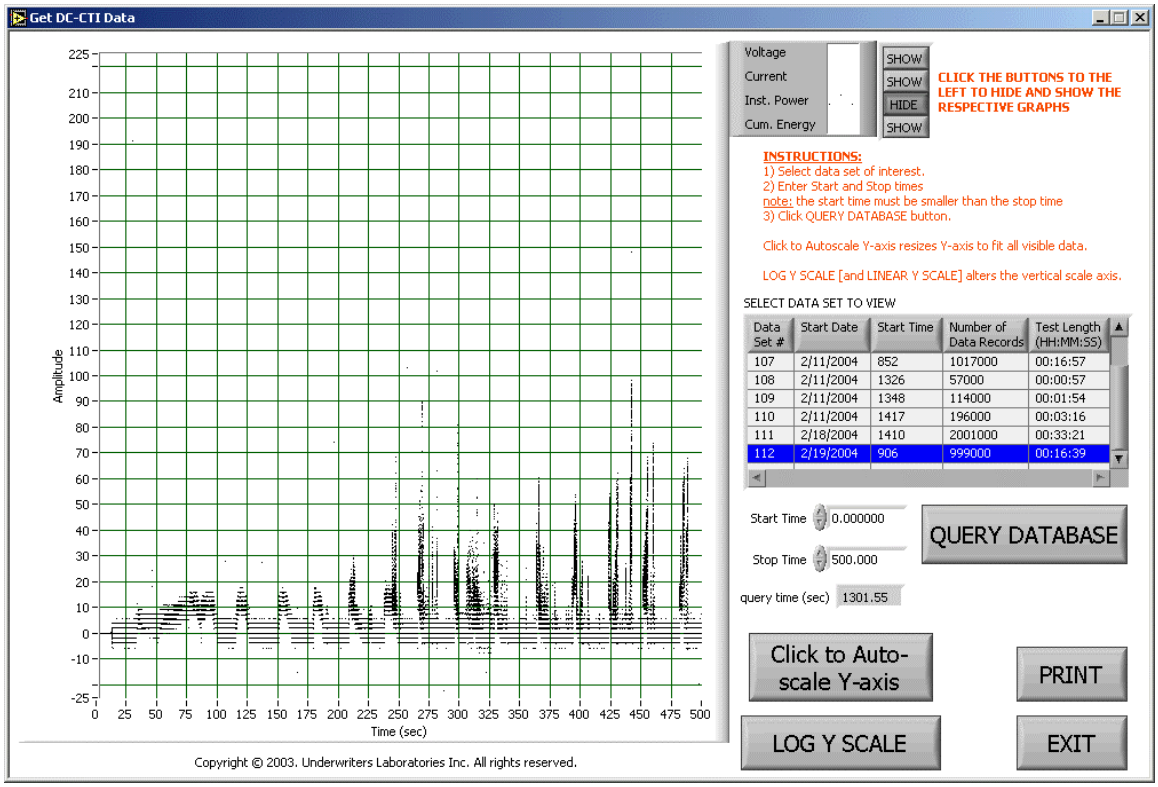
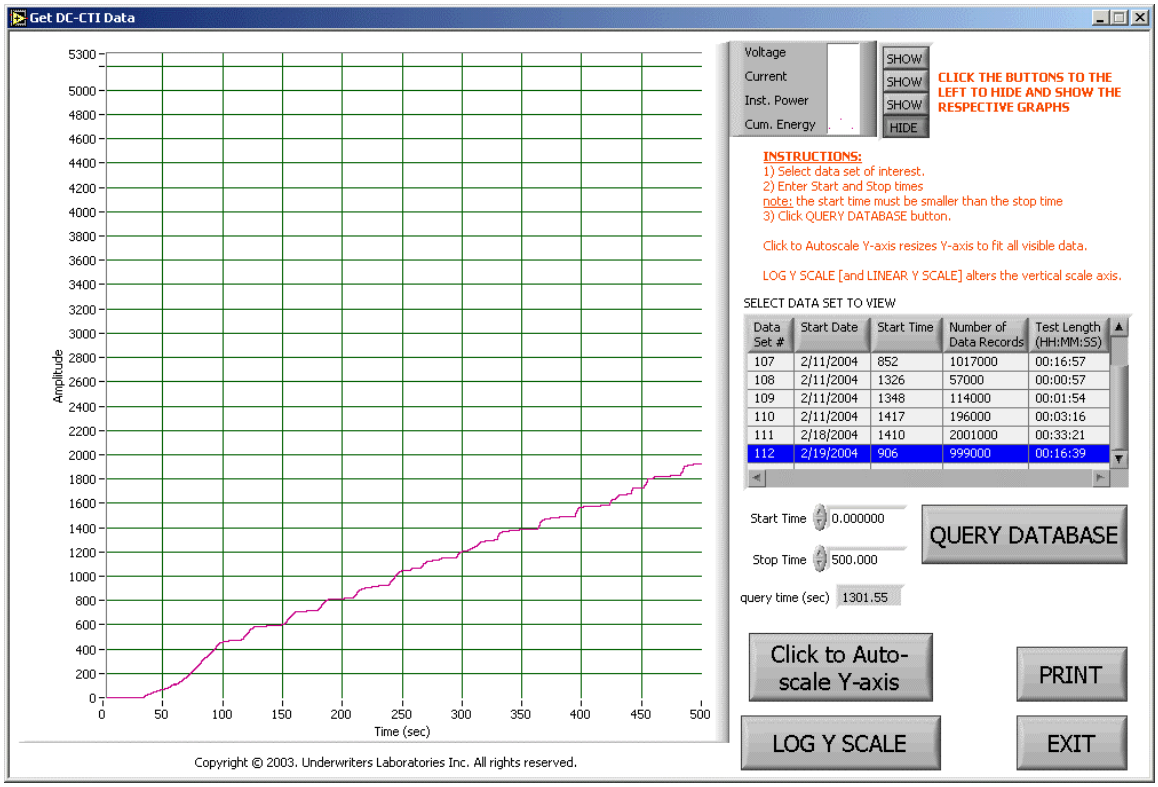
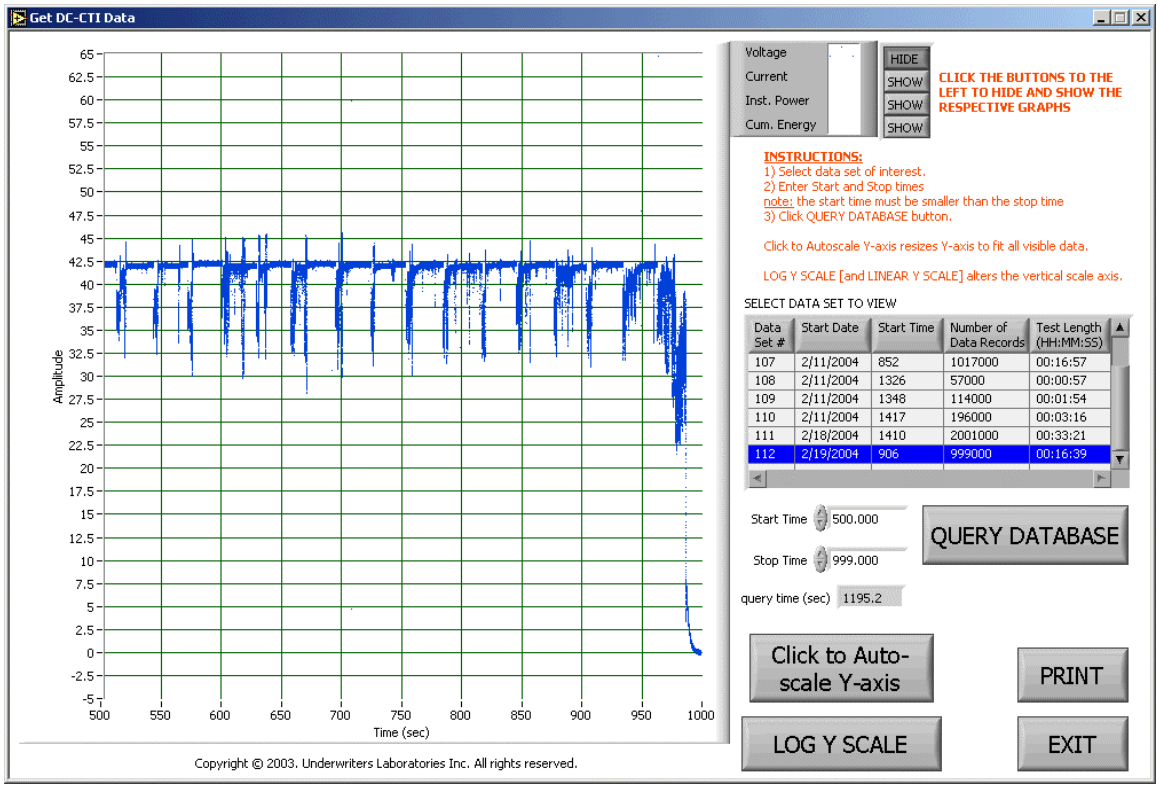


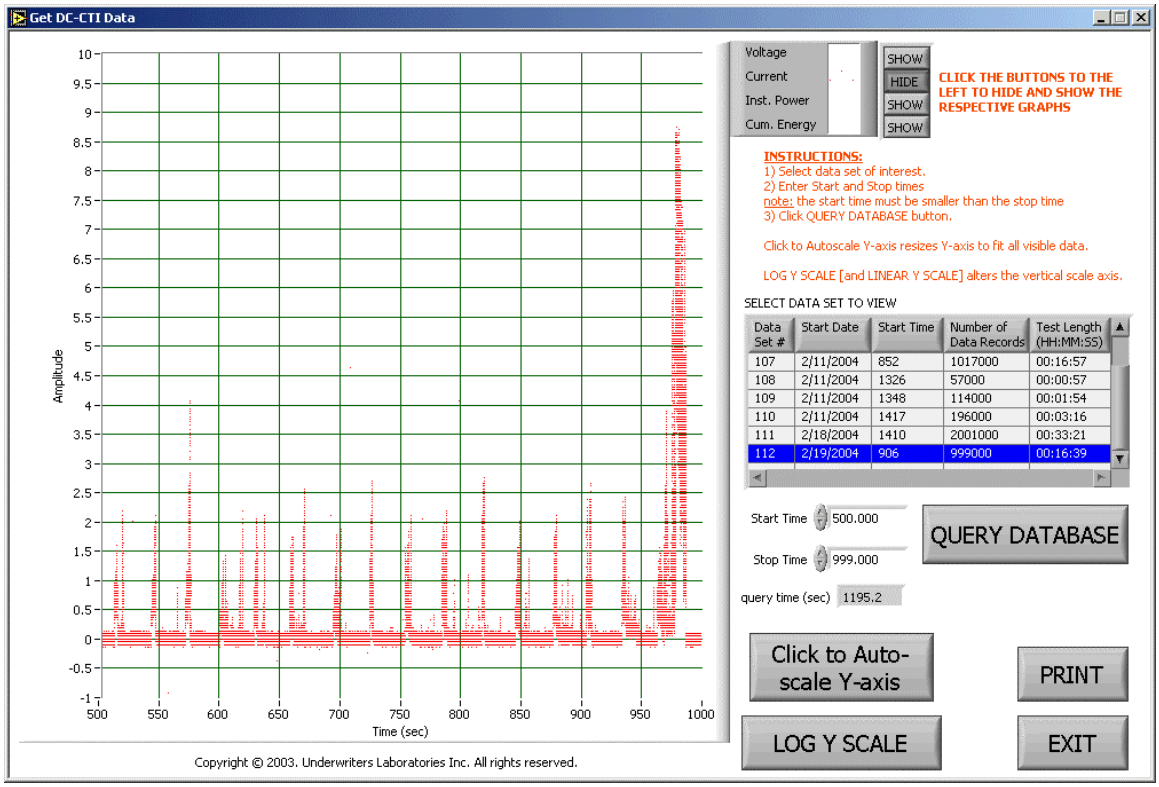
Energy



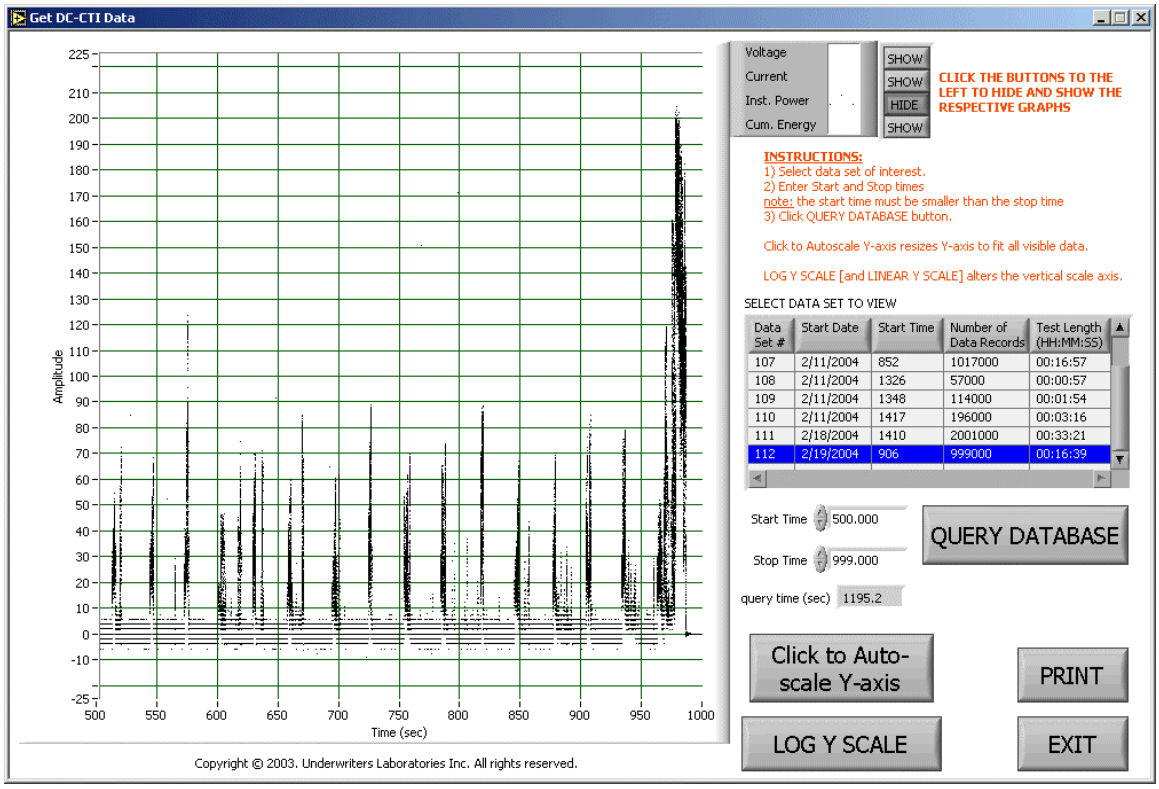
Voltage



Current



Power


Get DC-CTI Data
Amplitude
Time (sec)
Voltage
Current
Inst. Power
Cum. Energy
SHOW
SHOW
HIDE
SHOW
CLICK THE BUTTONS TO THE LEFT TO HIDE AND SHOW THE RESPECTIVE GRAPHS
INSTRUCTIONS:
1) Select data set of interest.
2) Enter Start and Stop times
note: the start time must be smaller than the stop time
3) Click QUERY DATABASE button.
Click to Autoscale Y-axis resizes Y-axis to fit all visible data.
LOG Y SCALE [and LINEAR Y SCALE] alters the vertical scale axis.
SELECT DATA SET TO VIEW
Data Set # | Start Date | Start Time | Number of Data Records | Test Length (HH:MM:SS)
107 | 2/11/2004 | 852 | 1017000 | 00:16:57
108 | 2/11/2004 | 1326 | 57000 | 00:00:57
109 | 2/11/2004 | 1348 | 114000 | 00:01:54
110 | 2/11/2004 | 1417 | 196000 | 00:03:16
111 | 2/18/2004 | 1410 | 2001000 | 00:33:21
112 | 2/19/2004 | 906 | 999000 | 00:16:39
Start Time 500.000
Stop Time 999.000
QUERY DATABASE
query time (sec) 1195.2
Click to Auto-scale Y-axis
PRINT
LOG Y SCALE
EXIT
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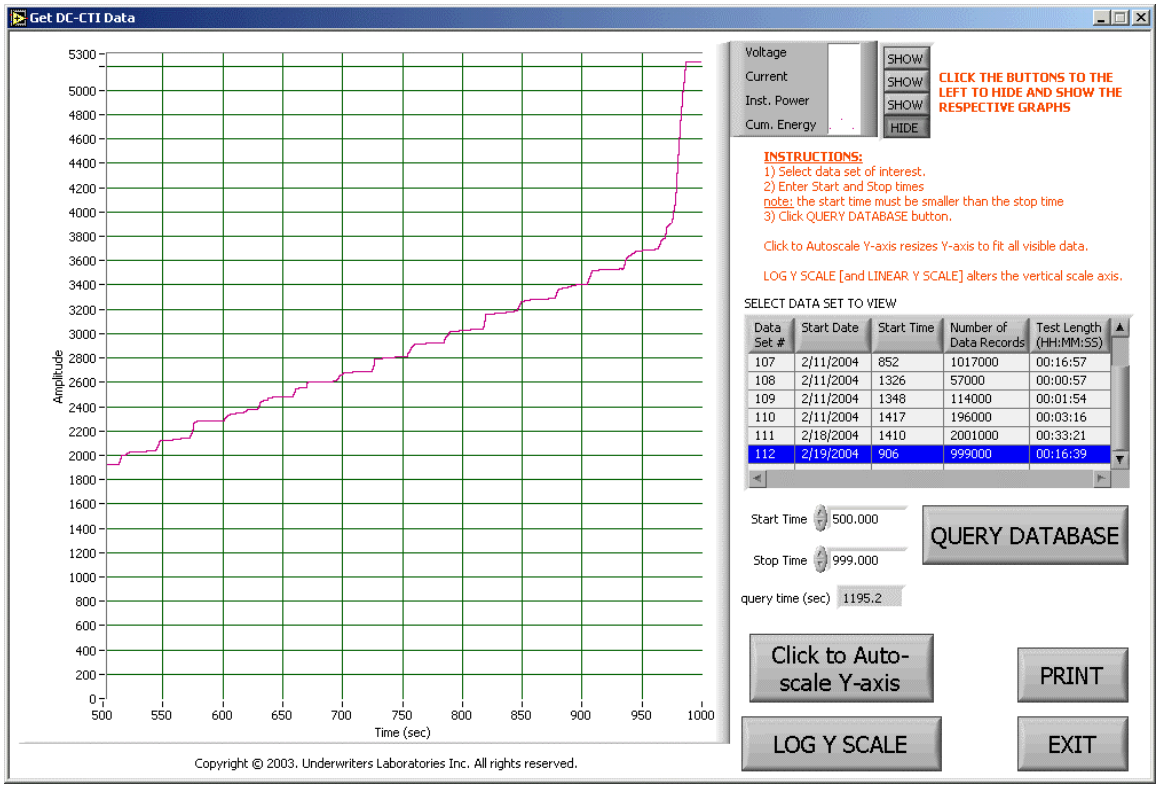
Energy


Get DC-CTI Data
Amplitude
Time (sec)
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SHOW
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110 | 2/11/2004 | 1417 | 196000 | 00:03:16
111 | 2/18/2004 | 1410 | 2001000 | 00:33:21
112 | 2/19/2004 | 906 | 999000 | 00:16:39
Start Time 500.000
Stop Time 999.000
QUERY DATABASE
query time (sec) 1195.2
Click to Auto-scale Y-axis
PRINT
LOG Y SCALE
EXIT
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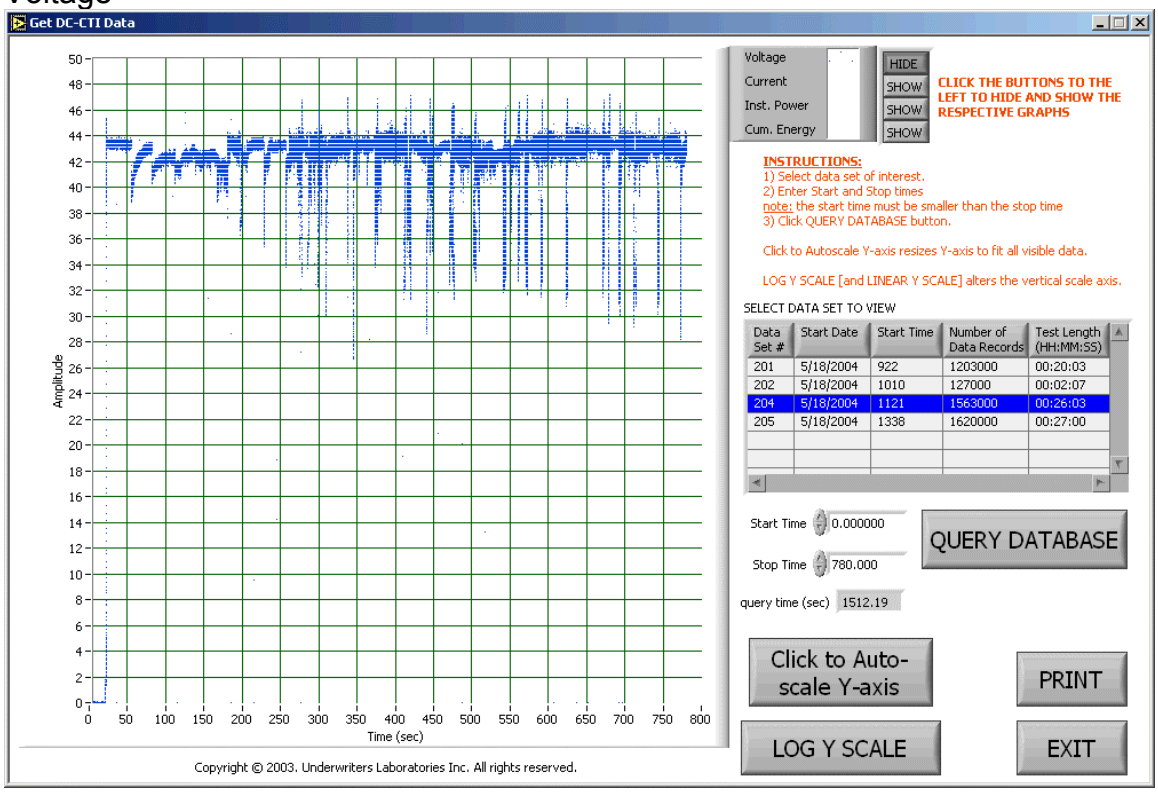
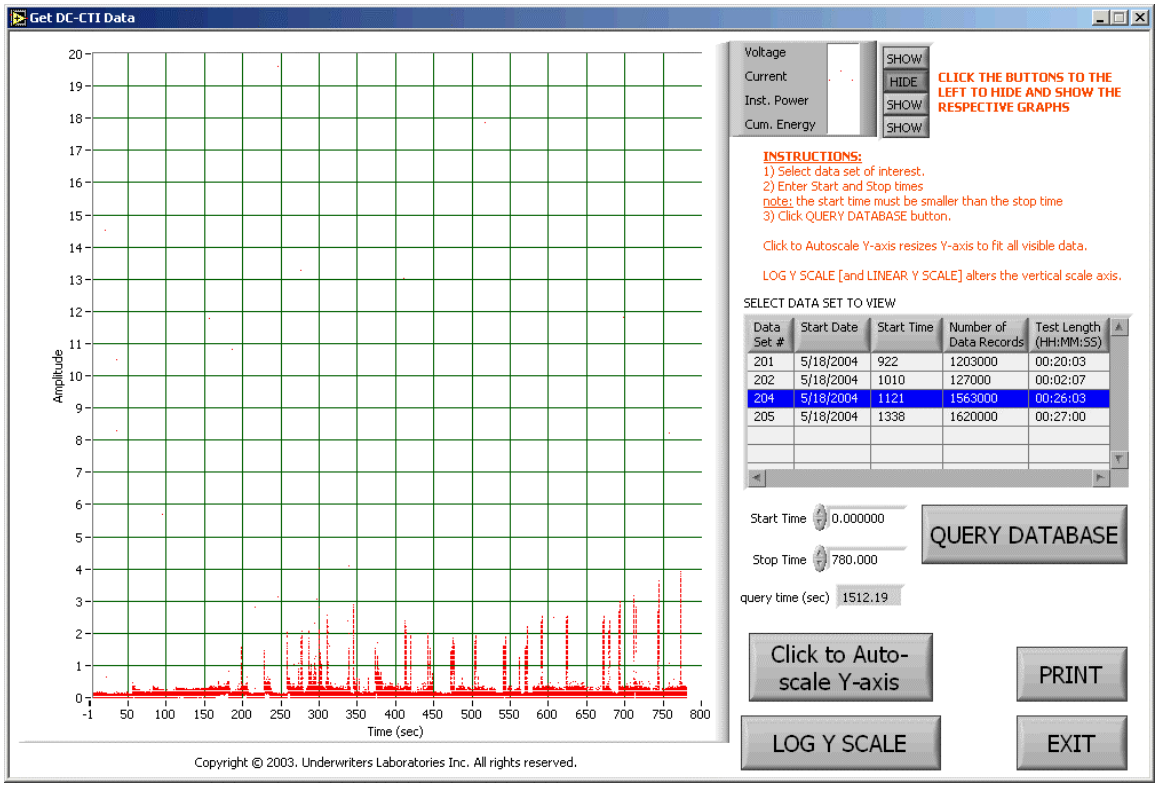
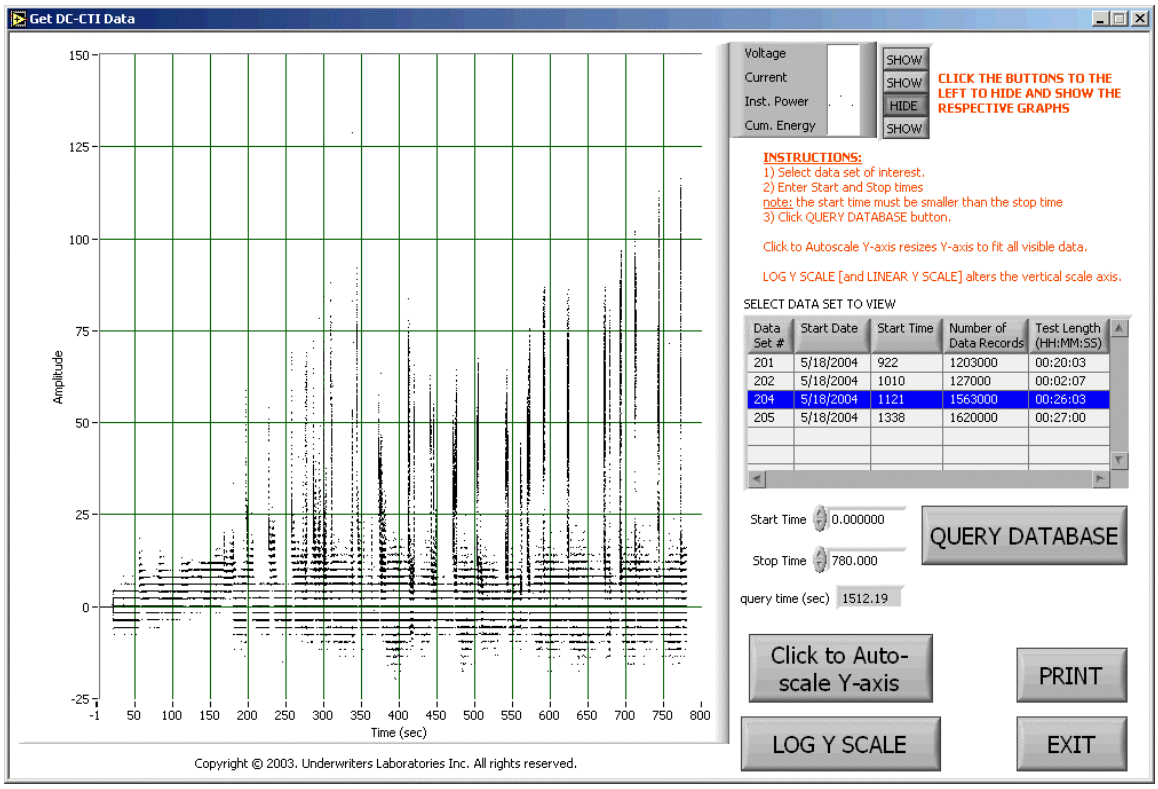
Voltage



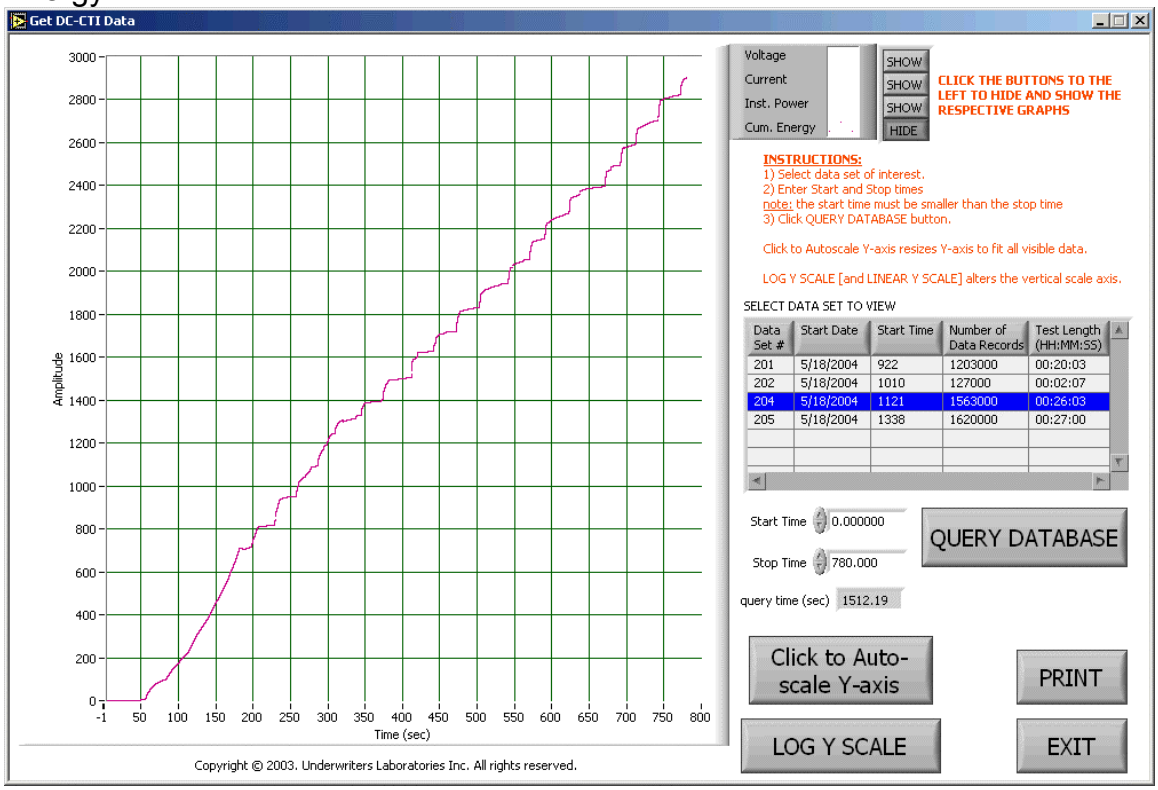
Current



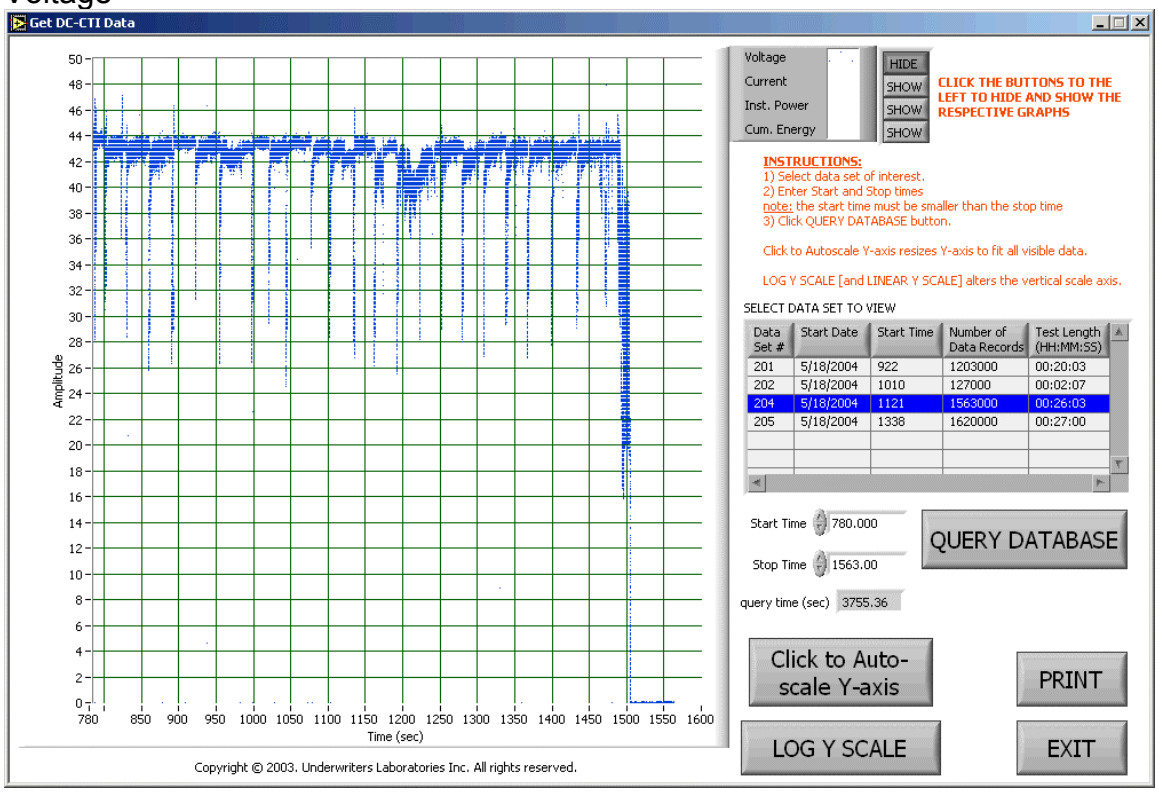
Power



Energy



Voltage



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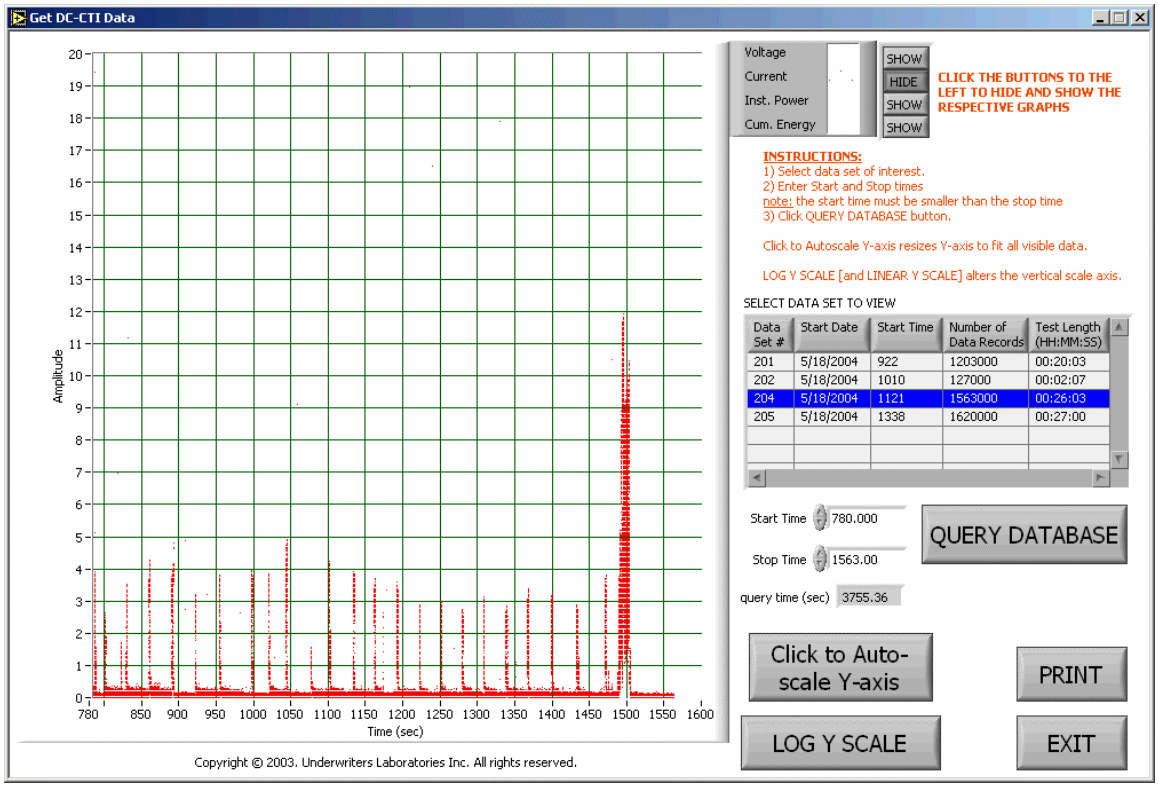
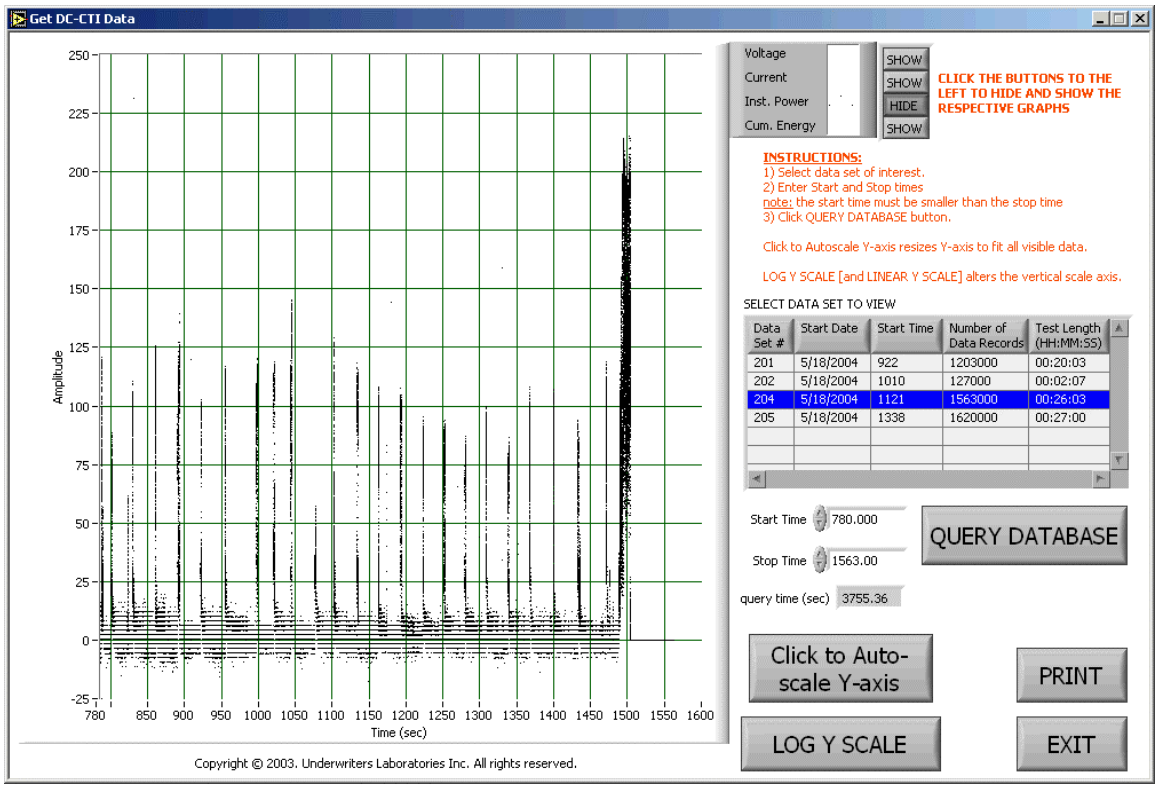
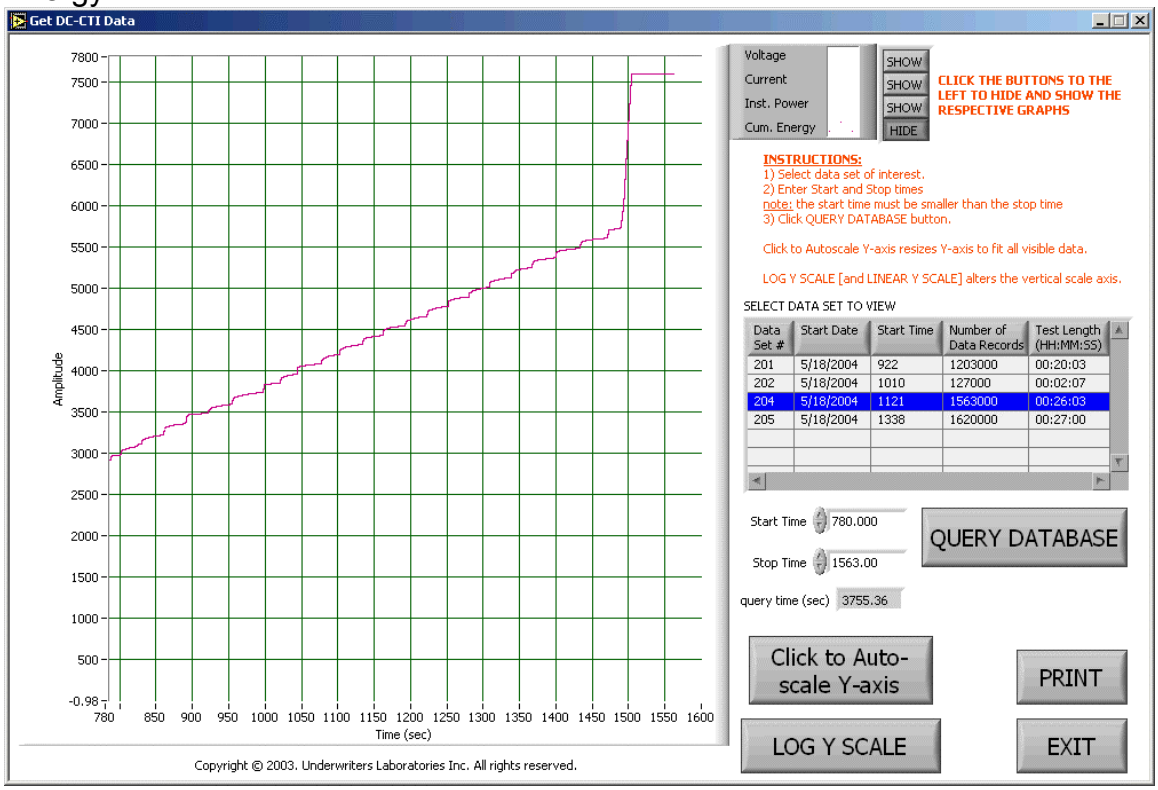


Power

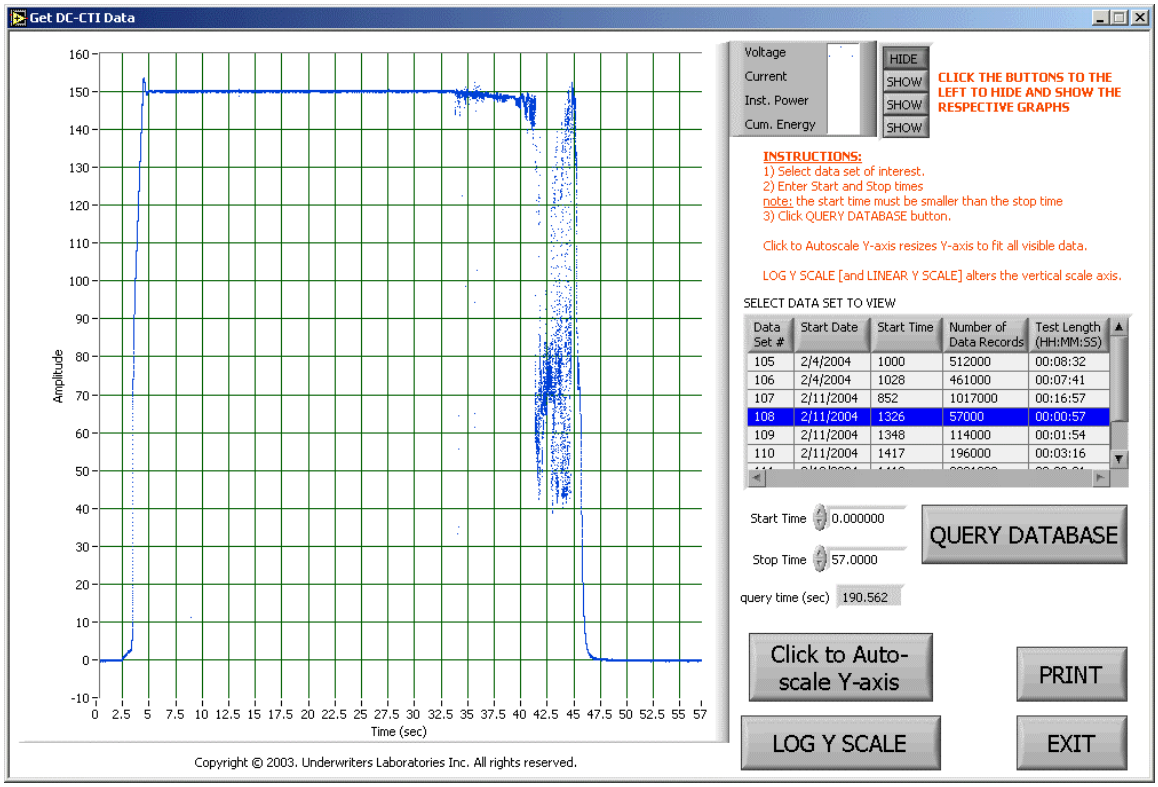


Energy



Test #8, Trial 1
(Material # 5, 150 V DC, 5% NaCl)

Voltage



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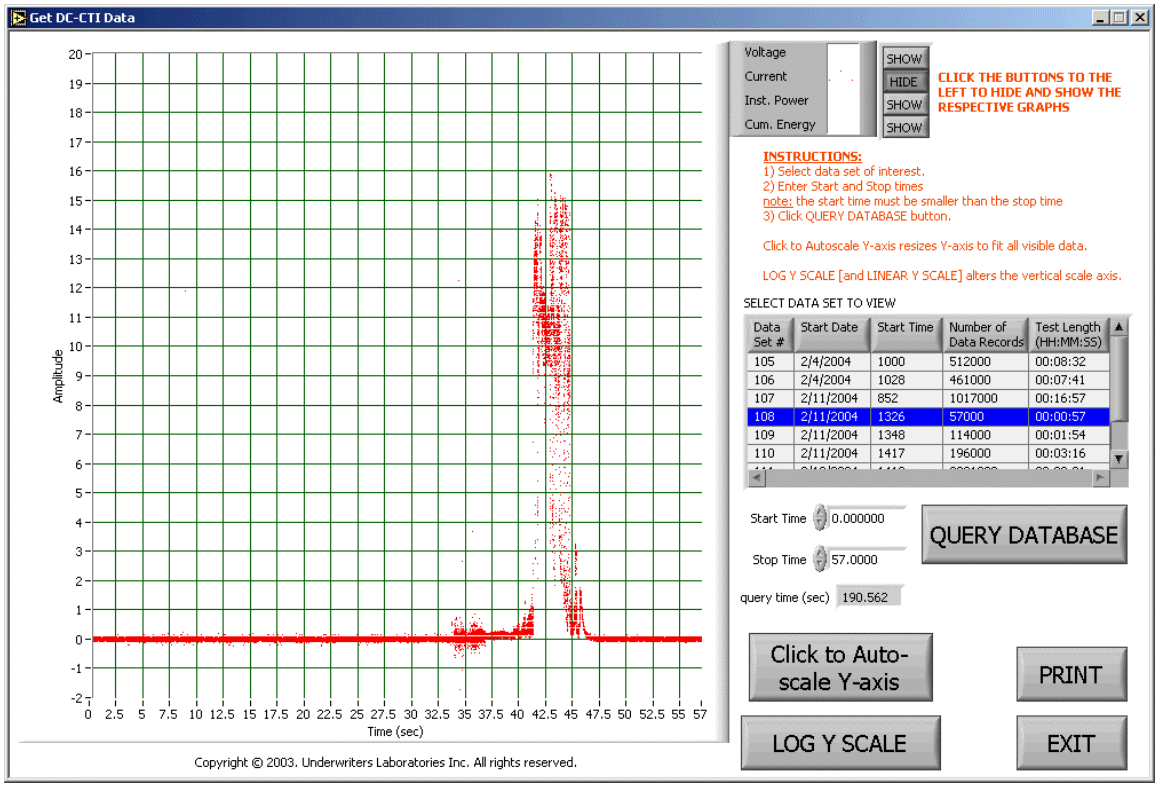
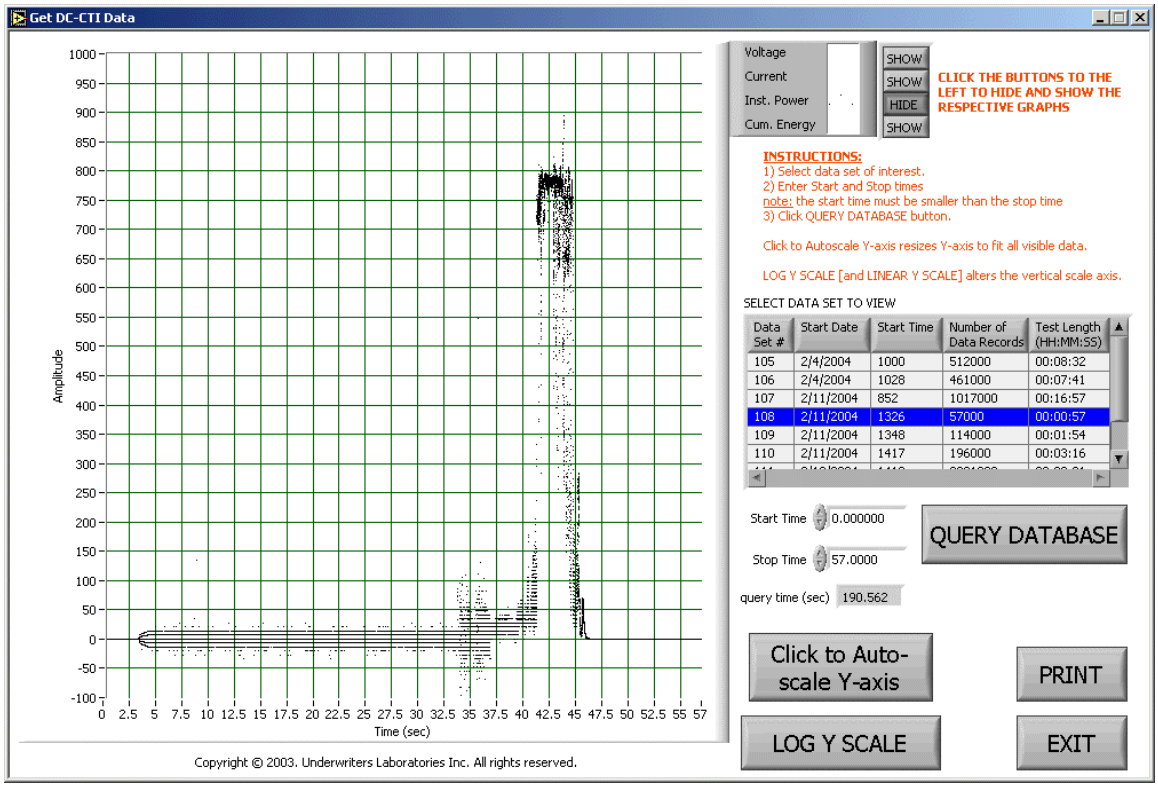
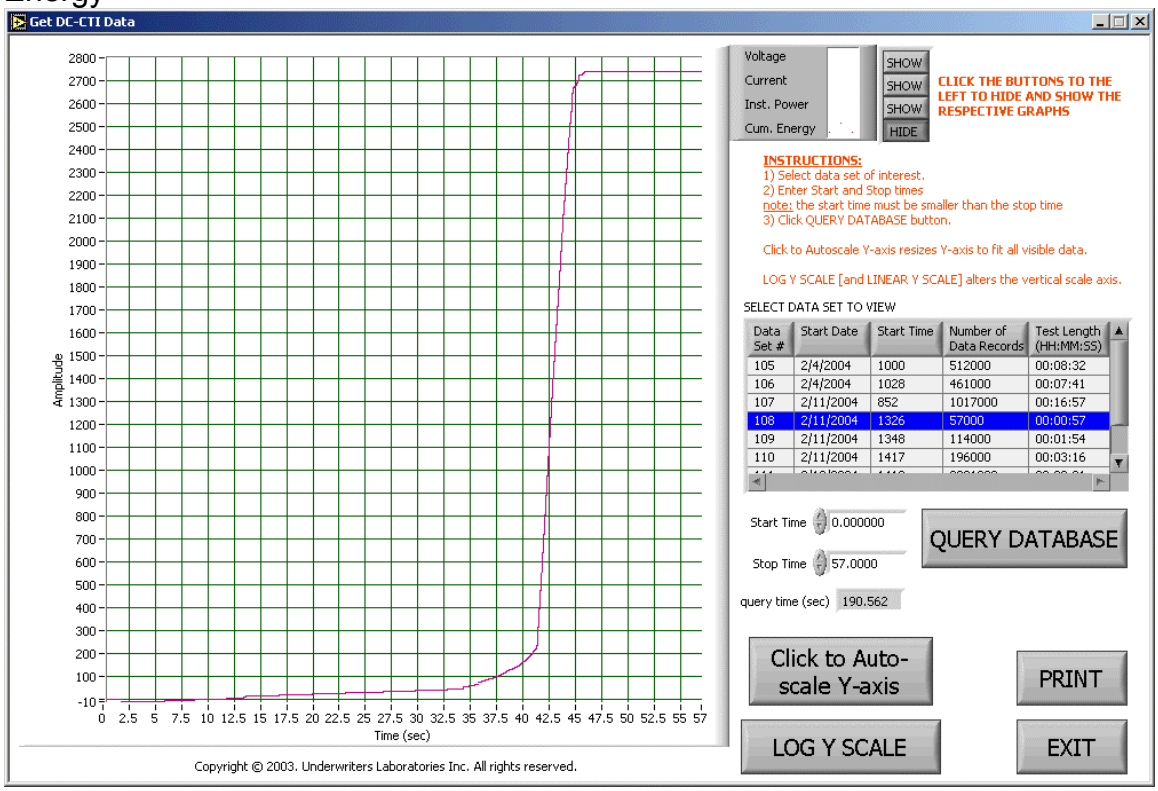


Test #8, Trial 1
(Material # 5, 150 V DC, 5% NaCl)

Power

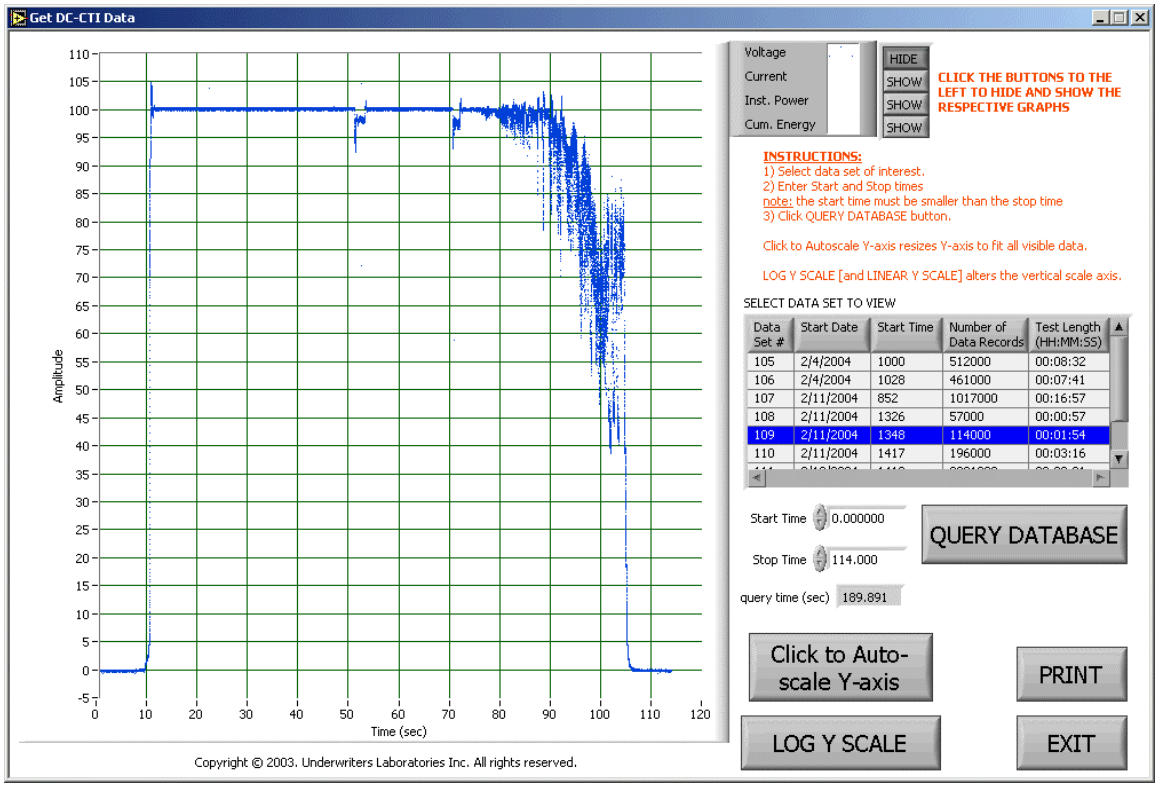


Energy

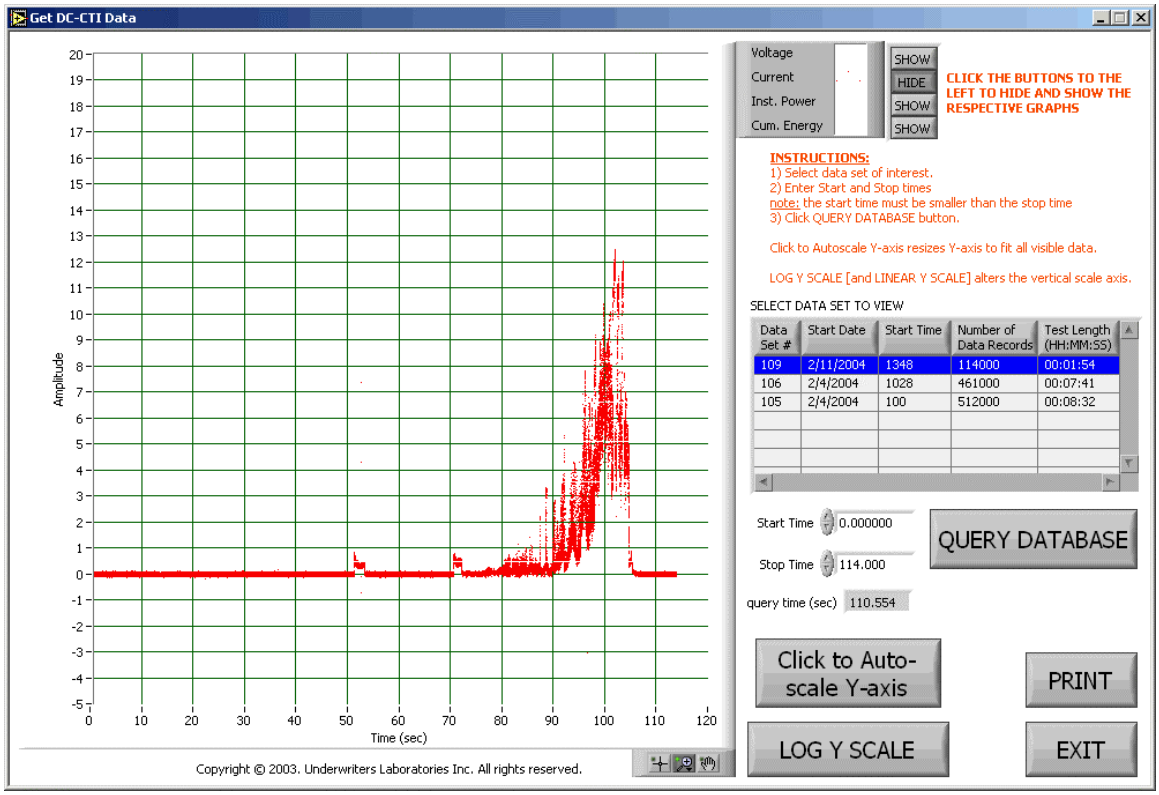


Test #9, Trial 1
(Material # 5, 100 V DC, 5% NaCl)

Voltage

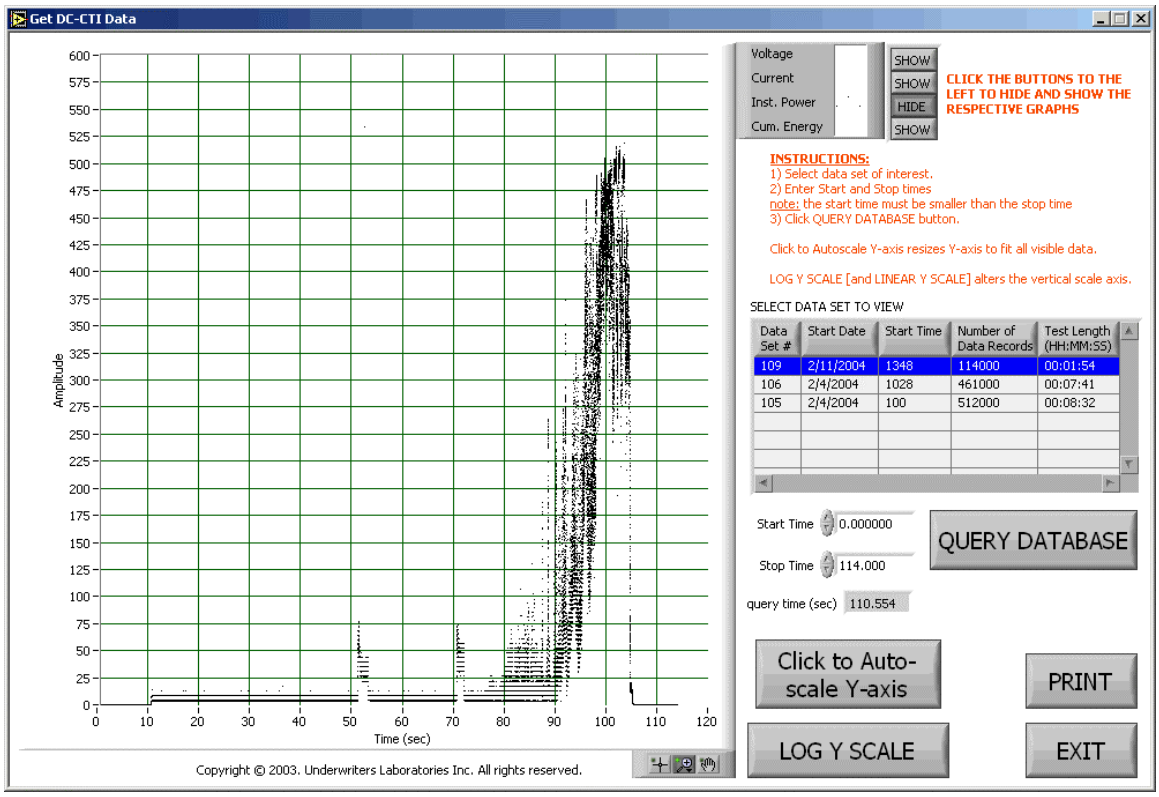


Current

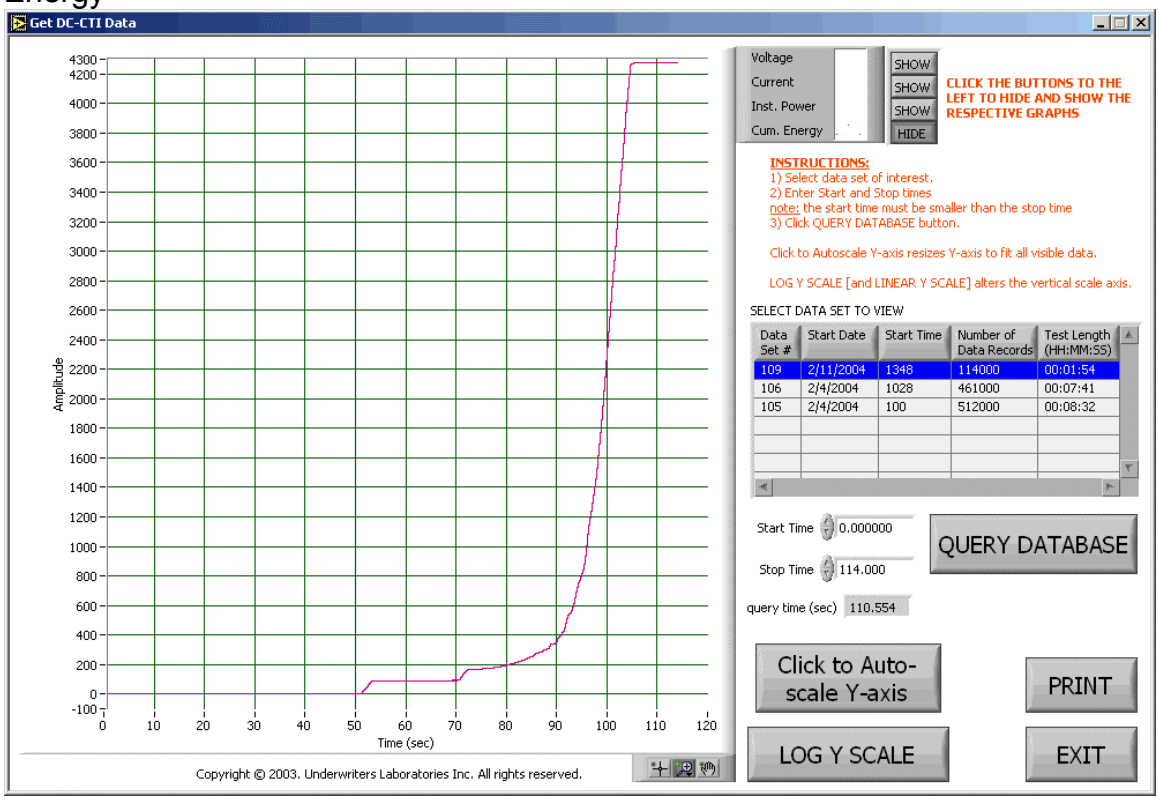


Test #9, Trial 1
(Material # 5, 100 V DC, 5% NaCl)

Power

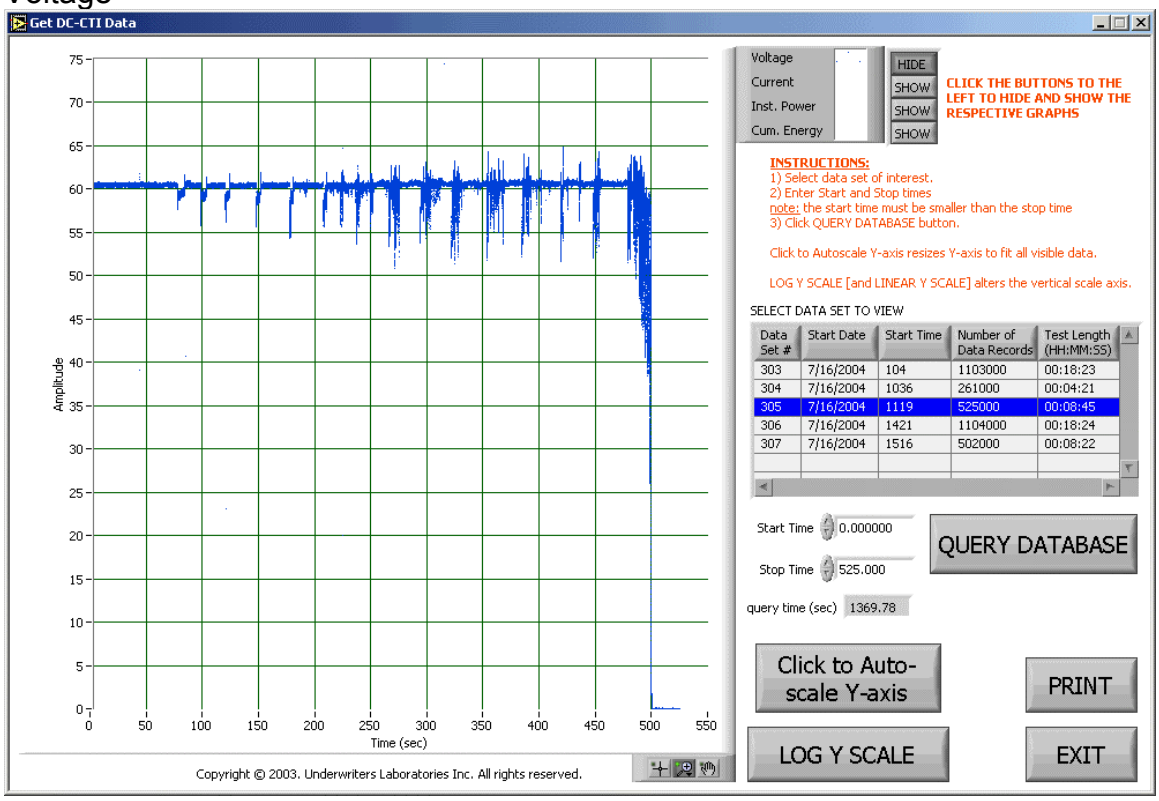


Energy



Test # 10, Trial 2
(Material # 5, 60 V DC, 5% NaCl)

Voltage



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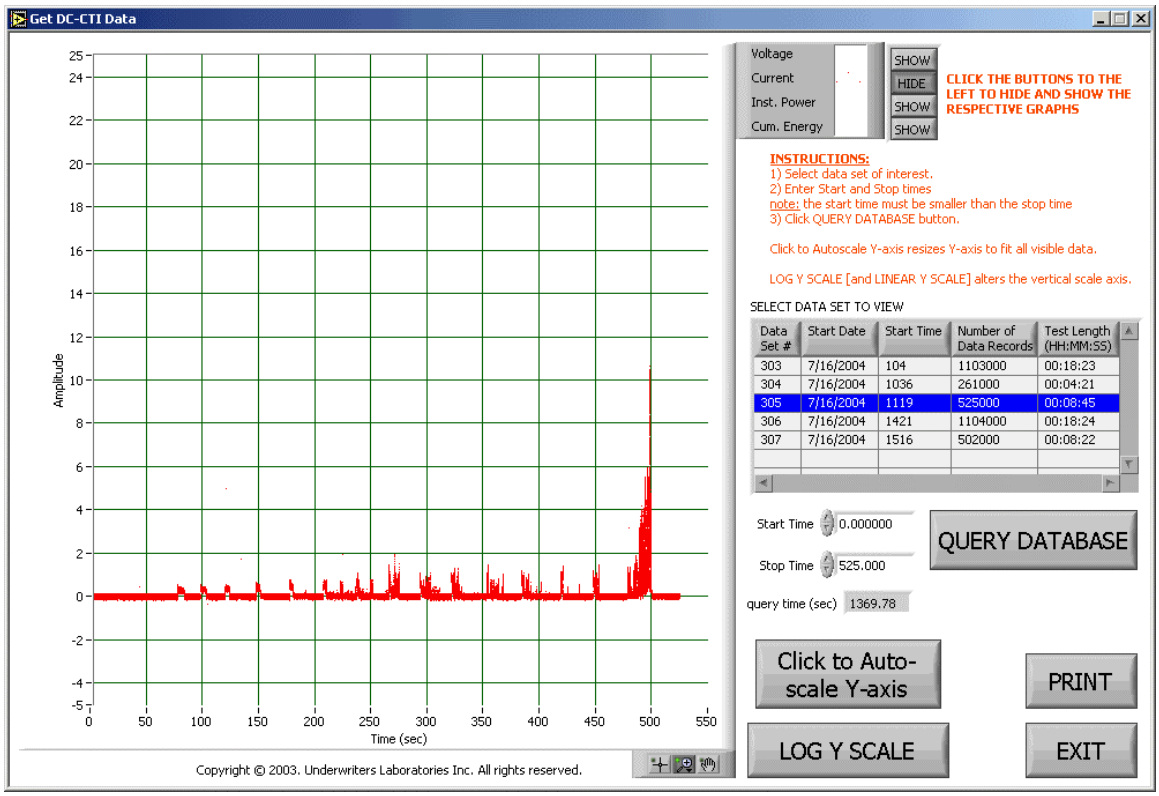
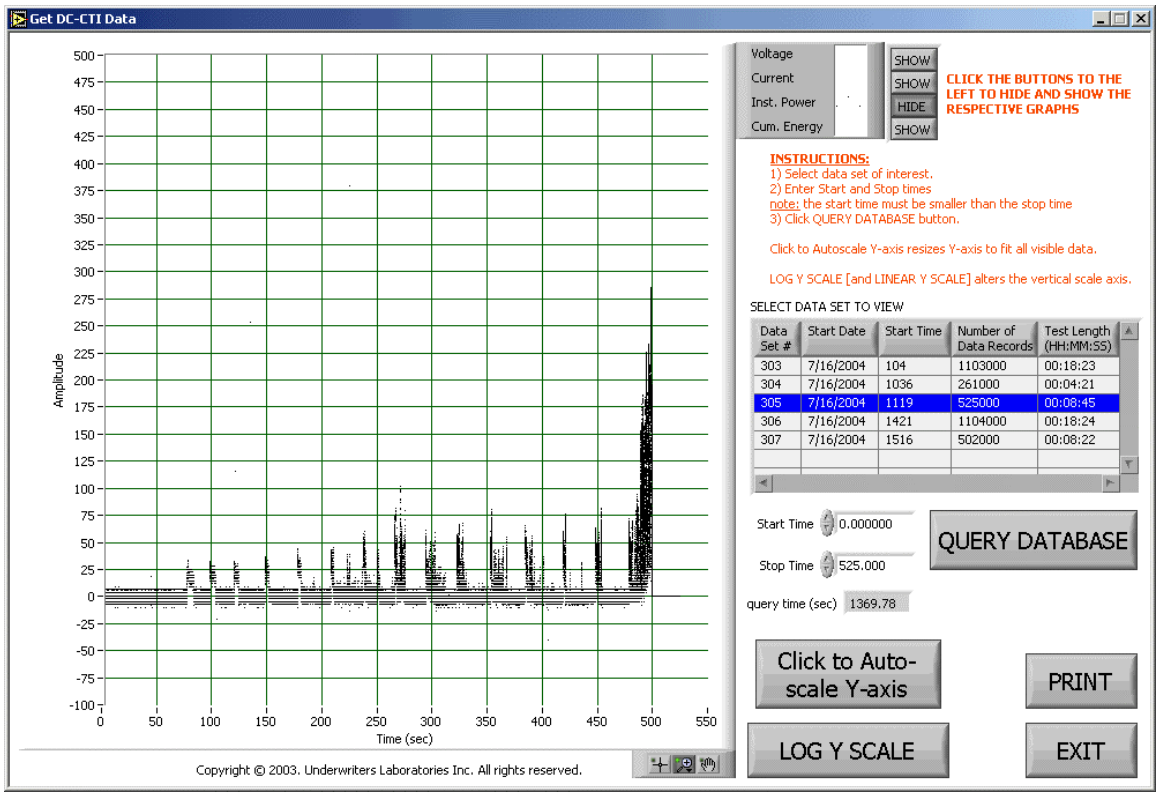
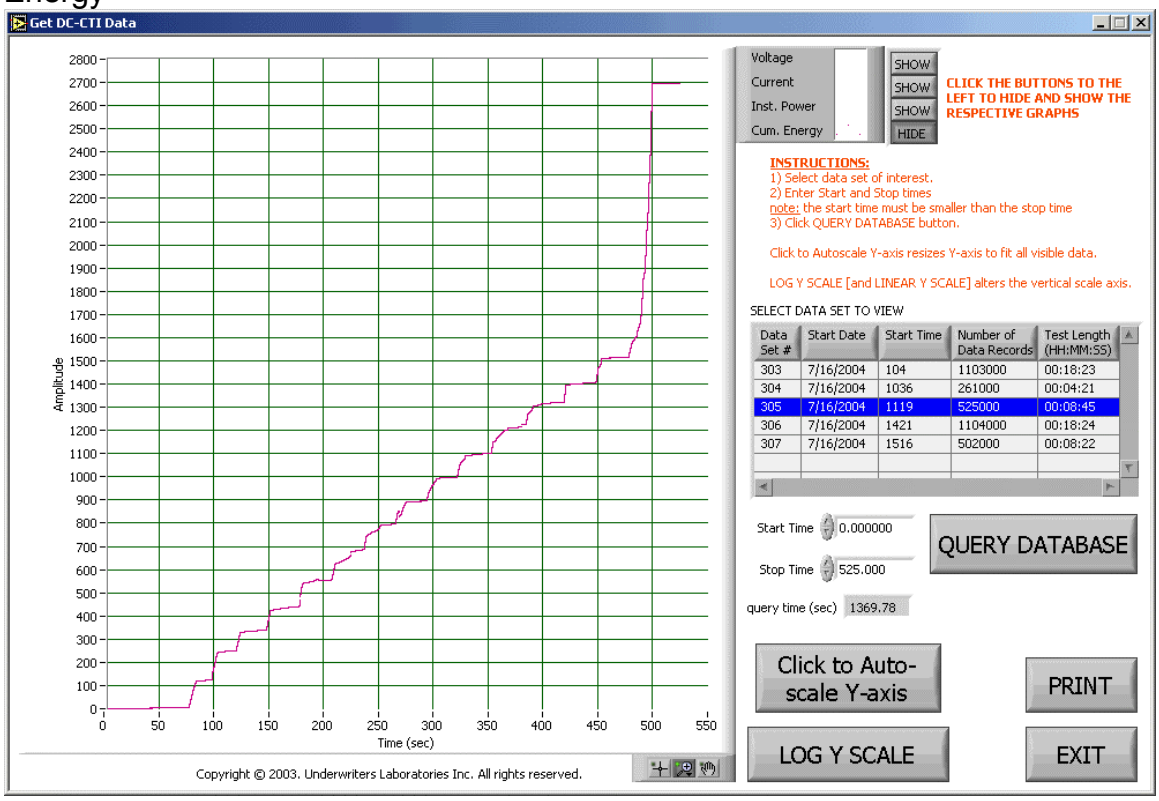


Test # 10, Trial 2
(Material # 5, 60 V DC, 5% NaCl)

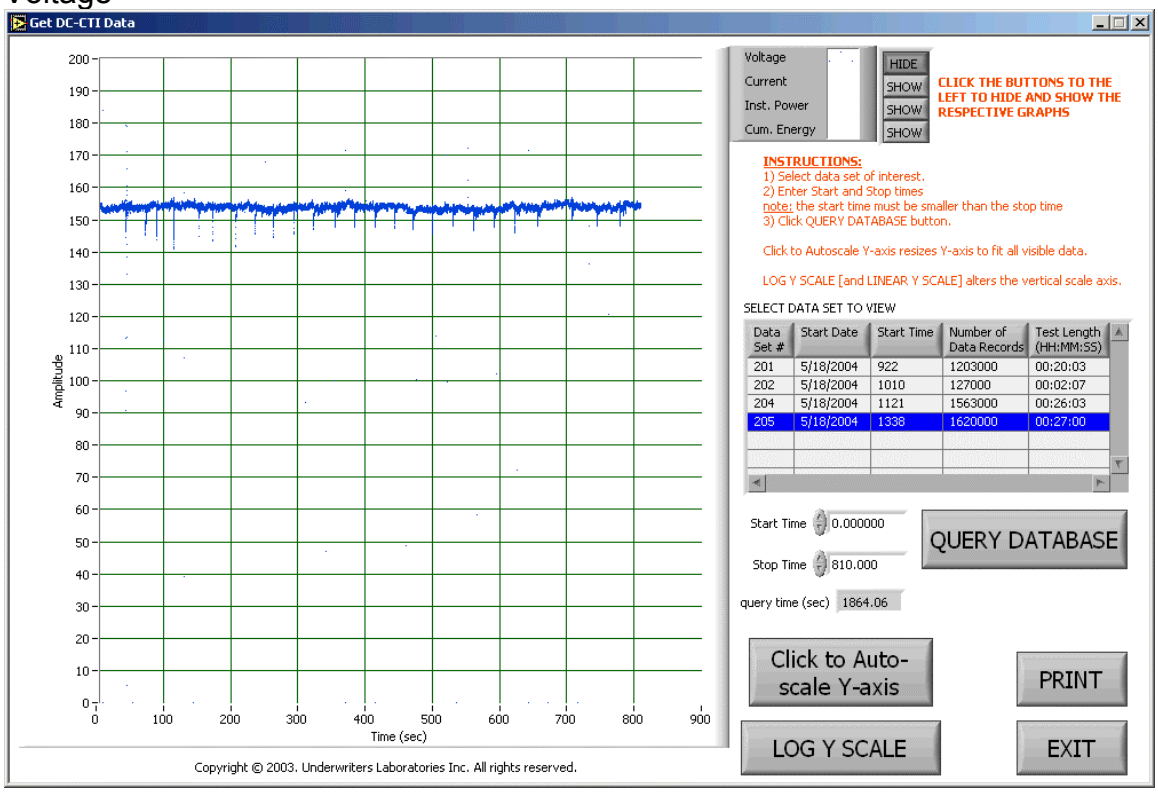
Power



Energy



Voltage



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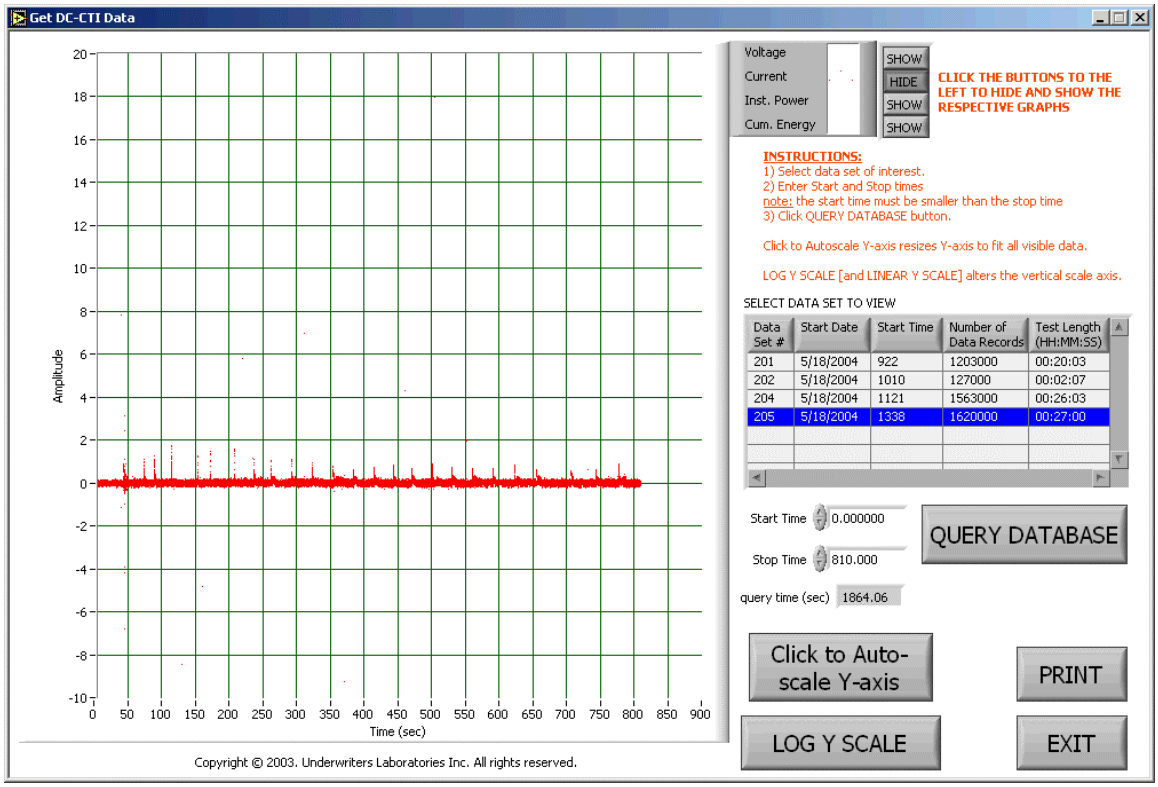
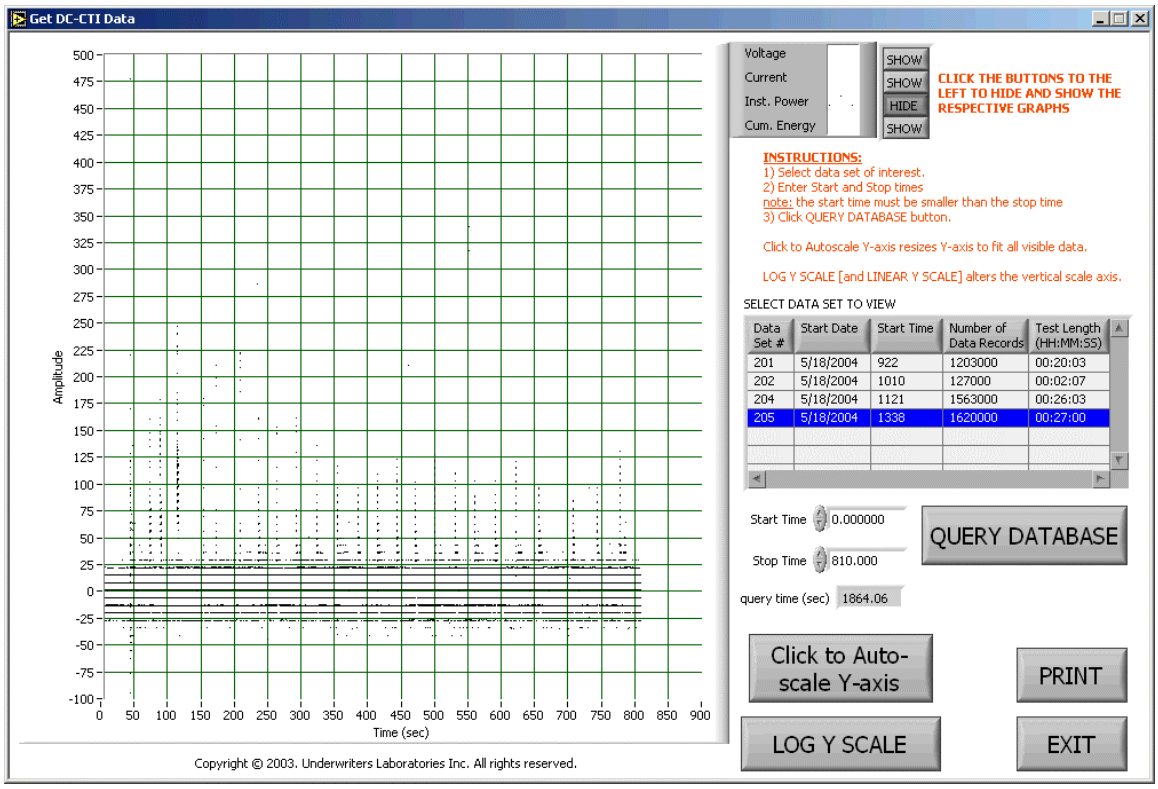
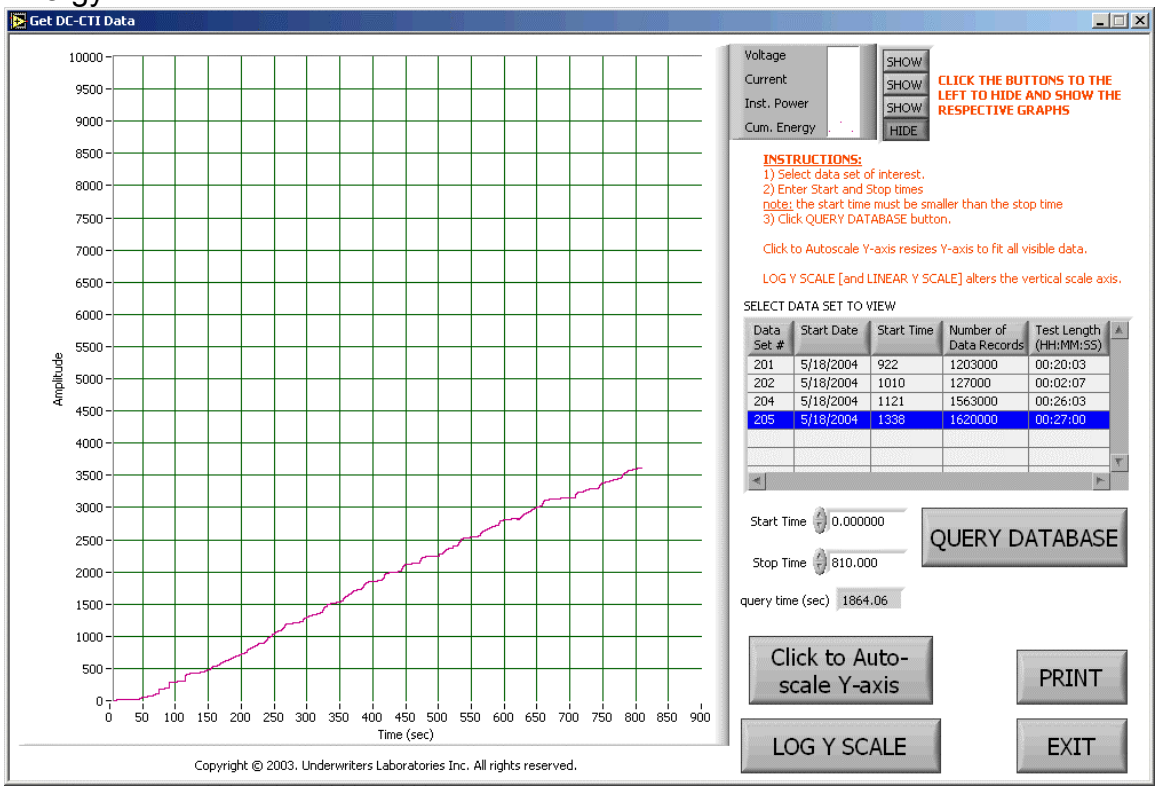


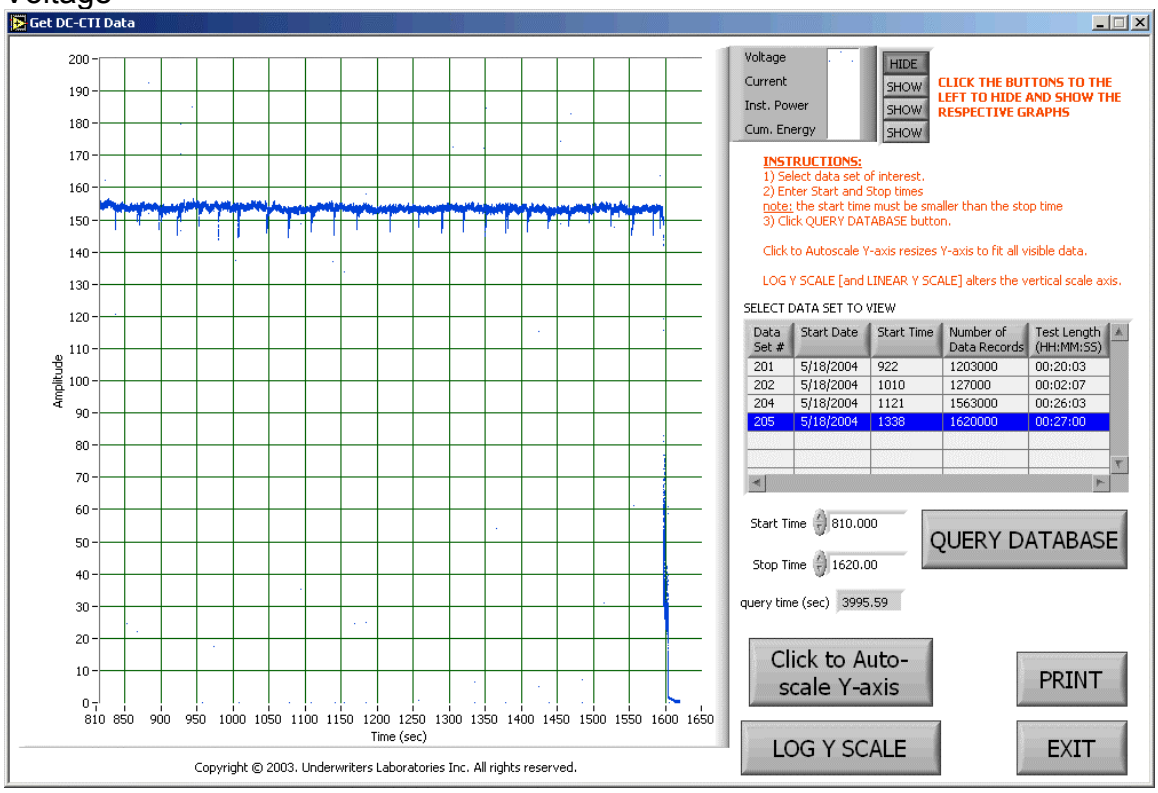
Power



Energy



Voltage



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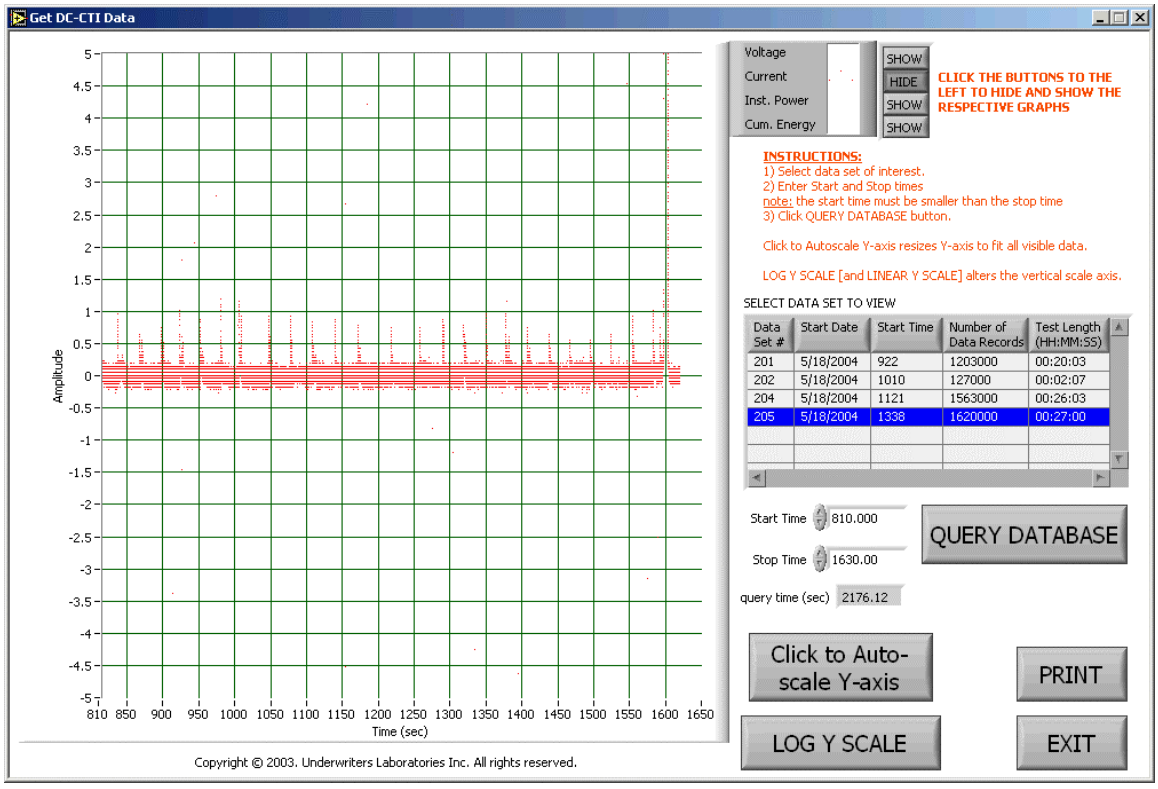

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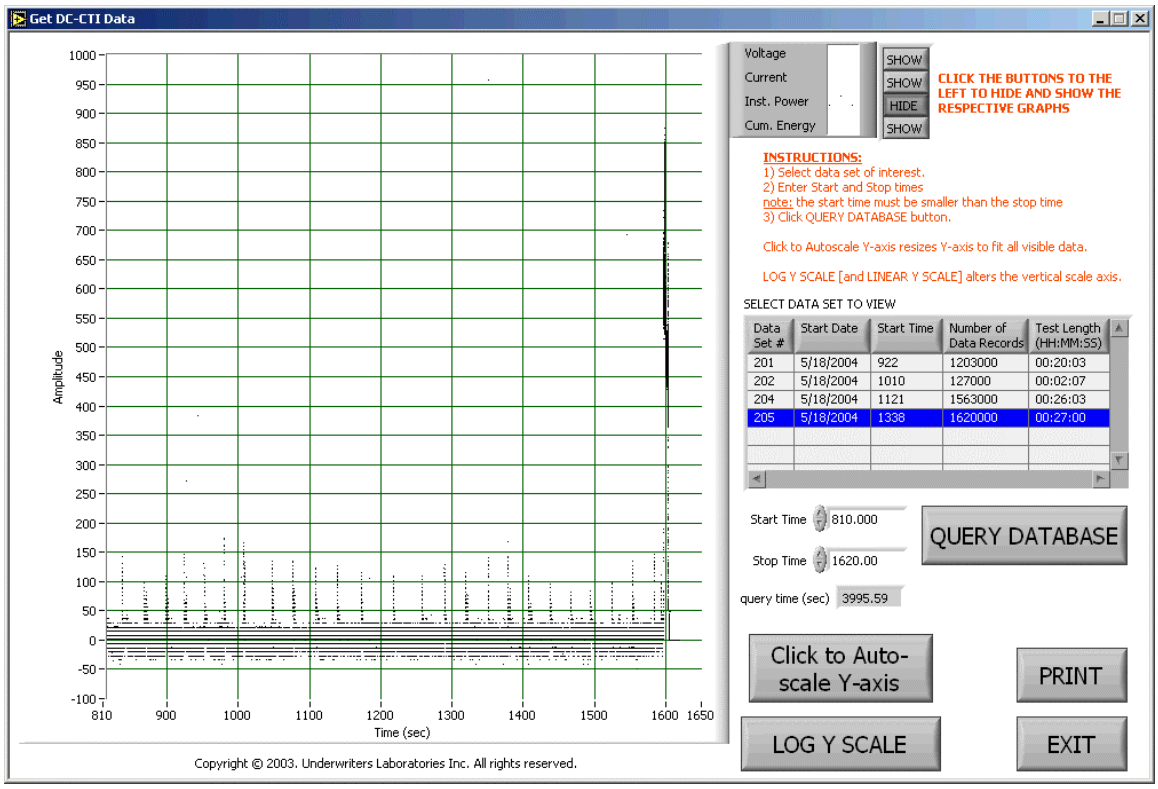

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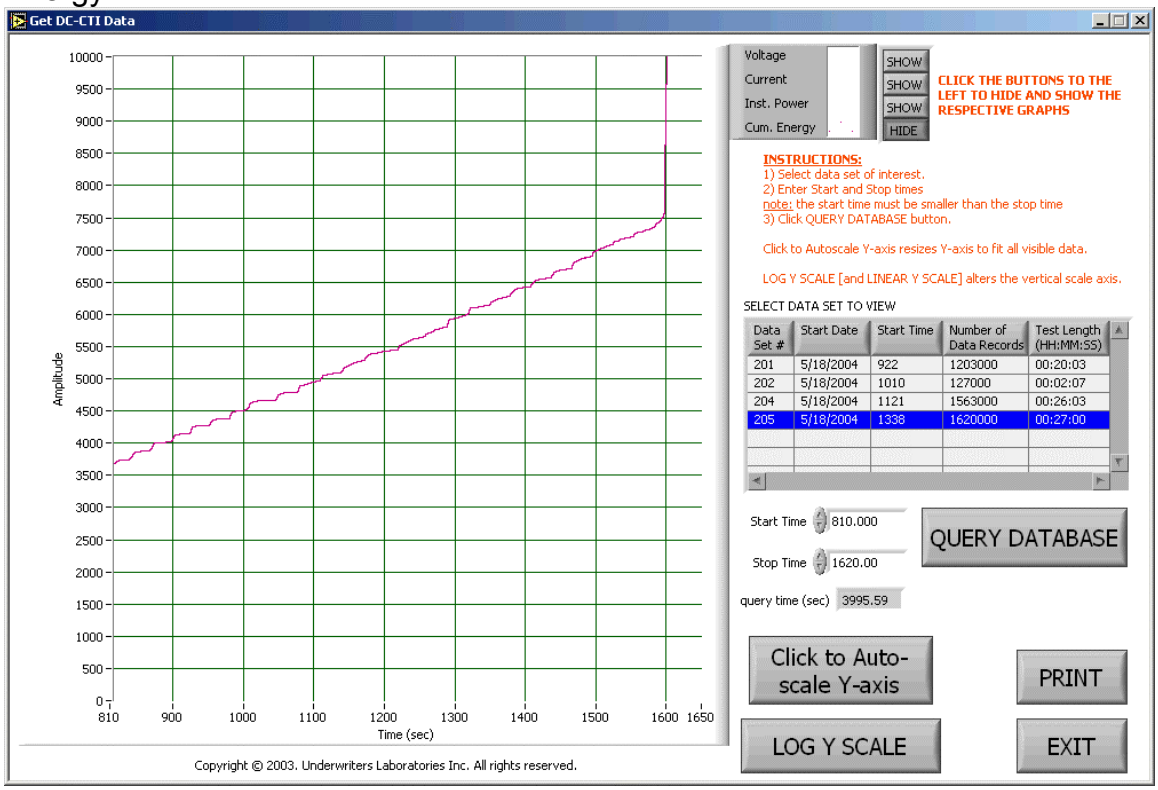

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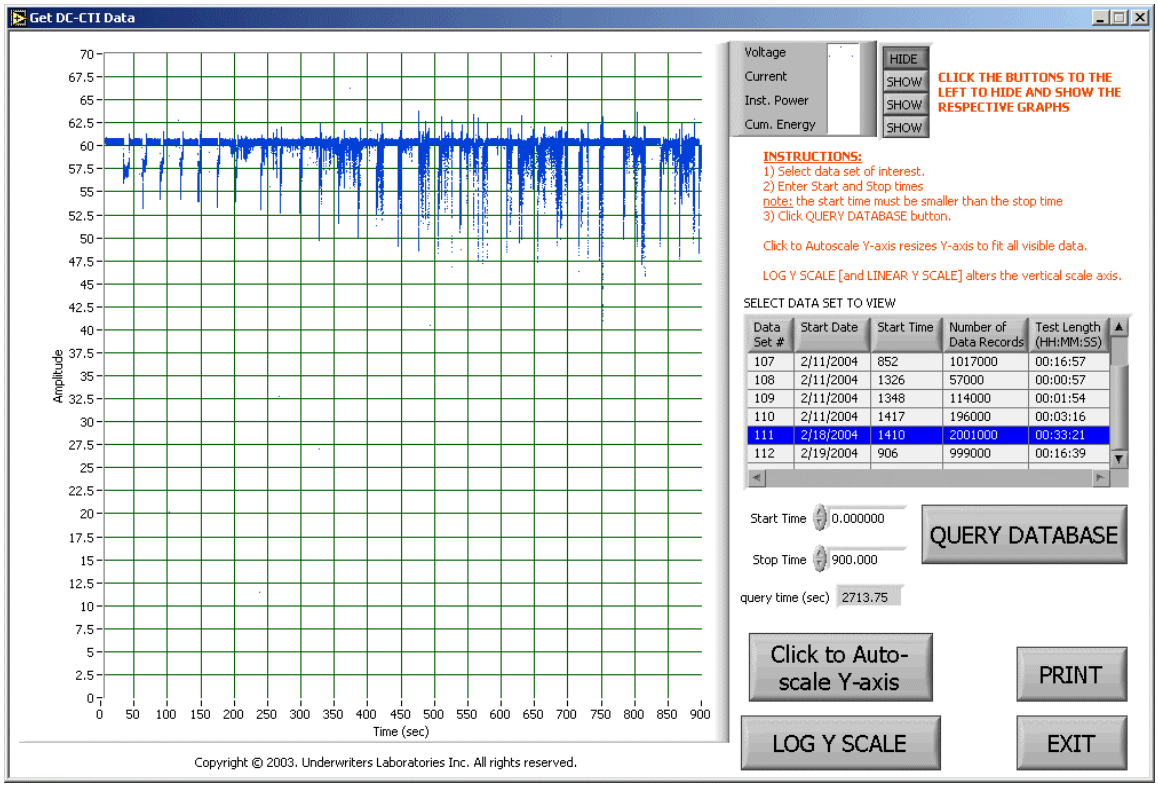

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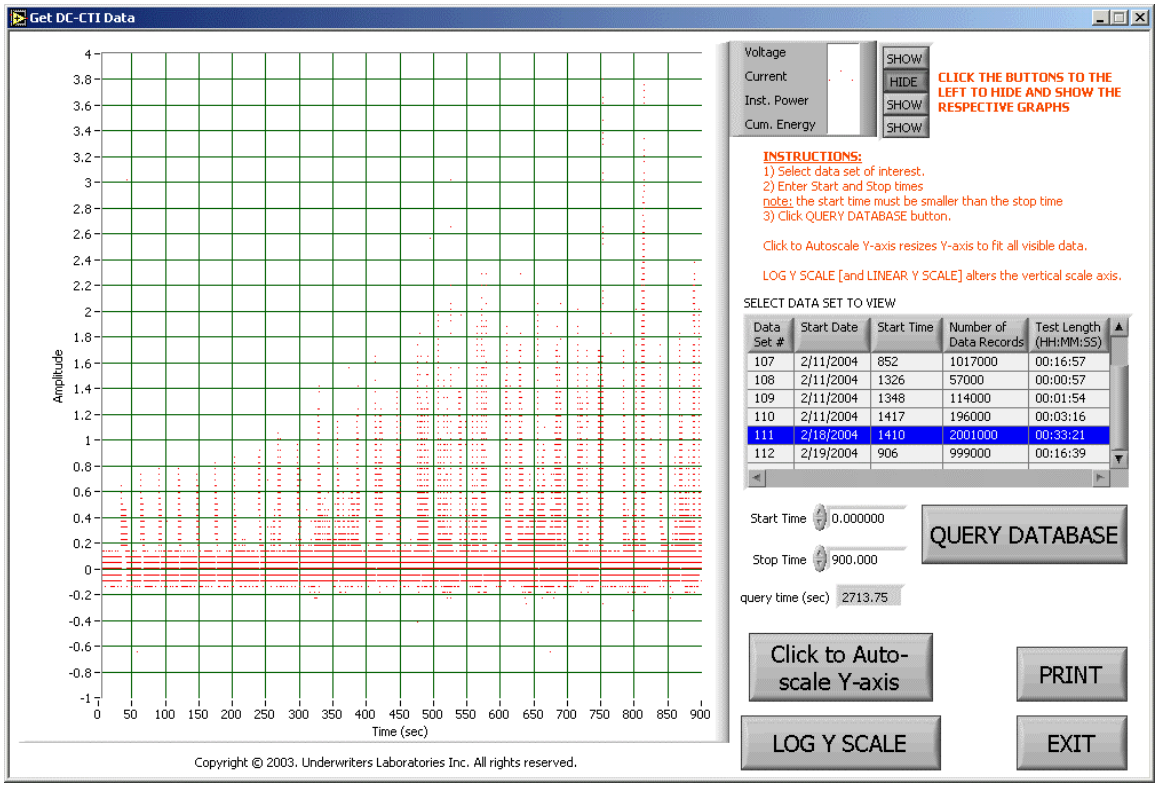
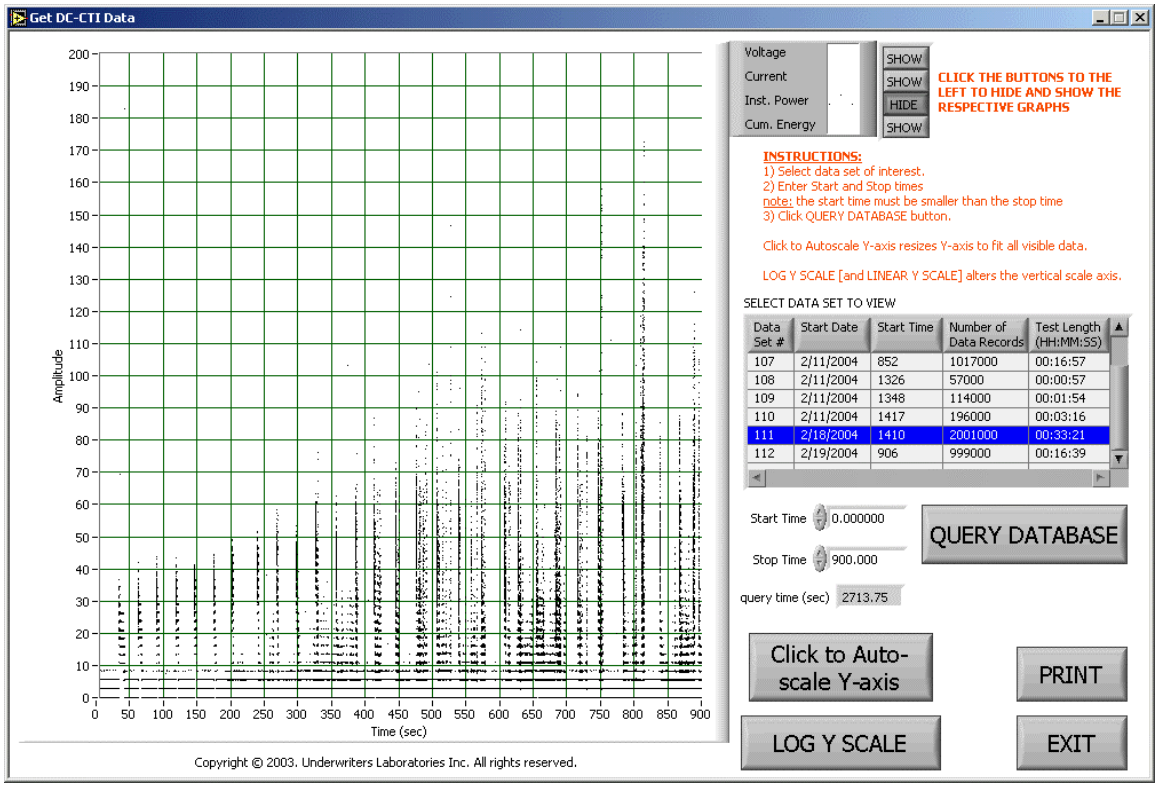
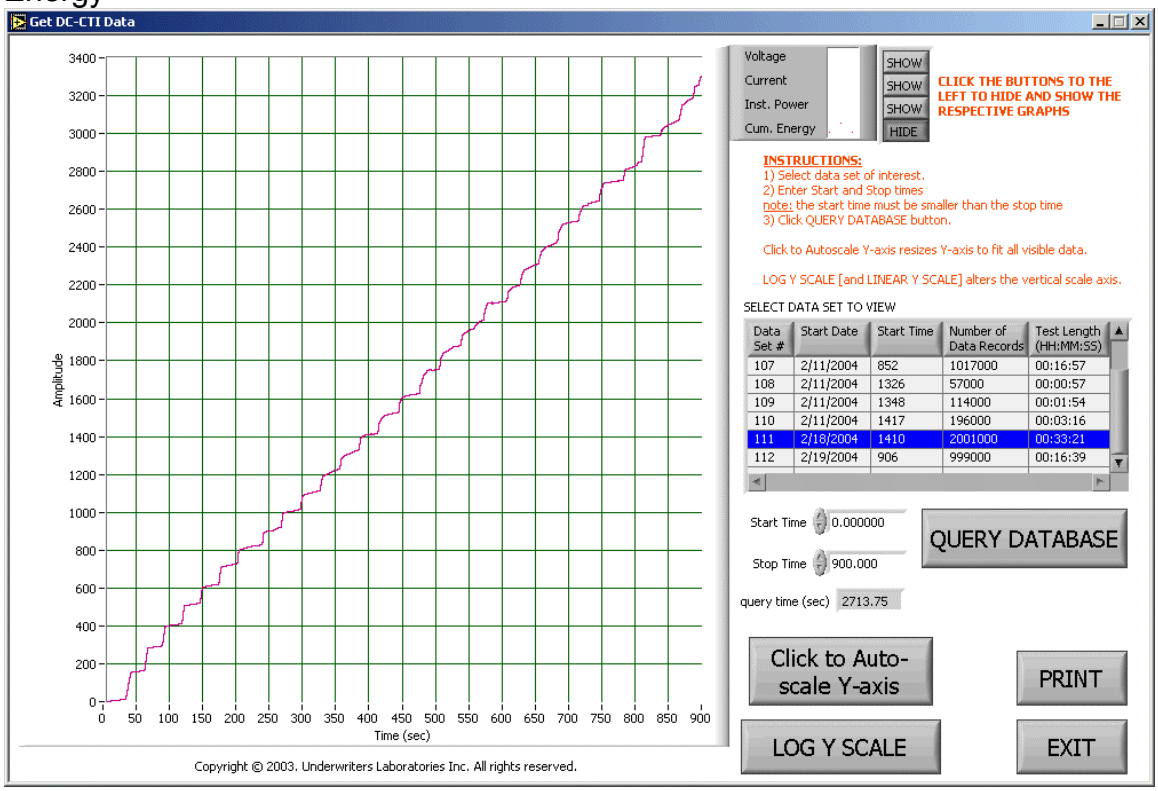


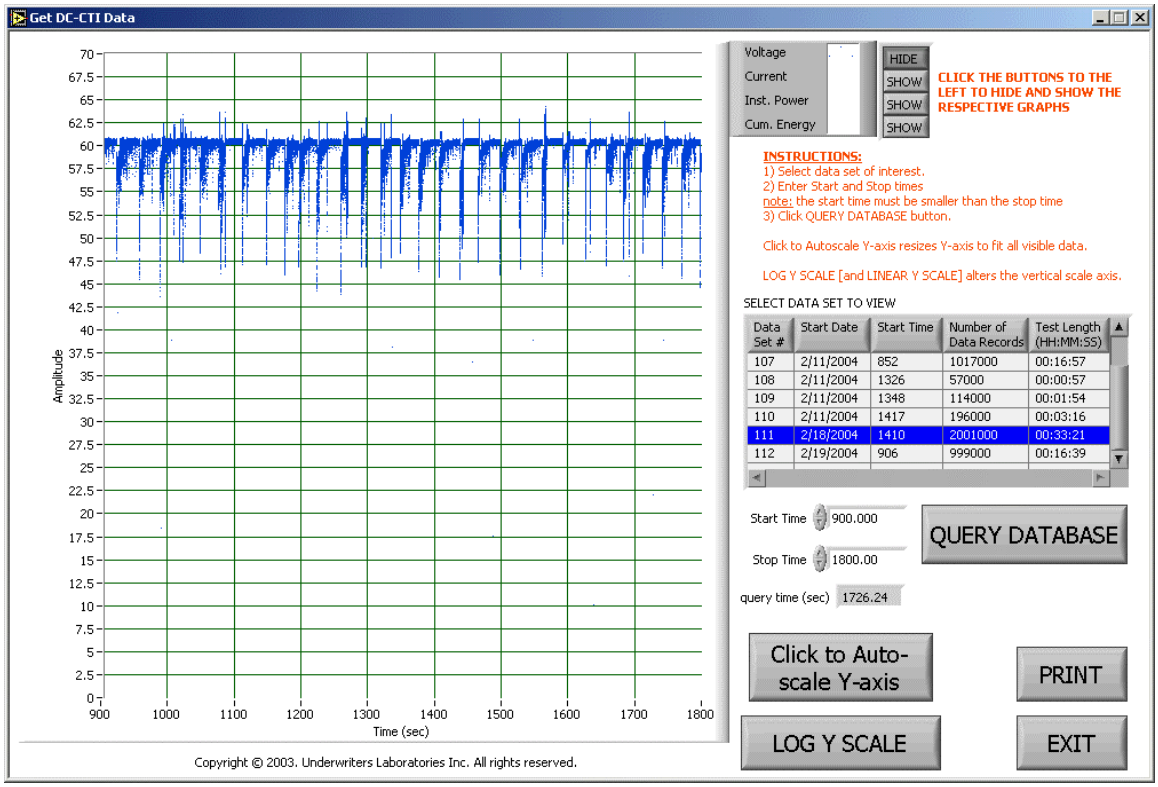
Power



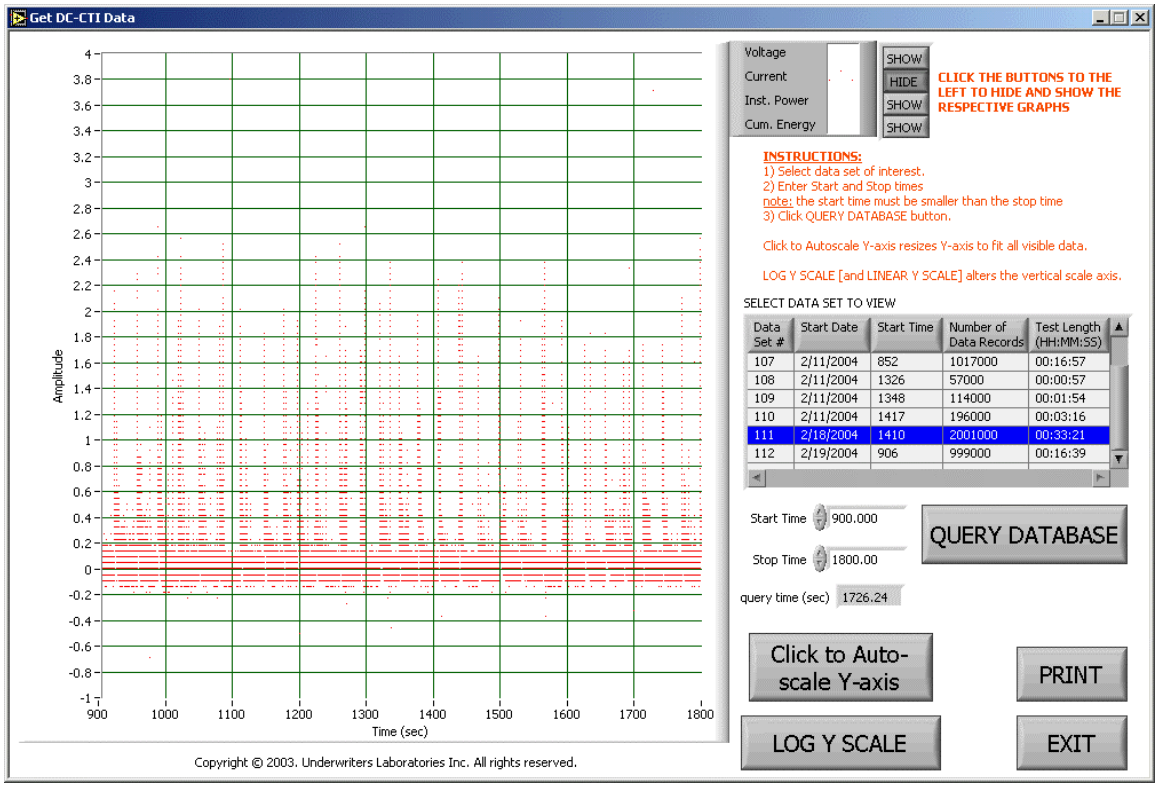
Energy



Voltage



Current



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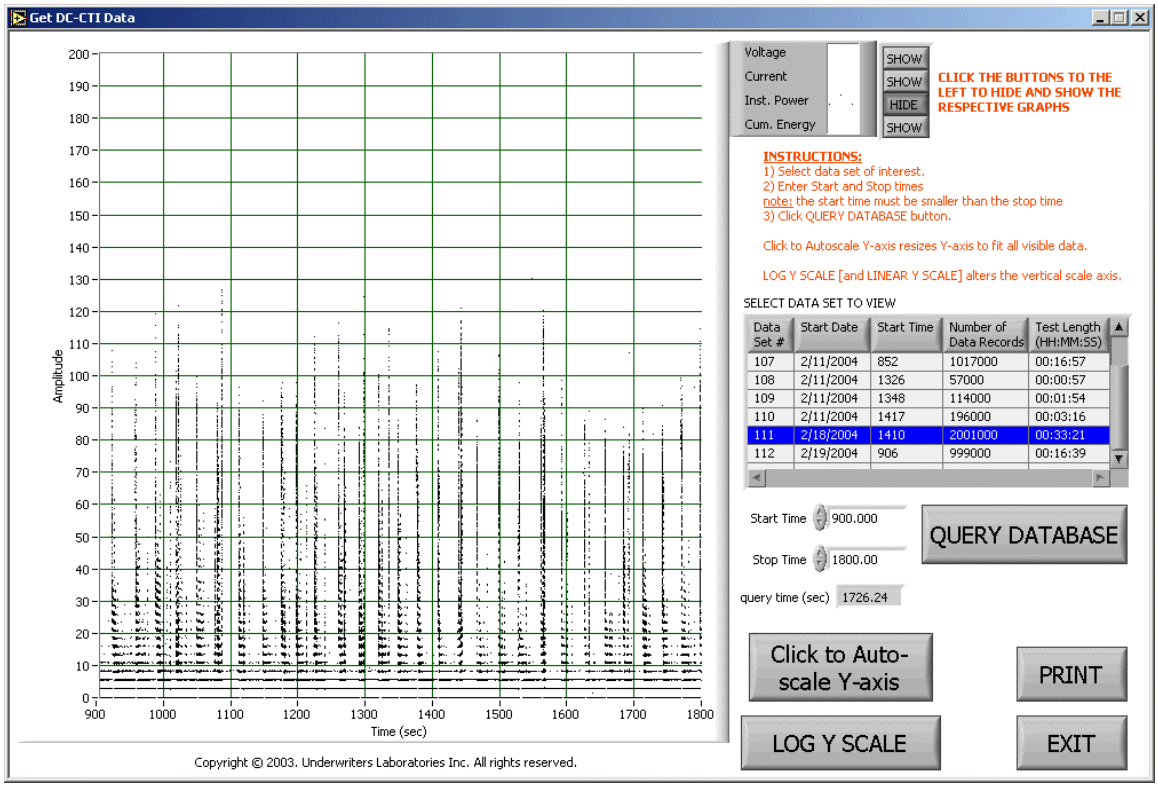
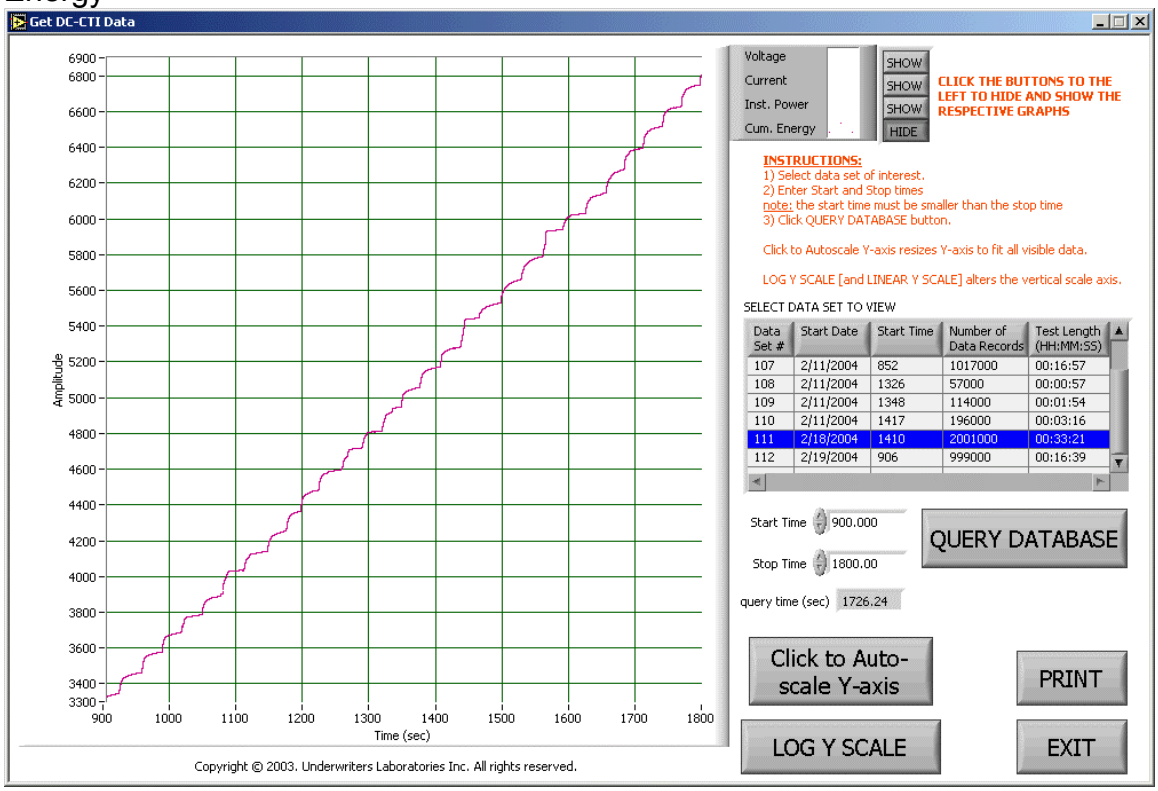
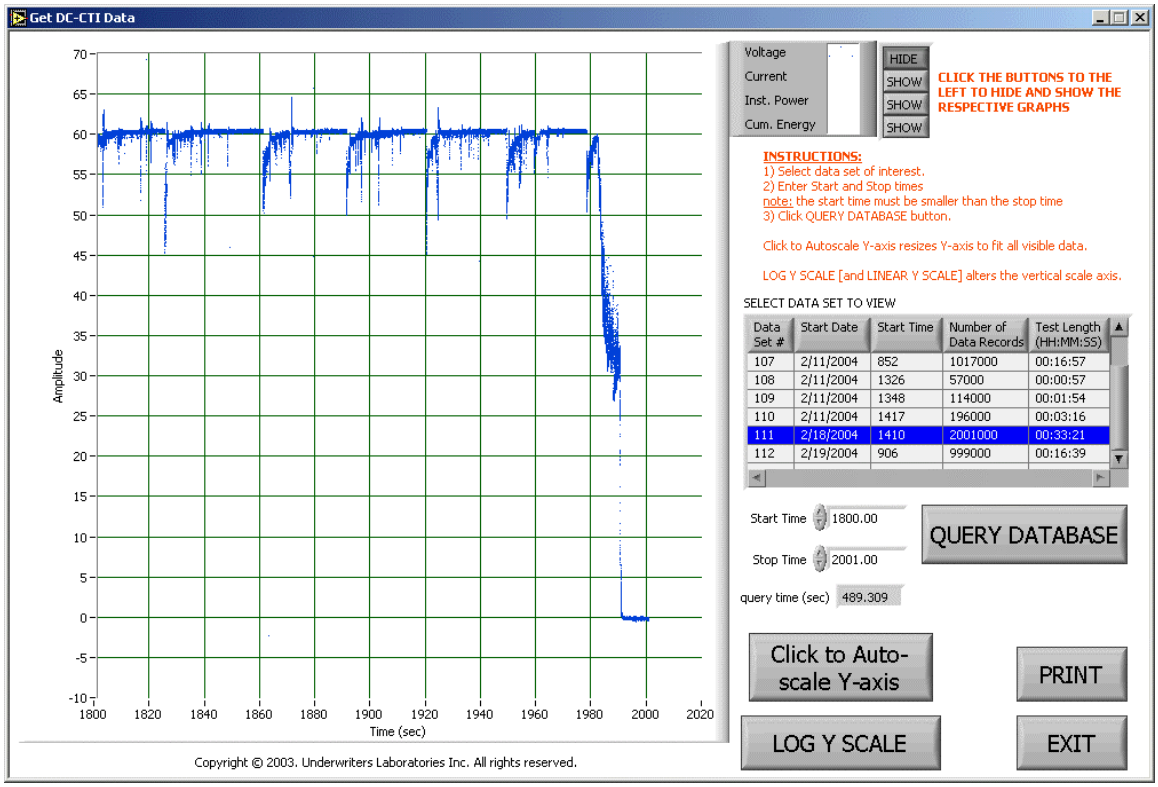


Energy



Voltage



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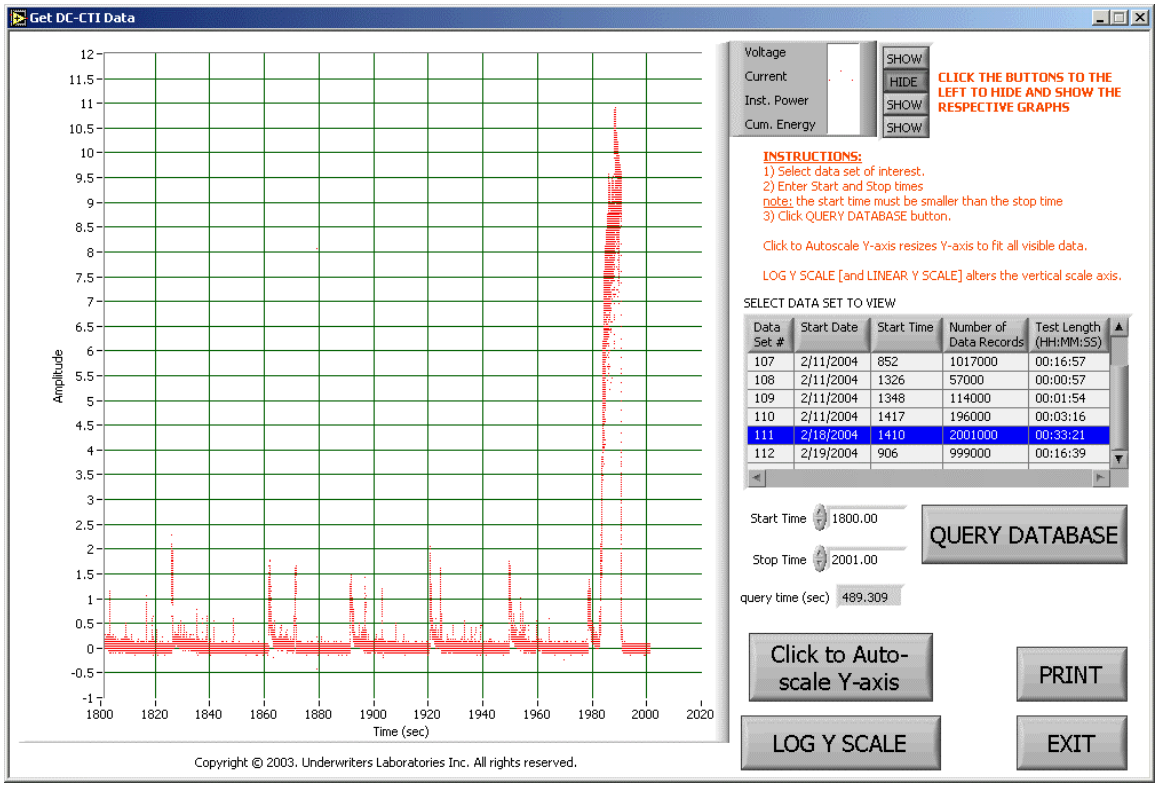

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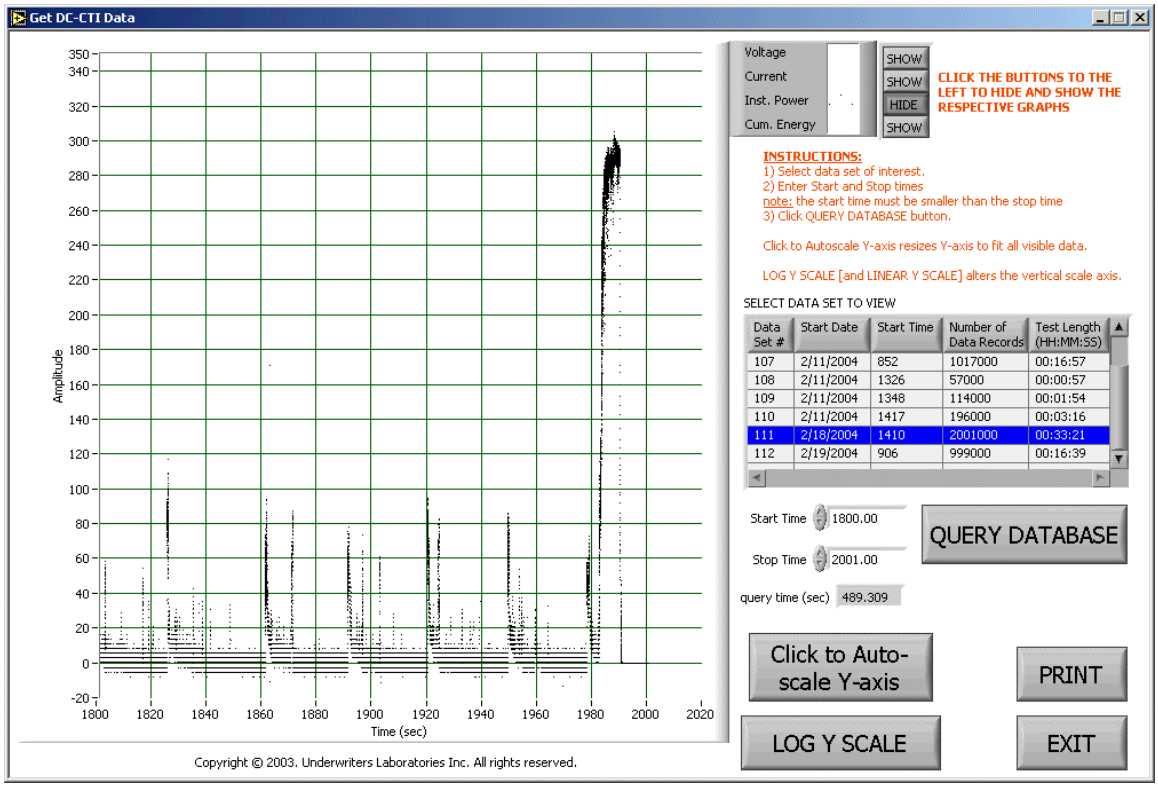

Energy