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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

Final Report

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ABSTRACT

The automotive industry is making a transition from 14 to 42 volt electrical systems. This paper describes the development of a new test methodology specifically designed to evaluate the arc (carbon tracking) properties of polymeric materials used in 42 V automotive applications under wet and contaminated conditions.

1. 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 25 different polymeric materials supplied by Daimler-Chrysler, Ford and General Motors.

2. FUNDING

This research project was jointly funded by the United States Council for Automotive Research (USCAR) and the Motor Vehicle Fire Research Institute (MVFRI).

3. TECHNICAL PLAN

The technical plan was broken into multiple defined tasks as described in the following pages of this report.

4. SITUATION ANALYSIS

4.1 LITERATURE SEARCH – ABSTRACTS

A literature search was conducted using the New England Research Assistance Corporation (NERAC), UL Technical References, ASTM Technical References, IEEE Technical References and the World Wide Web. As a result of this search 32 citations/ web sites were found. A complete listing of each technical article and its associated abstract are included in the attached Appendix A.

4.2 INTRODUCTION

Electrical equipment may fail as a result of electrical tracking of insulating material that is exposed to various contaminating environments and surface conditions. An accelerated test method may be used to provide an indication of the performance of insulating materials under wet and contaminated conditions.

When organic electrical insulating materials are subjected to conduction currents between electrodes on their surfaces, many minute tree-like carbonaceous paths or tracks are developed near the electrodes. These tracks are oriented randomly, but generally propagate between the electrodes under the influence of the applied potential difference. Eventually, a series of tracks span the electrode gap, and failure occurs by shorting of the electrodes.

Arc tracking of an insulating material in the presence of a combination of moisture and surface contamination is a well-documented phenomenon. Various investigators, however, have rendered slightly differing opinions regarding the physical phenomenon.

According to Mitchell [30], *When a voltage is applied across the surface of electrical insulation in the presence of moisture and conductive contaminants, an electrical current begins to flow. Localized heating produces nonuniform evaporization of moisture, resulting in high resistance dry areas or "dry bands." The available voltage which is now essentially applied across the dry area, causes small surface electrical discharges (scintillation). The very high temperature of the small arcs causes most plastic and elastomeric insulation to carbonize. When electrical breakdown results from the progressive growth of a carbon path, tracking is said to have occurred.*

On the other hand, the Japan Society of Plastics Technology report [10] states*: When the surface of an insulating material is contaminated with conductive material, the potential difference existing there will form conductive paths, producing heat by Joule's effect. The heat thus produced dries up the surface of the insulating material increasing surface insulating resistance. As a part of this process, the dried part of the surface becomes high in electric field leading to the* *occurrence of scintillation (local tiny glow-like-discharge), which decomposes a part of the insulating material into carbonized products. The resulted carbonized products with their high conductivity further produce higher electric field causing more scintillation and carbonized products until the carbonized portion grows to bridge the electrodes followed by total breakdown of insulation. This phenomenon is called tracking and the resistance of a material to this phenomenon is termed as tracking resistance. Some of the insulating materials, however, form no track if they are eroded by heat due to electrical discharge.*

Middendorf [11] addresses both theories as follows:
The three heat sources caused by creepage (i.e. leakage current) are:

a. *Joule heat,*
b. *The heat of chemical reactions, and*
c. *Scintillation*

The conditions by which Joule heat and/or chemical reactions are intense enough to degrade insulation surfaces occur very seldom. These processes require, among other things, a very severe state of contamination. Conditions which are more likely to occur are those which produce scintillation; at least they are a modest amount of contamination and moisture. Depending upon the applied voltage, scintillation is micro-flashovers between two nearly touching, moist paths of opposite polarity or micro-arcs upon the interruption of current in a drying creepage path.

To a person viewing a laboratory tracking test, the most obvious causes of deterioration of polluted insulation surfaces are the many, minute, white-hot arcs (sparks) which occur as the shifting pattern of moisture and conductivity variation create points of high voltage gradients in the current paths between electrodes. In contrast to the thermal stress by Joule dissipation, scintillation can occur on relatively clean (but moist) insulation. Although each spark exists for a very short time, it is much more effective in damaging the insulation because of the high energy density.

4.3 DEFINITIONS

In discussing arc tracking the following definitions are useful:

Track—a partially conducting path of localized deterioration on the surface of an insulating material.

Tracking—the process that produces tracks as a result of the action of electric discharges on or close to an insulation surface.

Tracking contamination—tracking caused by scintillations that result from the increased surface conduction due to contamination.

Tracking resistance—the quantitative expression of the voltage and the time required to develop a track under the specified conditions.

Erosion – a wearing away of the test material by the action of electrical discharges and is generally accompanied by melting of the material.

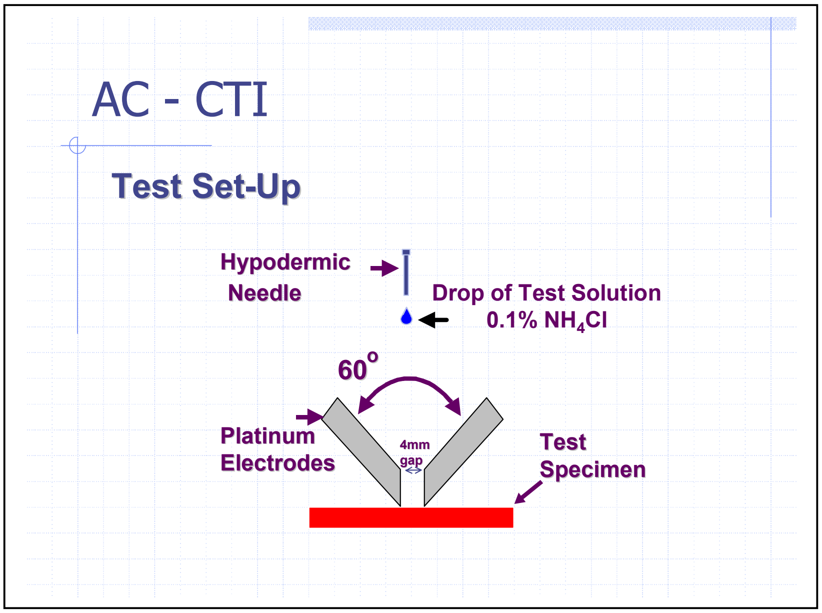
4.4 REVIEW OF EXISTING STANDARDS REQUIREMENTS

Depending upon the intended environment, knowledge of an insulating material's arc track performance characteristics could be an important parameter to a component designer. Preselection testing can be a valuable tool because it enables the designer to compare the relative performance of different materials. Experience has shown that materials that perform favorably in small-scale laboratory tests are likely to perform favorably in the finished part. The use of a suitable pretested material can often reduce time-consuming and costly tests on finished parts. In order to assist the designer in this regard, a procedure for evaluating the comparative tracking performance of polymeric materials is described in a number of international standards.

UL 746A [15] – Underwriters Laboratories (UL) Standard for Polymeric Materials – Short Term Property Evaluations.
UL publishes a sequence of standards documents describing the evaluation of polymeric materials. The requirements contained in UL 746A cover short-term test procedures to be used for the evaluation of materials used for parts intended for specific applications in electrical end products. The testing described in the UL 746A Standard includes an evaluation of both the mechanical as well as short-term electrical properties. One of the electrical properties tests included in this document is the Comparative Tracking Index (CTI).

For the CTI test, two platinum electrodes spaced 4 mm apart are placed in contact with the surface of a nominal 3 mm thick test plaque molded from the polymeric material to be evaluated. Droplets of a 0.1% Ammonium Chloride reagent solution are made to fall on the surface of the material between the two electrodes at the rate of one droplet every 30 seconds. The test is performed with an AC voltage up to a maximum of 600 VAC applied to the electrodes. A diagram of the test set-up is shown in Figure 1.

Figure 1 - AC CTI Test Setup



The Comparative Tracking Index is expressed as that voltage which causes tracking after 50 drops of a 0.1% ammonium chloride solution have fallen on the material. The results of testing a nominal 3 mm thickness plaque are considered representative of the material's performance in any thickness.

A Comparative Tracking Performance Level Category (PLC) is then assigned to each material tested based on the Comparative Tracking Index (Voltage) in accordance with the ranges specified in Table 1 below.

Table 1 – Performance Level Categories for AC-CTI Test

Range – Tracking Index Volts					PLC
600	≤	TI			0
400	≤	TI	<	600	1
250	≤	TI	<	400	2
175	≤	TI	<	250	3
100	≤	TI	<	175	4
0	≤	TI	<	100	5

ASTM D3638 [20] - Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials. The test method described in the ASTM document evaluates in a short period of time the low-voltage (up to 600 VAC) track resistance or comparative tracking index (CTI) of materials in the presence of aqueous contaminants.

IEC 60112 [12] - Method for the Determination of the Proof and the Comparative Tracking Indices of Solid Insulating Materials - This International standard specifies the method of test for the determination of the proof and comparative tracking indices of solid insulating materials on pieces taken from parts of equipment and on plaques of material using alternating voltages. The standard provides for the determination of erosion when required. The proof tracking index is used as an acceptance criterion as well as a means for the quality control of materials and fabricated parts. The comparative tracking index is mainly used for the basic characterization and comparison of the properties of materials.

4.5 TEST INCONSISTENCIES WITH AC - CTI TEST METHOD

Round-robin tests have been performed in which various international testing organizations perform the CTI testing on identical thermoplastic materials and compare the results of the CTI test. According to Middendorf [24], *There is little doubt as to the importance of the test that establishes the CTI value but there is much concern about its accuracy. There is an uncomfortably wide variation in data obtained from this test when performed in a single sequence with specimens from the same sheet of material tested in a single laboratory or from a group of laboratories all of which test specimens from the same sheet. In response to the inability of the test to give repeatable results standard writing agencies have modified the failure criterion. Underwriters Laboratories standard*

UL746A offers an alternate test in which specimens of a material are exposed to various voltages and failure is defined as any voltage for which tracking with several specimen occur at less than 50 drops.

4.6 TEST EQUIPMENT MODIFICATIONS

In an effort to produce more consistent test results and to develop a test protocol consistent with an automotive 42VDC environment, an AC - CTI piece of test equipment was modified as follows:

<u>Electrodes:</u>

In reviewing the referenced standards, it was found that the electrode material was specified as platinum. Suzuki writes [28], *In IEC Publication 112 it is stated that platinum must be used for electrode metal. The reason why platinum must be used is that platinum is chemically stable. Compared to platinum, copper is relatively chemically active.*

Middendorf [17] counters this argument by stating, *It is important that the user know what the CTI value is with the electrode material to be used in the product under development, not with electrodes of precious metal.*

With the exception of platinum tipped spark plugs, platinum is not a material normally used as an electrical conductor in an automotive environment. To be more realistic, copper electrodes were used in place of platinum.

In a further review of ASTM Standards it was found that validation for the use of copper electrodes exists in *ASTM D 5288 [21] Standard Test Method for Determining the Tracking Index of Electrical Insulating Materials Using Various Electrode Materials (Excluding Platinum).*

This test method was developed using copper electrodes to evaluate the low-voltage (up to 600 V) tracking resistance of materials in the presence of aqueous contaminants. This test method is similar to Test Method D 3638 (referenced in UL746A), which determines the comparative tracking index of materials using platinum electrodes to produce the tracking on the specimen surface. As a result of testing performed by the University of Cincinnati, National Electrical Manufacturers Association (NEMA) laboratory on industrial laminates, it was found that, in general, tracking tests performed with copper electrodes tend to give lower values than platinum electrodes in the same type of (AC) test. The relative "soft" nature of the copper electrodes may require more frequent cleaning and regrinding of the electrode faces in order to produce consistent test results. On the other hand copper electrodes are less expensive and may be replaced rather than cleaned.

In studies of copper electrodes, Middendorf [17] comments, *Different metals have been used giving ample indication that the electrode material has a major influence on the CTI number. Other than electrolytic copper and platinum, most metals are alloys of various consistencies and for that reason are not acceptable. However, copper has the advantage of being approximately as pure (>99.5%) in commercial grades as does the platinum electrodes presently used. Copper is also less expensive. It has the property of causing failure after few drops with high voltage and making an abrupt change to no failure as the voltage is reduced to the appropriate value for the CTI. In general, the CTI value for a given insulation is lower when copper electrodes are used than when platinum electrodes are used. Copper affects different insulations differently. It is important that the user know what the CTI value is with the electrode material to be used in the product under development, not with electrodes of precious metal.*

Middendorf comments further [25], *The mechanism by which copper exacerbates tracking is by deposition from the electrodes of particles of cuprous oxide (Cu_2O) upon the insulation surface. These particles are later oxidized to cupric oxide (CuO). This exothermic reaction takes place at voltages above the CTI value in conjunction with the scintillation which normally exists in this test, caused by surface current in the space between electrodes. At lower voltages the area near the electrodes is green, giving evidence that the second oxidation did not take place. The scintillations are noticeably brighter with copper electrodes than they are with platinum electrodes.*

The opposing electrode spacing of 4 ± 0.2 mm is unchanged from the AC-CTI test.

<u>Test Voltage:</u>

The use of an AC test voltage may contribute to the imprecision of the CTI test. The carbonization of the material under test is a result of micro-arcs across the surface of the material. When a time varying AC voltage is used, the intensity of these micro-arcs may vary depending upon the applied voltage at the point of circuit interruption. If a DC voltage were used for this test, it was thought that each micro-arc would be of a more uniform nature since the applied voltage is independent of time. It was also believed that the use of a DC voltage would improve the precision of the test and in addition would represent a real-world automotive situation.

Du [5] indicates, *Although the use of dc voltage is increasing, there is no recommended method for determining the CTI of dc tracking resistance.*

A piece of equipment normally used for AC-CTI testing was modified to permit DC-CTI testing. The AC voltage supply to the electrodes was replaced with a DC power supply. The maximum current that the supply source was capable of delivering during a CTI test was limited by insertion of a series ballast resistor in the supply output. This resistor was adjusted for each selected test voltage such that with a short circuit (bolted fault) placed across the test electrodes, the maximum current in the test circuit was approximately 20 A DC.

End of Test:

The UL 746A CTI test apparatus incorporates an overcurrent relay (circuit breaker) to sense when an arc track path is established across the surface of the specimen under test and automatically end the test. In accordance with ASTM D 3638-85 this relay shall not trip at currents up to 0.1 A and the tripping time on short circuit shall be at least 0.5 seconds (the AC current shall be limited on short circuit to 1 A with a tolerance of $\pm$ 10 % at a power factor of 0.9 to 1.0). Some instruments have used a Heinemann Model Series JA, Curve 2 circuit breaker, which is probably the closest standard commercial breaker to that described in the ASTM method. As an alternative the tripping action can be accomplished with electronic circuitry.

An equivalent DC rated circuit breaker for incorporation into the DC-CTI tester was not readily available. Instead it was decided to limit the maximum fault current that could be drawn with a shorting bar placed across the electrodes to approximately 20 A by means of a non-inductive ballast resistor. This current represents the rated current of many automotive accessory circuits.

The IEC 60112 document defines a tracking failure as - Failure of insulation due to tracking between conducting parts. In the IEC test, tracking is indicated by operation of an over-current device due to the passage of a current of at least 0.5 A for at least 2 s across the test surface and/or within the specimen. If ignition of the material occurs prior to the occurrence of a tracking failure, a persistent flame (i.e. a flame that burns continuously for more than 2 seconds) shall also be considered a test failure. Although a non-persistent flame is allowed in the test without constituting failure, materials which generate no flame at all are preferred unless other factors are considered to be more important.

It was planned to modify the DC test apparatus to incorporate a combination of optical sensors (IR & UV) to monitor ignition. However, UL/USCAR/MVFRI agreed, for the purposes of this investigation, in the event that continuous flaming occurred prior to the establishment of an arc track path, the test was to be continued until either an arc track path occurred or a maximum of 55 drops of reagent had fallen on the test specimen. A maximum 55 drop level was selected to be consistent with the AC-CTI test protocol specified in UL 746A. In these situations, both the number of drops to produce continuous flaming and the number of drops (maximum of 55) to produce tracking were recorded. In most cases, it was noted that tracking (denoted by a spontaneous increase in current) occurred followed immediately by the ignition of the material.

<u>Reagent</u>:

The UL 746A document specifies that a 0.1% Ammonium Chloride (NH_4Cl) reagent solution be used in the AC test. Although the situation analysis did not reveal the reasoning behind selecting either ammonium chloride or the 0.1% concentration level, it is believed that this reagent solution was selected to minimize the buildup of a conductive residue on the test specimen between droplets.

According to Middendorf [11], *The most important contributors to surface deterioration are the ionic conductors which derive from salts, acids and bases. In the dry condition at ambient temperatures these materials are virtually non-conductors. However, in the presence of water they disassociate into positively charged cations and negatively charged anions. The water around the ions allows them to become mobile and follow the applied field.*

In developing the DC-CTI test protocol, emphasis was placed on relating the test parameters to the real world automotive environment. The under hood environment of an automobile is a hostile one, especially in the northern climates where snow and road salting are prevalent throughout the winter months.

In addition to the public health and environmental problems associated with chloride deicers, the corrosivity of road salt adversely impacts motor vehicles and infrastructure. Chloride ions in salt increase the conductivity of water, which induces and accelerates corrosion. In automobiles, corrosion can affect critical vehicle parts, such as brake linings, frames, and bumpers, and can cause cosmetic corrosion. One alternative is Calcium Magnesium Acetate (CMA). While gaining in popularity, CMA is both less effective than road salt in cold climates and more expensive. For this reason rock salt (sodium chloride) remains popular for road salting following a snowfall.

The run off from street and highway salting following a snowfall is a known source of contamination in an automotive environment. The salinity of this runoff was a consideration in a previous Research project [32] conducted for Consolidated Edison (the power utility in NYC a.k.a. Con Edison). The referenced report documents data collected from 48 different manhole, service box and transformer vault locations around Manhattan. Based on the water samples taken, the calculated electrical resistivity was in a range from 9 to 670 ohm-cm.

The ASTM B117 [8] Standard Practice for Operating Salt Spray (Fog) Apparatus specifies a 5% salt solution for testing. In addition, a 5% NaCl solution has a resistivity of 15 ohm-cm and is within the observed resistivity measurements made by Con Edison. For these reasons, the reagent fluid was changed from a 0.1% ammonium chloride to a 5% sodium chloride solution for most of the testing.

One consideration regarding the use of the 5% sodium chloride solution is the possible build-up of a moist salt (NaCl) residue between the electrodes as the reagent solution evaporates. If this residue is capable of conducting current independent of any tracking current across the surface of the material under test, this could produce erroneous test results and invalidate the test.

Tests were conducted using inorganic materials (i.e. ceramic and glass) that do not carbonize in order to assess the effects that a salt build-up between electrodes could have on the test results. The results of these tests are described in Section 7 of this report – *Additional Testing*.

In order to observe the effects that reagent type and resistivity had on the arc track performance, testing was also performed using sodium chloride solutions of 0.15%, 1% and 15% and ammonium chloride solutions of 0.1% and 35%. The associated resistivity of each reagent solution is summarized in Table 3.

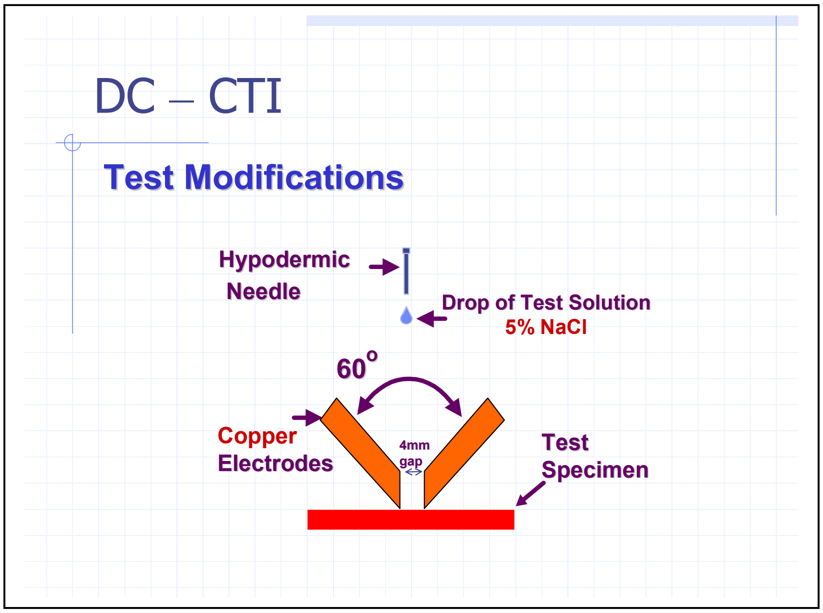
Table 2 - Reagent Solutions

Reagent	% Solution	Resistivity (ohm-cm.)
NaCl (Sodium Chloride)	0.15	285
NaCl (Sodium Chloride)	1	60
NaCl (Sodium Chloride)	5	15
NaCl (Sodium Chloride)	15	6
NH_4Cl (Ammonium Chloride)	0.1	385
NH_4Cl (Ammonium Chloride)	35	15

The results of these tests are described in Section 6.5 of this report – *Variation in Reagent Resistivity Test Results*.

The finalized DC – CTI test setup is shown in Figure 2.

Figure 2 - DC CTI Test Setup



A photograph of the test apparatus is shown in Figure 3.

Figure 3 – Photograph of DC CTI Test Setup

5. EXPLORATORY TESTING

The following exploratory testing was performed prior to initiating testing on the 25 automotive materials,:

5.1 TESTING ON CERAMIC

As previously noted, in switching to the copper electrodes and NaCl reagent solution, a concern was raised whether the combination of compounds of copper plus salt residue could be deposited between the electrodes such that a permanent arc track path could be established independently of the arc track properties of the polymeric material under test. Such occurrence could invalidate the test.

In order to assess the possibility of this occurring, the following test was performed using an inorganic material – a piece of ceramic material (bathroom tile) as a test specimen. The ceramic is an inorganic material meaning that it contains no carbon. If a current carrying path could be established across the ceramic material it would not be a result of carbonized tracking across the material. However, it could be a result of the salt/copper residue deposited during the test. This would tend to invalidate the test since this type of failure mode would be independent of a carbon track failure of the polymeric material under test.

The test was performed at 48 V DC, 96 V DC and 150 V DC. In each case 50 drops of a 5% NaCl reagent did not result in any appreciable build up of a salt deposit between the copper electrodes and a conductive path across the ceramic material was not produced.

Two additional tests were performed at 150 V DC for an extended number of reagent drops. The results of these tests are reported in Section 6.4 of this report - *Five Hundred Drop Test Results*.

5.2 REPEATABILITY TESTING

Before extensive testing of the 25 automotive materials, it was important to demonstrate the repeatability of the test protocol. If the results were heavily influenced by variables not within our control, the testing of the automotive materials could lack sufficient precision to yield meaningful test results.

DC-CTI testing was initially performed on three materials selected at random from materials on hand. They were not supplied by the automobile industry. These materials were not identified by generic type, manufacturer or grade designation and they are simply identified as materials A, B and C in Table 4.

Encouraged by the repeatability of test results obtained in testing materials A, B and C, two of the automotive materials were selected for further repeatability testing. Ten specimens of each of two different materials were subjected to a DC-CTI test. The mean, standard deviation and variance was calculated using this larger sample population. The results are included in Table 4.

Table 3 - Results of Repeatability Testing

Material	DC TEST	Number of Drops to Track												
		Specimen Number												
Designation	VOLTAGE	1	2	3	4	5	6	7	8	9	10	Mean	Standard Deviation	Variance
A	Thickness (mm)	3.19	3.20	3.27	3.27									
	84	13	12	8	4							9		
B	Thickness (mm)	3.90	3.90	3.93	3.93									
	150	55+	55+	55+	55+							55+		
C	Thickness (mm)	3.24	3.24	3.24										
	80	9	9	9								9		
5	Thickness (mm)	3.12	3.11	3.11	3.11	3.12	3.12	3.11	3.13	3.11	3.13			
	42	54	48	37	26	52	55+	33	51	55+	55+	46.6	10.64	113.155
	Notes:	[-]a	[-]a	[-]a	[25]a,c	[51]a,c	[-]a	[31]a,c	[50]c,d	[-]a	[-]a			
16	Thickness (mm)	3.14	3.11	3.05	3.10	3.11	3.12	3.09	3.10	3.11	3.12			
	100	6	5	4	3	6	3	7	5	3	6	4.8	1.48	2.18
	Notes:	[-]a	[-]a	[-]a	[-]a	[-]a	[-]a	[-]a	[-]a,c	[-]a,c	[-]a,c			

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

This represents a 22.8% variance for material designation 5 and a 30.8% variance for material designation 16. As noted in ASTM D 3638 describing the AC-CTI Test, …*some variance in breakdown data can be expected with this (i.e. AC-CTI) test method, particularly as the test voltage approaches an asymptotic value*…

The results of the DC-CTI repeatability test results were judged to be within the acceptable range of performance variation consistent with the AC-CTI test.

6. TESTING OF AUTOMOTIVE SAMPLES

6.1 IDENTIFICATION OF TEST SAMPLES

Twenty-five (25) materials were provided by USCAR for our DC-CTI testing. To the best of our knowledge, each material was obtained from a single production run in order to eliminate the possibility of any production run differences.

6.2 TEST DIFFICULTIES

As already described, our DC-CTI testing was performed utilizing a modified AC-CTI test apparatus. It was anticipated that some difficulties would be encountered during the testing sequence. The following records the problems encountered and the resolution of each problem. This information is being documented so that anyone choosing to construct a DC-CTI Tester for commercial availability will benefit from our experience.

<u>Voltage Supply</u> - The DC supply for this test originally utilized a bank of twenty-12Volt batteries (YUASA Model NP7-12, 12V, 7.0 Ah) and an associated charger. Test voltages (in multiples of 12 V) could be selected by connecting the appropriate number of batteries in series. The problem maintaining these batteries at full charge before each test was eliminated by replacing the rechargeable batteries with a DC power supply manufactured by Soerensen Model DCR 300-33T. This supply is capable of a maximum DC voltage output of 300 volts DC and a maximum current of 33 amperes DC. USCAR/MVFRI were informed of this change and they were in agreement to use this supply as a substitute for the bank of batteries.

<u>Reagent Delivery System</u> - The AC powered syringe pump; timing circuit and droplet count mechanisms were retained. During initial testing it was noted that as droplets were formed at the tip of the needle orifice they tended to "wick" up on the outside surface of the needle before dropping onto the plastic specimen under test. This resulted in a "larger than normal" size droplet falling between the electrodes and a larger than specified quantity of conductive reagent dropping on the test specimen every 30s. Cleaning of the needle tip resulted in the correct droplet size forming at the tip of the needle orifice. During the test sequence, the equipment was thoroughly cleaned and the droplet size was carefully monitored before each test. Both the ASTM D3638 and IEC 60112 documents emphasize the cleanliness of the test apparatus when performing CTI testing in order to achieve consistent test results.

<u>Reagent Drop Sensor</u> – The reagent delivery system on the AC CTI tester consists of a motor driven piston which pushes on a plastic syringe filled with the reagent solution. The reagent is forced out of the syringe, through a plastic hose

and into the specified tip. Every 30 seconds, the pump motor is turned on by a cycle timer. In order to prevent the possibility of more than one drop falling per 30-second interval, the pump is turned off by an optical sensor which detects that a drop has fallen thereby interrupting the pump motor. This optical sensor consists of a light source and receiver positioned on either side of the needle tip. A drop of reagent briefly interrupts the light path to the optical detector. Once a drop is detected, the pump remains turned off until again activated by the cycle timer (30 seconds later). During initial DC testing, it was found that an appreciable amount of smoke was generated. In some cases this smoke was sufficient to block the light path of the optical sensor. This in turn caused the syringe pump motor to turn off prematurely before a drop had actually fallen. Once deactivated in this fashion, the pump motor remained off until again activated by the cycle timer. It was observed that, depending upon the amount of smoke produced, droplets of reagent would only fall once every 60 seconds, or longer. Various attempts were made at shielding the optical detector from the smoke or by intensifying the light beam. None of these fixes, however proved satisfactory and the entire reagent delivery system was changed to a precision solenoid activated pump (Valor Scientific Model SV525)) controlled by a cycle timer.

The pump selected had a manual control of the solenoid displacement. It was found that if the pump stroke was adjusted to produce one droplet each time the pump was activated by the cycle timer that rather than the droplet falling naturally the pump caused the reagent to “spit” out of the syringe tip onto the test sample. This “spitting” was eliminated by reducing the pump stroke and pulsing the cycle timer such that several pump activations were required to produce a droplet to fall naturally by gravity. In most cases this worked satisfactorily but occasionally a droplet did not fall as a result of the multiple activations of the solenoid pump. In accordance with the UL 746A Standard, one droplet must fall every 30 $\pm$ 5 Seconds. A manual override switch was added such that if need be the technician could manually pulse the pump to produce a droplet within the permitted $\pm$ 5 second window every 30 seconds.

This method proved satisfactory and testing was initiated utilizing the new pump set-up to evaluate a number of the automotive materials. During routine cleaning it was discovered that the normally clear reagent (visible through a length of clear plastic tubing) was becoming discolored. Upon disassembly of the pump, it was found that the solenoid spring had begun to rust even though it was supposed to be stainless steel. Concern that rust in the reagent solution could change conductivity and the test results, caused us to suspend further testing as soon as the rust was discovered. The pump manufacturer was contacted and suggested that a high purity solenoid operated piston pump be substituted for the existing pump.

Replacement solenoid pump – The pump was replaced by a Model SV653 made by the same manufacturer. This pump employed nonferrous metals for its internal construction. A new problem arose attempting to adjust the solenoid displacement such that the droplets did not "spit" out of the syringe tip. For this particular pump, small adjustments in the solenoid displacement produced widely varying reagent droplet sizes and it was not possible to fine adjust this pump to produce the required droplet size ($20 + 5 - 0\ mm^3$) on a consistent basis. This was determined by weighing 5 drops of reagent and confirming that the weight was in the range of 0.020 – 0.025 grams.

Both solenoid pumps were ultimately abandoned in favor of a return to the original syringe pump with the following modifications. The cycle timer was modified to add two switches that could either extend or shorten the amount of time the syringe pump was activated every 30 seconds. The technician conducting the test would either activate the pump longer if the droplet of reagent had not fallen when the cycle timer turned off the syringe pump or would interrupt the syringe pump drive motor if a droplet of reagent had already fallen before the cycle timer turned off the pump. Although this occasional manual intervention increased the labor involved in conducting each test, it proved to be the most satisfactory without a total re-design of the prototype DC-CTI tester. If this test is adopted for production testing, the reagent delivery system will have to be re-designed and automated.

Reagent Solution - A suggestion was made to conduct additional testing using sulfuric acid representative of battery acid as an alternate reagent to the 5% NaCl solution. Although this would represent an additional point of electrical conductivity, this suggestion was rejected due to:

1. Concern for handling of a hazardous substance including potential spills or splatter in the laboratory.
2. Corrosive effects that the fluid would have on the test equipment, especially the reagent pump.
3. Corrosive effects that the sulfuric acid would have on the copper electrodes.
4. The possibility of inhaling fuming acid vapors as the sulfuric acid solution boils off the test specimen due to the applied voltage.
5. While introducing an additional conductivity, it also introduced an acid solution rather than a salt solution. Electrode chemistry could be altered possibly introducing a new variable into the test.
6. It was believed that while battery acid does represent a potential under hood contaminant, modern battery technology makes such contamination infrequent.

In place of testing using sulfuric acid, additional DC-CTI testing was performed using 15%, 1% and 0.15% NaCl solutions; a 35% NH_4Cl solution as well as the 0.1% NH_4Cl reagent solution used for the AC-CTI test.

Conductivity Bridge – Conductivity of the reagent solution was closely monitored on a daily basis utilizing a Cole Parmer Model 5800-05 Solution analyzer (conductivity bridge). During a review of the data it was noted that there were some variations in the 5% NaCl reagent solution conductivity. Conductivity of the solution was re-checked with an alternate bridge and the conductivity of the solution found to be within the range of readings obtained earlier. In examining the conductivity bridge it was discovered that foreign deposits had accumulated at the electrodes of the test cell. After the test cell was thoroughly purged and cleaned, consistent readings of reagent conductivity were again obtained.

Optical Ignition Detector – We planned to modify the test apparatus to incorporate a combination UV and IR sensor in order to monitor ignition of the test specimen. This plan was abandoned because:

1. The anticipated prototype ignition detector on an existing AC CTI tester could not be made available to us.
2. Difficulties encountered with the reagent delivery system required constant monitoring of the equipment thereby diminishing the need for automation as part of this research, and
3. In the event that continuous ignition occurred prior to the establishment of an arc track path, we were requested to observe and record the number of drops required to initiate persistent flaming (i.e. flaming that lasts for more than 2 Sec.) and then continue the test noting the number of drops of reagent required to cause the specimen to arc track. .

6.3 FIFTY-FIVE DROP TEST RESULTS

For each material, a DC CTI test was performed using a minimum of 3 specimens. Prior to initiating testing each day, the reagent conductivity was measured and recorded and droplet size verified by capturing 5 drops of reagent and then measuring the weight.

Testing was started at a maximum 150 V DC and working down in discrete voltage increments to a minimum of 12 V DC or until 50 drops of the 5% NaCl reagent solution no longer produced an arc track. These voltage level increments were 150, 100, 60, 42 and 12 VDC. USCAR/MVFRI requested that an additional voltage increment of 50 Volts be added to the test sequence for materials that did not arc track at 42 volts but showed marginal performance at 60 volts. Material designations 2, 3, 6, 8, 16, and 21 were tested at 50 volts.

The results are reported in the attached test record as Appendix B.
For each test, the number of drops (maximum 55) to cause ignition was recorded. In the event that the material ignited and produced continuous flaming (more than 2 Seconds), but without arc tracking, the test was continued until either a permanent arc track path occurred or 55 drops had fallen. Both the number of drops to produce continuous flaming as well as the number of drops to produce arc tracking are recorded in the attached Appendix.

A plot of the number of drops to track vs. test voltage is included for each material. Intercept with the 50 drop axis may be read off of each graph. However, the limited number of data points collected for each material does not lend itself to graphical analysis for some of the materials evaluated.

Each test specimen was photographed following testing and these photos are included as part of this report in Appendix C.

- Anomalies

In conducting the 55 drop testing several anomalies (outliers) were noted as identified in Table 5. In these cases the test results of the (generally) three specimens tested at a selected voltage were not consistent since the result of testing one of the specimens was not in agreement with the results obtained from testing the other specimens. In those cases where outliers were noted, testing was repeated to resolve these inconsistencies as indicated below. With the exception of material designation 17, the repeat testing on an additional test specimen produced results consistent with the earlier tests and in each case the outlier was replaced with the new data. In Appendix B, the outlier data information was retained but with a line drawn through it.

Table 4 - Outliers

Material Designation	Test Voltage	Comment
3	60	Two specimens went to 55+ drops without arc tracking. One specimen went to 14 drops and arc tracked. The test was repeated on a fourth specimen that went to 55+ drops without tracking and the outlier was replaced.
4	150	One specimen went to 55+ drops without arc tracking. Three other specimens arc tracked at 5, 5,and 12 drops respectively. The test was repeated on a fifth specimen that arc tracked after 26 drops. The outlier was replaced.
11	150	Two specimens went to 55+ drops without arc tracking. One specimen arc tracked after 27 drops. The test was repeated on an additional specimen that went to 55+ drops without tracking. The outlier was replaced.
17	150	Two specimens went 55+ drops without arc tracking. One specimen arc tracked after 26 drops. The test was repeated on four additional specimens. The fourth specimen arc tracked after 20 drops and the sixth specimen tracked after 25 drops. The fifth and seventh specimens went 55+ drops without arc tracking. Unable to resolve outliers.

In the case of the testing of Material 17, three of the test specimens arc tracked in the 20 – 26 drop range while four of the specimens did not arc track after 55 drops. A close examination of the sample coupons did not reveal that the filler material was axially oriented and the test results varied regardless of sample orientation.

- Specimen erosion

Upon examining the test specimens following the completion of a 55+ drop test sequence, it was generally observed that erosion of the test specimen occurred in the area between the test electrodes and this erosion was anticipated. In some cases (i.e. at the higher test voltages of 150 and 100 V) this erosion was judged to be appreciable as shown in the attached photographs of each test specimen (Appendix C).

UL 746 A, ASTM D3638 and IEC 60112 permit erosion to occur during this test. However, in order to evaluate if this erosion may have affected the test outcome, the test was repeated at the next lowest voltage increment. If the test specimen again went the full 55 drops without arc tracking, it was re-examined for the extent of erosion. This sequence was repeated at sequentially lower voltage increments until erosion was minimal and no longer considered to be a potentially influencing factor in the test outcome.

The Test Results are Summarized In Table 5.

Table 5 – Test Summary (See Table 9 for Material Descriptions)

	Average No. of Drops to Track						
	Voltage						
Material Designation	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	Material Deleted by Request						
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.

6.4 FIVE HUNDRED DROP TEST RESULTS

Five materials were selected for the performance of an expanded Comparative Tracking Test using up to a maximum of 500 drops of the 5% NaCl reagent solution. The materials selected for this test successfully completed the arc track test at 60 V DC without arc tracking (55+ drops). This test was performed to determine whether the introduction of additional reagent solution beyond the normal 55 drops can produce an arc track. The results of this test are shown in Table 6.

Table 6 - Results of 500 Drop Test

	Material Designation				
	4	14	20	24	25
Thickness (mm)	3.08	3.10	3.05	3.12	3.13
DC TEST VOLTAGE	No. of Drops to Track				
60	500+	96	86	264	70
Notes:	[99]d	[-]d	[-]a	[-]d	[-]a

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

During these tests the equipment was instrumented to capture the current and voltage across the electrodes at a sampling rate of every millisecond. A CDROM containing this data accompanies the final report in the event that further analysis of the arc track phenomenon is of interest. Such an analysis, however, is beyond the scope of this investigation and not included as part of this report.

At the applied electrode voltage of 60 Volts DC, a wide range of test results were obtained ranging from 70 drops to tracking failure (Material No. 25) to completing 500 drops without tracking (Material No. 4). In the case of material No. 4, burn through of the material occurred which may have enabled the material to complete the 500 drop test without establishing an arc track path. In accordance with IEC 60112 specification, it would normally be necessary to double the thickness of the material and repeat the test. However, it was also observed that continuous flaming of Material No. 4 occurred after 99 drops of reagent had fallen. Even though a permanent arc track path was not formed, the continuous flaming of the material after 99 drops would be considered a test failure by IEC specifications.

Conducting a 500 drop test at a maximum droplet fall rate of once every 30 seconds is very time consuming requiring more than 4 hours to complete.

Performing the testing at 50 drops and varying the electrode voltage produces a sufficient variation in performance for material comparison purposes while at the same time permitting each test to be completed in a reasonable amount of time.

The results of these tests are discussed further in Section 10 – Summary.

6.5 VARIATION IN REAGENT RESISTIVITY TEST RESULTS

Testing was performed on three material designations to evaluate the effect that the resistivity of the reagent solution had on arc track properties at a given test voltage. In addition to the 5% NaCl reagent solution already used, testing was performed at NaCl solutions of 15% (6 ohm-cm.), 1% (60 ohm-cm.), and 0.15% (285 ohm-cm.). In addition, testing was performed using the 0.1% NH_4Cl (385 ohm-cm.) solution used for the AC-CTI test and a 35% NH_4Cl solution having a resistivity of 15 ohm-cm corresponding to the resistivity of the 5% NaCl reagent. See Table 3.

This testing was performed using material designation 16 at an applied electrode voltage of 100 Volts DC; material designation 25 at a voltage of 60 V DC and material designation 5 at an applied electrode voltage of 42 Volts DC. In the case of materials nos. 16 and 25, testing was limited to a maximum of 55 drops of reagent. In the case of material No. 5, testing was extended to a maximum of 500 drops of reagent.

The results of this testing are summarized in Table 7.

Table 7 - Effects of Reagent Resistivity

Material Designation	Reagent/ Solution	DC TEST VOLTAGE	Number of Drops to Track			
			Specimen Number			
			1	2	3	AVERAGE
		Thickness (mm)	(min. 3 mm)			
5	NaCl 5%	42 Notes:	77			77*
	NH_4Cl 35%	42 Notes:	32			32*
16	NaCl 15%	100 Notes:	3 [2]a,c	3 [2]a,c	3 [2]a,c	3
	NaCl 5%	100 Notes:	5 [-]a,c	3 [-]a,c	6 [-]a,c	5
	NaCl 1%	100 Notes:	21 [20]a,c	20 [-]a	11 [-]a	17
	NaCl 0.15%	100 Notes:	55+ [-]a	55+ [-]a	55+ [-]a	55+
	NH_4Cl 0.1%	100 Notes:	55+ [-]a	55+ [-]a	55+ [-]a	55+
25	NaCl 15%	60 Notes:	22 [22]a,b,c	54 [46]a,b,c	35 [35]a,b,c	37
	NaCl 5%	60 Notes:	55+ [-]a	55+ [-]a	55+ [-]a	55+
	NaCl 1%	60 Notes:	55+ [-]a	55+ [-]a	55+ [-]a	55+
	NaCl 0.15%	60 Notes:	** [-]e			
	NH_4Cl 0.1%	60 Notes:	*** [-]e			

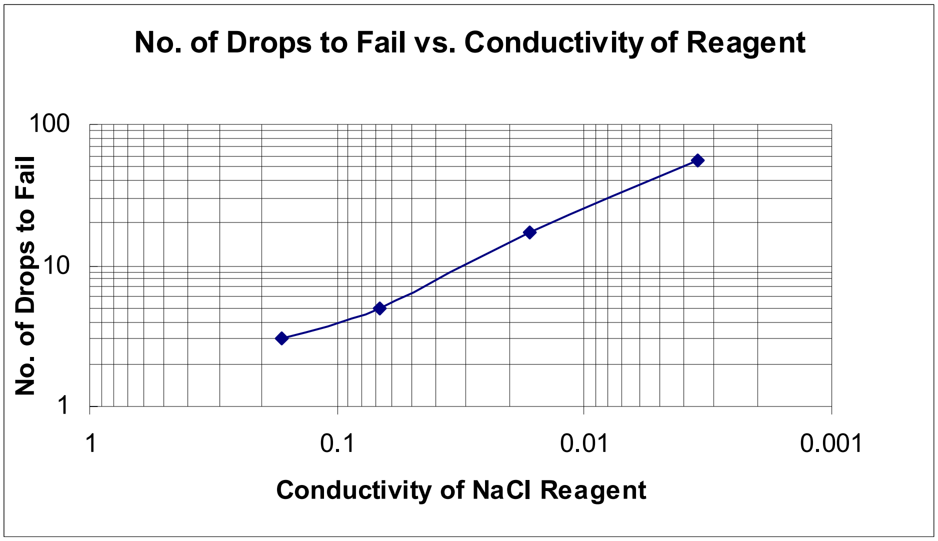
Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
e	No scintillation.
*	Maximum of 500 drops of reagent.
**	Test terminated after 3 drops.
***	Test terminated after 6 drops.
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S).

As anticipated, the number of drops of reagent to produce an arc track decreased as the conductivity of the solution increased (resistivity decreased) for both materials 16 and 25.

A plot of the number of drops to fail vs. the reciprocal of the reagent solution resistivity (1/R) for material designation No. 16 and a NaCl reagent is shown in Figure 4.

Figure 4 - No. of Drops to Fail vs. Conductivity of Reagent (Material 16)



Plotted on a log-log scale, a near linear relationship was observed. Due to the number of data points in excess of 55 drops when the same test was performed on material designation 25, a similar plot was not developed for this material.

When testing was performed with the 0.15% NaCl solution and the 0.1% NH_4Cl solution, indistinguishable tracking results occurred. In the case of material designation 16 (tested at 100 V DC), both tests went 55+ drops. In the case of material designation 25 (tested at 60 V DC), scintillations were not observed with either reagent. The test was arbitrarily interrupted since it was judged without such micro-arcing to pyrolyze the surface of the material and establish a carbon track, testing would have exceeded 55 drops.

In the testing performed using material designation #5, 77 drops of the 5% NaCl reagent were required to produce arc tracking whereas only 32 drops of the NH_4Cl solution were required to produce arc tracking even though both reagent solutions exhibited the same resistivity (15 ohm-cm.).

The results of these two tests are consistent with the previous data obtained. In reviewing the 10 tests previously performed using Material #5, and a 5% NaCl reagent solution at 42 VDC, it was noted that the number of drops to produce an arc track failure ranged from a minimum of 26 to more than 55 drops of reagent (3 trials). Previous testing was arbitrarily stopped after a maximum of 55 drops. It appears that Material #5 is at a transitional stage with regard to arc tracking at a test voltage of 42 VDC and a 5% NaCl (or 35% NH_4Cl) reagent solution.

7. ADDITIONAL TESTING

A series of tests were performed on inorganic materials to determine whether the introduction of additional reagent solution beyond a nominal 50 drops (up to a maximum of 500 drops) could result in a sufficient salt deposit on the material under test to establish a current path between the test electrodes without carbonization of the material. Five tests were performed using a ceramic (bathroom) tile and four tests using a Pyrex watch glass as summarized in Table 8.

Table 8 - Additional Testing Method & Results

Test	Material	Voltage (VDC)	Reagent	% Solution	Resistivity (ohm-cm.)	Max. No. of Drops	No. of Drops (Actual)
1	Ceramic (rough side)	150	NaCl	5	15	500	<118
2	Ceramic (rough side)	150	NaCl	5	15	500	77
3	Ceramic (rough side)	42	NaCl	5	15	500	210
4	Ceramic (rough side)	42	NH_4Cl	35	15	500	202
5	Ceramic (rough side)	42	NaCl	15	6	500	32
6	Watch Glass	42	NaCl	15	6	150	150
7	Watch Glass	150	NaCl	5	15	500	61
8	Watch Glass	150	NaCl	5	15	500	61
9	Watch Glass	60	NaCl	5	15	125	125

Test 1 – A test voltage of 150 VDC was used. This test was observed continuously for 55 drops using a 5% NaCl reagent solution. There was no appreciable salt buildup although scintillations were observed as the salt solution evaporated and continuity through the conductive fluid between the electrodes was interrupted. The test was permitted to run unsupervised beyond 55 drops. At a count of 118 drops it was discovered that during the period of unsupervised operation, a low impedance path had been established between the electrodes independent of the introduction of any further droplets of reagent. The resultant heating had caused melting of the copper electrodes.

Test 2 – Test 1 was then repeated observing the test continuously. The ceramic material again completed 55 drops without evidence of an appreciable salt deposit or the establishment of a low impedance conductive path between electrodes. However, when the test was permitted to continue, introducing additional drops of reagent, a low impedance conductive path was established between the electrodes across the ceramic material after 77 drops and the test was stopped.

<u>Tests 3 and 4</u> - Two tests were performed on the ceramic material at a test voltage of 42 VDC. Test 3 utilized a 5% NaCl reagent and Test 4 utilized a 35% NH_4Cl reagent solution. Both reagent solutions had a resistivity of 15 ohm-cm. Comparable test results were obtained as in Test 2 albeit after an increased number of drops of reagent. A low impedance conductive path was created after 210 drops using the NaCl reagent and 207 drops using the NH_4Cl reagent respectively.

<u>Test 5</u> – This test was performed on the ceramic material using a 15% NaCl reagent solution having a resistivity of 6 ohm-cm and an applied electrode voltage of 42 VDC. During this testing it was observed that with the first drop of reagent, bubbling of the fluid bridging the copper electrodes occurred. After only 4 drops of reagent, brief periods of flickering were observed at the positive electrode and became semi-continuous flaming after 6 drops. Persistent flaming was noted after 8 drops. After only 32 drops, persistent arcing occurred and the test was terminated. Upon stopping the test it was observed that a molten globule had formed between the electrodes. After allowing it to cool, it was observed that this globule was hollow inside. A green splatter surrounded the globule. According to Middendorf [17], such green deposits are indicative of the formation of cuprous oxide (Cu_2O).

In the testing performed by Stimper, Sachsenweger and Middendorf [25], using copper electrodes for the performance of the AC-CTI test, they observed similar bright green coloring around the test area and they hypothesized that this was a result of the formation of copper oxides during the electrolysis process.

Considering the likely composition of the ceramic tile, the majority of raw materials used by the ceramic industry are the oxides of metals. The three metals which have been the mainstays of the industry for many years are clay, flint, and feldspar. These are the major materials contained in what is sometimes referred to in the industry as "classical ceramic bodies."

- Clays are hydrated aluminosilicates (Al_2O_3 - $2SiO_2$ - $2H_2O$)
- Flint is a form of silicon dioxide (SiO_2) usually produced from quartzite, sand or rock. It is used in a finely pulverized form as a filler to give the clay and final product the desired properties.
- Feldspar is a broad, generic name applied to a group of alkali-aluminosilicates. For example, feldspars in which the alkali is potassium (K_2O - Al_2O_3 - $6SiO_2$) are called "potash feldspars," and those containing sodium (Na_2O - Al_2O_3 - $6SiO_2$) are called "soda feldspars." Most feldspars, however, are combinations of these two types. Feldspar is used and known as a "flux" in the ceramic industry. The flux is the material which starts to melt at the lowest temperature during the heat-treating process,

thereby acting as the cementing element which gives the ceramic body its strength.

Electrolysis could be an explanation for the observed flaming when the energy is great enough to pull the water (-2H_2O in each molecule) off of the clay component of the ceramic tile. This would provide a continuing source of hydrogen generation. The hydrogen formation would occur at the cathode and oxygen at the anode.

The porosity of the rough (unglazed) side of the ceramic material may have influenced the outcome of the test since the reagent was absorbed into the surface and was not able to be evaporated quickly. For this reason, four additional tests were performed with a watch glass that had a smooth non-porous surface.

Test 6 – Test 5 was repeated using a Pyrex watch glass material in place of the ceramic tile. Although an appreciable deposit formed at the anode (see Figure 5), the watch glass completed 150 drops of reagent without the establishment of a low impedance path between electrodes. Since failure of the ceramic tile occurred after only 32 drops using a 15% NaCl reagent, Test 6 was arbitrarily stopped after 150 drops. An infrared analysis of the deposit identified the presence of both cuprous oxide (Cu_2O) as well as cupric oxide (CuO). The presence of sodium silicate was also identified possibly due to thermal decomposition of the watch glass.

Figure 5 - Test Electrodes Following Completion of Test 6

Test 7 – Test 2 using a 5% NaCl reagent solution and a 150 VDC supply was repeated using a watch glass in place of the ceramic tile. In this case a low impedance path was established between electrodes after 61 drops of reagent.

Test 8 –This test was identical to test 7. As in Test 7, a low impedance path was established between electrodes after 61 drops of reagent

Test 9 –This test was similar to Test 7, except that the voltage supply was reduced to 60 VDC. In this case the test was continued until 125 drops of reagent had fallen. The watch glass completed 125 drops of reagent without the establishment of a low impedance path between electrodes.

Additional discussion is included in Section 10 – Summary.

8. OBSERVATIONS

8.1 DC-CTI PERFORMANCE

The DC Comparative Tracking Index test is intended as a basis for the comparative ranking of polymeric materials with regard to DC arc tracking. It is not intended to represent performance of a material at or near "end-of-life."

In the future as experience with a variety of plastic materials is acquired, a polymeric material, which has a proven track record of acceptable performance during anticipated life, may be used as a "benchmark" reference to establish the desired DC-CTI performance for new or unproven materials.

DC-CTI performance is only one performance characteristic that may need to be taken into consideration. When selecting a material for a particular end use application, there may be numerous performance characteristics (both mechanical as well as electrical) that need to be considered as well.

A wide range of DC-CTI performance levels were noted by this investigation as shown in Table 9 on the next page. Materials of the same generic family did not necessarily produce consistent tracking results.

Each material tested represented a manufacturer's proprietary mix of resin, flame inhibitors, fillers, modifiers, plasticizers, etc. The effect that acid acceptors, antimicrobials, antioxidants, antistatic agents, blowing agents, catalysts, colorants (organic/inorganic), compatibilizers, conductive materials, copolymers, corrosion inhibitors, coupling agents, crosslinking agents, curing agents, drip inhibitors, flame retardants, halogen scavengers, heat stabilizers, hydrolytic stabilizers, impact modifiers, low wear additives, release agents, nucleating agents, plasticizers, polymer blends, processing aides and UV stabilizers had on arc track performance was not included within the scope of this project. This could be an area for a future and much more detailed investigation.

Table 9 - DC – CTI Performance Ranking

Material Designation	Generic Description	Usage	DC CTI
7	15% GR PPA polyphthalamide	Connector	150
11	Polyamide/PPE Unfilled	PDC Box	150
12	PVC Wiring insulation	Insulation	150
13	XLPE Wiring insulation	Insulation	150
23	15%GR Hi Performance Polyamide,Heat Stabilized, toughened	Connector	150
1	Polyamide 46 Unfilled	Connector	100
15	13%GR Nylon 66 Impact Modified, Low Tracking Index	Connector	100
17	15%GR Nylon 66 Dimensionally Stabilized, Low Tracking Index, High Flow	Connector	100
22	35%GR Hi Performance Polyamide,Heat Stabilized, toughened	Connector	100
3	PBT unfilled FR	Connector	60
4	Polyamide 46 GF15 HS	Connector	60
9	PBT unfilled FR	PDC Cover	60
10	Polyamide/PPE 10% GF	Connector	60
14	15% GR PBT Hydrolysis Resistant, High Flow	Connector	60
19	15%GR PBT Hydrolysis Resistant, High Flow	Connector	60
20	30%GR PBT Hydrolysis Resistant, High Flow	Connector	60
21	30%GR PBT Fire Retardant (V-0)	Connector	60
24	35%GR Hi Performance PA,Heat Stabilized, water mold temp.	Connector	60
25	15%GR Fire Retardant (V-0) PBT	Connector	60
2	Polyamide 46 Unfilled FR	Connector	50
8	PBT 17% GF FR	Connector	50
16	15%GR PBT	Connector	50
6	Polyamide 46 GF15 HS	Connector	42
5	Polyamide 46 GF30 HS FR	Connector	12
18	Material Deleted by Request		

Legend :

FR - Fire Retardant
GF - Glass Filled
GR - Glass Reinforced
HS - Hydrolysis Stabilized
PA - Polyamide
PBT - Polybutylene Terephthalate
PPA - Polyphthalamide
PPE - Polypropylene
PVC - Polyvinylchloride
XLPE - Cross-linked Polyethylene
V-0 - Flammability rating based on Vertical Flame Test described in UL 94 – *Tests for Flammability of Plastic Materials for Parts in Devices and Appliances*

8.2 MATERIAL SELECTION CRITERIA:

The AC-CTI PLC selection criteria shown in Table 10 serves as a guideline for choosing a material for use in an AC rated end-use product. The desired PLC rating is based on the anticipated environment. It should be noted that the operating voltage of the end-use-product is generally not factored into the material PLC selection, although in most cases these products operate at less than 300V AC.

Table 10 - PLC Selection Criteria

Maximum PLC	Higher CTI values are required where a greater degree of contamination is involved, as follows:
4	Indoor equipment exposed to relatively clean environment
3	Outdoor and indoor equipment exposed to moderate contaminate environments
2	Outdoor and indoor equipment exposed to severe contaminate environments

As seen in Table 10, AC utilization equipment used either indoors or outdoors and subjected to severe contaminate environments, must have a maximum PLC rating of 2 corresponding to a minimum AC-CTI tracking voltage of 250 VAC.

8.3 COMPARISON TO AC-CTI RATINGS

A review of UL's plastics database (http://data.ul.com/ULiQ_Link/index.asp) revealed that sixteen (16) of the polymeric materials that USCAR submitted were also UL Recognized Component thermoplastic materials and fourteen (14) of these material had been previously subjected to an AC - CTI test as part of the plastic material evaluation. As a result of this testing, these materials had been assigned an AC-CTI Performance Level Category (PLC). The AC-CTI PLC rating is shown in Table11 for each of these materials.

Table 11 - Recognized Component Materials

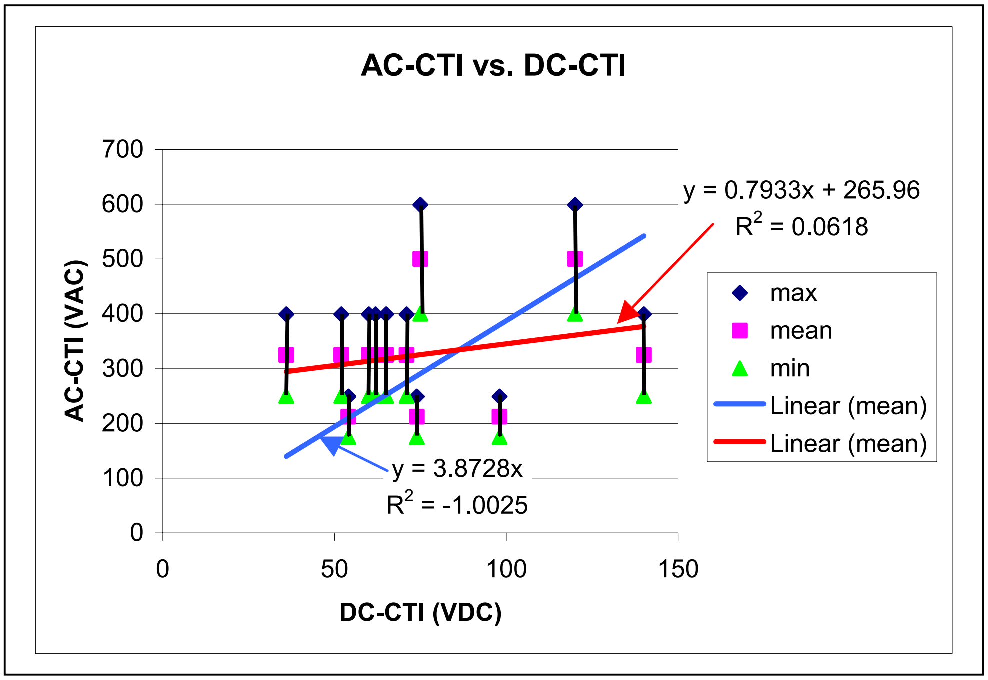
Material Designation	Material Description	AC CTI PLC Rating
1	PA 46 Unfilled	2
2	PA 46 Unfilled FR	2
3	PBT Unfilled FR	3
4	PA 46 GF15 HS	3
5	PA 46 GF30 HS FR	2
6	PA 46 GF15 HS	-
8	PBT 17% GF FR	3
9	PBT Unfilled FR	2
10	PA/PPE 10% GF	-
15	13%GR Nylon 66 Impact Modified, Low Tracking Index	0
16	15%GR PBT	2
17	15%GR Nylon 66 Dimensionally Stabilized, Low Tracking Index, High Flow	1
21	30%GR PBT Fire Retardant (V-0)	2
22	35%GR Hi Performance Polyamide,Heat Stabilized, Toughened	0
24	35%GR Hi Performance Polyamide,Heat Stabilized, Water Mold Temp.	1
25	15%GR Fire Retardant (V-0) PBT	2

Legend: See Table 9

CTI Range Tracking Index(in Volts)	PLC Assigned
600 and Greater	0
400 through 599	1
250 through 399	2
175 through 249	3
100 through 174	4
Less than 100	5

In order to determine if a correlation exists between the DC-CTI results and the previously obtained AC-CTI results, the AC mean, maximum and minimum were plotted for each AC-CTI PLC range against the DC-CTI results on the scatter diagram shown in Figure 6.

Figure 6 - AC vs. DC CTI Ratings



Material designations 15 and 22 were removed from consideration since the observed AC-CTI voltage ratings exceeded 600 VAC and an exact AC-CTI voltage rating could not be established.

If the regression line is forced to pass through the origin (0,0), R^2 = -1.0025. If the regression line is not forced to pass through the origin R^2 = 0.0618. The poor correlation may be due to a number of factors including:

- Plastic samples from the same production lot were not used for the DC-CTI test as the AC-CTI Test. The AC-CTI values were obtained from data in UL's plastics database.

The exact AC-CTI value could not be recovered from the original testing. In the case of materials assigned a PLC of 1 – 5, the mid point of the PLC voltage range was assigned as the AC-CTI value.

- DC-CTI values were obtained from the graphs plotted for each material in Appendix B. In some cases, the limited number of data points observed may have skewed this data interpolation.

- The end of test criteria is different between the AC-CTI and DC-CTI tests. For the AC-CTI test, testing is automatically terminated when sufficient tracking current is drawn to cause a 0.1 A rated circuit breaker to trip. In the case of the DC-CTI testing, testing was continued until visual arc tracking was observed. In the event that persistent flaming (> 2 Seconds) occurred prior to the establishment of an arc track path, the number of drops to cause such flaming was also noted.

- The relationship between the AC-CTI rating and DC-CTI rating may be non-linear. In addition, attempting to force the regression line to pass through the origin extends the curve into an area that is undefined. The meaning of a CTI rating of 0 volts is unclear.

9. FURTHER TESTING

As a result of the testing performed, a number of areas were identified for further study that were beyond the scope of this project. These areas are identified below.

9.1 EFFECTS OF ADDITIVES

Section 8 - *Observations* of this report noted that a wide range of DC-CTI performance levels were observed. Materials of the same generic family did not necessarily produce consistent tracking results. The effects that resin additives such as flame inhibitors, fillers, modifiers, plasticizers, etc. have on DC-CTI performance could be an area for detailed investigation.

9.2 TESTING AT HIGHER DC VOLTAGES

The DC-CTI test procedure developed was validated at a maximum voltage of 150 VDC. Applications that may require the utilization of a plastic material that has a DC-CTI rating in excess of 150 VDC may necessitate additional testing at DC voltages in excess of 150 VDC to continue to validate the DC-CTI test procedure at these higher voltages.

9.3 ADDITIONAL TESTING ON INORGANIC MATERIALS

When two inorganic materials (e.g. ceramic tile and glass) were subjected to DC-CTI testing as described in Section 7 – *Additional Testing* with either an increased number of droplets (i.e. >55) of the 5% NaCl reagent or with a reagent solution having a decreased resistivity (i.e. 6 ohm-cm.), a low impedance arc path was established between the test electrodes that was judged to be independent of any pyrolysis of the inorganic material or subsequent arc tracking of the inorganic material.

Examination of the video recordings and a rudimentary infrared analysis of the deposits formed between the electrodes on the two inorganic materials tested provided some insight into possible cause and effect relationships for the observed phenomenon. The exact cause(s) of this phenomenon may be 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.

9.4 ROUND ROBIN TESTING

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. 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 will 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; Research Triangle Park, NC and Novi, MI.

The DC-CTI testers will incorporate all necessary modifications and safety upgrades to permit DC-CTI testing of thermoplastic materials on a production basis.

Two of the suggested upgrades will 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. In the testing performed, it was observed that when tracking did occur, the current generally stabilized at 7 – 10 A DC. This suggests that a circuit breaker rated 150 VDC and with a trip current rating of 2 – 3 A DC may be acceptable for this application.

10. SUMMARY

The testing performed to date validates the DC-CTI test protocol developed under this investigation as substantiated by the following:

10.1 REPEATABILITY OF TEST RESULTS

Prior to initiating extensive testing of the 25 automotive materials, it was important to demonstrate the repeatability of the test protocol. If the results were heavily influenced by variables not within our control, the testing of the automotive materials could lack sufficient precision to yield meaningful test results.

DC-CTI testing was initially performed on three thermoplastic materials selected at random from materials on hand (these materials were not supplied by the automobile industry) and two of the automotive materials.

The results of the DC-CTI repeatability test results were judged to be within the acceptable range of performance variation consistent with the AC-CTI test.

10.2 REPEATABLE VS. REPRESENTATIVE

In developing a suitable test protocol it was considered that it may be necessary to tradeoff the differences between a repeatable test (i.e. does repeating the same test under identical test conditions produce identical results, or do the results vary as a result of some unspecified or otherwise uncontrolled variable(s)?) and one that is representative (i.e. does the test represent likely operation and/or failure mode scenarios?).

This was not the case with the developed DC-CTI test. The use of a DC test voltage is both representative of the automotive electrical system and at the same time appears to increase the precision of the test results.

10.3 RANGE OF DC-CTI TEST RESULTS

The testing of the 24 materials submitted produced a sufficient range of DC-CTI test results in the range of 12 VDC to 150 VDC to allow the DC-CTI test to be used as a pre-selection guideline for thermoplastic materials for use in 42 V DC automotive applications.

10.4 RESOLVING OUTLIERS

In several instances, test results were obtained that were not consistent among the three (or more) specimens. These inconsistencies or outliers were noted when testing four materials (3, 4, 11 and 17) as shown in Table 4 (page 21).

In all but one situation, (material designation 17) these outliers were resolved by additional testing.

10.5 SALT ACCUMULATION

By switching to copper electrodes and the 5% NaCl reagent solution, a concern was raised whether a combination of compounds of copper plus salt residue could be deposited between the electrodes such that a permanent arc track path could be established independently of the arc track properties of the polymeric material under test. Such occurrence could invalidate the test.

The testing performed on inorganic materials (i.e. having no carbon in their chemical makeup) demonstrated that a conductive residue was not established at voltages ranging up to 150 V DC, NaCl reagent solutions up to 5% and a maximum of 55 drops of reagent.

These tests are described in Section 5 – *Exploratory Testing* and Section 7 – *Additional Testing*

10.6 TESTING BEYOND 55 DROPS

The Situation Analysis did not reveal the basis for selecting a nominal 50 drop criteria for the AC-CTI Test. When UL initiated CTI testing on plastics (as described in UL 746A – Short Term Properties of Polymeric Materials [15]) the nominal 50 drop value was adopted from the ASTM specification D3638 [20]. This test criteria permits the DC-CTI test to be completed in a reasonable amount of time and produces a range of plastic performance taking into account the range of test voltages and reagent solution (0.1% NH_4Cl).

As demonstrated in the 500 Drop Tests, testing beyond 55 drops of reagent may eventually produce a low impedance arc path. However it is not the intent of the DC-CTI test to represent performance of a material at or near “end-of-life”.

The DC Comparative Tracking Index test is intended solely as a basis for the comparative ranking of polymeric materials with regard to DC arc tracking. Using copper electrodes, DC voltages ranging from 12 VDC to 150 VDC and a 5% NaCl reagent solution, a wide range of tracking performance was obtained from the 24 materials tested. At this time there does not appear to be a need to increase the test time by requiring more than 55 drops of reagent at the chosen voltage level.

10.7 REPRODUCIBLE TEST RESULTS

One concern that was identified early in the test program and remains unresolved at this time is whether or not the DC-CTI test is reproducible, i.e. can the same test be performed at different test locations, by a number of different technicians and produce the same test results?

This issue may be resolved by performing a series of round robin tests as described in Section 10 - *Further Testing* of this report. It was agreed, for the purposes of this investigation, that round robin testing would be performed under a separate phase (Phase 2) of the DC-CTI test development. Underwriters Laboratories is designing a production DC-CTI tester and plans to contract with a test equipment manufacturer to produce the necessary equipment to conduct round robin testing in 2004.

10.8 STANDARDS PROCESS.

In a parallel effort, UL is utilizing the standards making consensus process to have the developed DC-CTI test protocol adopted as a nationally recognized test standard.

APPENDIX A - SITUATION ANALYSIS

A literature search was conducted using the New England Research Assistance Corporation (NERAC), UL Technical References, ASTM Technical References, IEEE Technical References and the World Wide Web. As a result of this search some 32 citations/ web sites were found. A complete listing of each technical article and its associated abstract are included in this Appendix.

An asterisk (*) adjacent to the citation number indicates that the full article was reviewed as part of this project.

	Title	Author	Journal	Publication Date
1	A Laboratory Test for Tracking and Erosion of HV Outdoor Insulation	Gorur, et.al.	Transactions on Dielectrics and Electrical Insulation	1997

A new laboratory test for evaluating the tracking and erosion performance of\HV outdoor polymeric insulating materials is described. The materials evaluated include various formulations of\HTV* silicone rubber and polyolefin polymers. The test is based on combining some features of the \ASTM D2132 \DF* test and the \ASTM D2303 \IP* test. The new test employs \IP test geometry, \IP test equipment, and \IP specimen plaques. The plaque is coated with a mixture of clay and salt similar to the contaminant of the \DF test and identical to the contaminant used in the \IEC clean fog test to rate ceramic insulators for use in contaminated environments. A liquid contaminant with a conductivity similar to that of the \DF test is applied to the test specimen in the same way as in the \IP test. Data collected from the field on the maximum concentration of insoluble and soluble ionic materials on surfaces of contaminated insulators which have been for 21 years in contaminated regions, provide a basis for choosing the minimum concentration of the solid contaminant to apply to the specimens. This choice also serves to define, at least tentatively, the geographical area where the results of this test have significance. It is expected that this test could be used also for screening materials and obtaining a relative ranking of the tracking and erosion resistance of various materials. Measurements of the leakage current via a computerized data acquisition system, and the discharge activity with a high-speed camera were performed, and have resulted in a better understanding of the onset of material degradation.

2	Analysis of Electrical Activity Associated with Inclined-plane Tracking and Erosion of Insulating materials	R.J. Chang, L. Mazeika	Transactions on Dielectrics and Electrical Insulation	2000

Surface electrical activity and physical changes were measured and compared for several types of outdoor insulation materials, using a standard test method. The leakage current activities during the inclined-plane test (\ASTM D2303) were measured by using four representative materials: a silicone with high (>70\% by weight) loading of \ATH*, a silicone with no \ATH, a poly \EVA*, and a glazed porcelain. Quantitatively, the severity of the inclined-plane test was defined by detailed leakage current measurements. Qualitatively, it is observed that the test was severe enough to damage the glaze on porcelain. The study enabled us to compare polymers with porcelain, silicones containing no \ATH \vs. high loading of \ATH, and silicones with \EVA. The analysis showed that electrical activity, particularly the average leakage current and the distribution of peak current, depended on the surface wettability of the materials by the contaminant solution. The compound formulation is more important than the generic polymer types. It was demonstrated that silicone with no \ATH, and \EVA with only a medium level of \ATI-1, exhibited excellent tracking and erosion resistance, comparable to the silicone highly filled with \ATH. The presence of \ATH is not absolutely necessary to achieve the superior tracking and erosion resistance of a silicone elastomer.

3*	Analyzing and Modeling the 2D Surface Tracking Patterns of Polymeric Insulation Materials	M. Ugur, B.R. Varlow	Transactions on Dielectrics and Electrical Insulation	1998 - Vol 5 pp 824-829

The structure and topography of surface tracking patterns generated on the surface of unfilled and filled samples of polyester resin using the international standard procedure (IEC 587 Inclined-plane Tracking Test) have been studied. The effect of contaminant flow rate, applied voltage and the percentage content of particulate zinc oxide on tracking behavior has been determined. Three alternative mathematical algorithms have been used to establish the fractal dimensions of the tracking patterns as a function of the above three parameters. To model the surface tracking patterns two methods have been applied. Firstly, a resistive network has been used in which the insulator surface is assumed to consist of imaginary vertically and horizontally placed resistors. This model is capable of producing several types of trees observed in insulating materials. However the surface tracking patterns are mostly unbranched and it is not possible to produce realistic images with this model The second method, Brownian, motion, is mainly a recursive technique and does not take Laplacian field values into account The resolution of the images is high, hence the simulated patterns are almost indistinguishable from the real images.

4*	Burning, Arcing, Ignition and Tracking of Plastics Used in Electrical Appliances	Louis M. Kline	UL Bulletin of Research No. 55	Feb-64

This Bulletin of Research reports an investigation, conducted by Underwriters' Laboratories, Inc - to provide information and technical data related to the behavior of plastics and plastic materials when exposed to burning, arcing, ignition, and tracking such as might be experienced in electrical appliances. It is intended to provide a safety guide for use in selecting a plastic for a particular end-use application, and in substituting one plastic for another in an electrical appliance.

The investigation included a survey of the field record of plastics, the laboratory testing of samples of fifty plastic materials selected to represent the generic types typically used by the electrical appliance industry, and the exploration of ignition sources, flame paths, and rates of flame spread within representative electrical appliances.

The results of the burning, arcing, ignition$_1$ and tracking tests were analyzed, categorized, and illustrated by bar graphs to show the order of performance as related to ease-of-ignition, resistance to arcing, rate of tracking, flame spread, and similar characteristics. Each characteristic was considered independent of the others.

A study of the performance of individual plastics in all areas of concern resulted in the development of a numerical unit of measurement, designated herein as the Plastics Performance Index. This Index is intended to provide a numerical evaluation of the performance or merit of each plastic characteristic based on an established test program, designed to develop reproducible information covering such properties as burning, arcing, ignition, and tracking.

5*	Discharge Energy and DC Tracking Resistance of Organic Insulating Materials	B.X. Du	Transactions on Dielectrics and Electrical Insulation	2001 - Vol 8 pp 897-901

As an evaluation test method for surface insulation degradation of organic insulating materials, the tracking test method is described in \IEC Publ.112 as a safe and reliable evaluation. This publication has now been applied to the material selection. Due to the fact that the experimental values of the \CTI, have wide variations, problems in reliability testing are abundant. In this paper, the correlation is investigated between discharge energy and tracking resistance of organic insulating materials. The test method resembles the \IEC Publ.112 method, but with the application of dc voltages. The number of drops to tracking failure was measured with samples of paper based phenolic laminate, polybutylene terephthalate and epoxy resin. Discharge currents were detected when discharge occurred on the sample surface. A Gaussian wavelet analysis was applied to show energy levels of discharge currents. It was found that the tendency of discharge energy on organic insulating materials corresponded to the ‘CTI of dc tracking resistance, and the results were an improvement on the \IEC Publ.112 method for grading materials. The tracking resistance of organic insulating materials could be deduced from the discharge energy.

6*	Fire Hazard Caused by Thermal Degradation of Organic Insulating Materials at Plug and Receptacle Connection	Katsuhoro Okamoto, et. al.	National institute of Police Science, Japan

In cases of fires from plug and receptacle connection, it has been generally thought that the main cause of fire is arc tracking which results from the pollution on the surface of a plug. But insulating materials of plugs and receptacles has changed from tow tracking resistance materials such as Bakelite resin into PVC and urea resin that has high tracking resistance. Tracking resistance of the insulating materials is so high that an arc tracking on the surface cannot easily occur. If an overcurrent flows through a loose connection of a plug and a receptacle, heat may be generated. We suppose that the heat may degrade insulating materials of plugs and receptacles. Actually we have frequently found thermally deformed and discolored plugs in ordinary dwelling houses. In these cases, we think the insulation performance and the tracking resistance deteriorates and the. fire hazard at plug and receptacle connection increase.
In this paper, we discussed the fire hazard caused by thermal degradation of organic insulating materials at plug and receptacle connection.
We researched into the temperature rise at various loose connections of plugs and receptacle with an overcurrent and tracking resistance of plug insulating materials degraded thermally by heating in an electrical furnace.
Conclusions are as follows:

(1) The temperature of loose connection of plug and receptacle exceeded 200C with an overçunent and the average temperature was more than 15OC.
(2) Though PVC and urea resin had high tracking resistance before thermal degradation, by heating for a short time at 150 up to 200C tracking resistance easily deteriorated.
(3) It is clarified that the fire hazard increases by thermal degradation of insulating materials.

7	Fuse Wire Arc Tester	Peter G. Kovalchik	Pittsburgh Research Center, Bureau of Mines

To compare the viability of the new fuse wire arc test (FWAT) as a substitute for the comparative tracking index (CTI) for determining surface resistance to electrical tracking, the Bureau of Mines constructed a fuse wire arc tester and undertook a detailed testing program for testing insulating materials used on explosion-proof enclosures. This report describes the Bureaus apparatus, the two methods (CTL and FWAT), and the results of the Bureaus testing, showing comparisons of the FWAT with the CTI. Results showed strong correlation between the two methods, as all specimens tested that had CTI ratings of 400 V ac rms and above passed the 10-test sequence with the FWAT, whereas all specimens with lower CTI ratings failed, with the number of tests to failure corresponding roughly to the descending CTI rating order.

8*	Standard Practice for Operating Salt Spray (Fog) Apparatus	ASTM B 117	ASTM Specification	Oct-02

This practice describes the apparatus, procedure, and conditions required to create and maintain the salt spray (fog) test environment.

9*	Insulating Materials		Electronic Design	7-Jun-69

This report is adapted from a chapter *of* the *Handbook* of *Electronic Packaging,* Charles A. Harper, Editor, McGraw-Hill Book Co., *New* York, N.Y., May 1969.

10*	Interim Report on Study in the Testing Method for Tracking Resistance of Plastic Insulating Materials	The Japan Society of Plastics Technology		Feb. 1985

A dielectric surface breakdown phenomenon called tracking may be observed on solid organic insulating materials. This phenomenon is caused by the carbonized conductive track formed on their surface. As one of the several methods which have been reported concerning the evaluation of tracking resistance or the resistance of a material to the above phenomenon, there is a method to determine the comparative tracking index (CTI). This method is specified in Publ.112. First edition (1959), Second edition 1971 and Third edition 1979, which were published by International Electrotechnical Commission. The Institute of Electrical Engineers of Japan (IEE of Japan) carried out a study on the testing methods for determining the tracking resistance including that of IEC Publ.112, the results of which were published as one of the Technical Report of TEE of Japan.
In this interim report, a part of the first round-robin test results will be presented. It will he very happy for members of the Sub-Committee that this interim report helps the people who are concerned with the designing and testing of various electrical appliances and parts which have some connection with CTI, as well as the people who are working at the material manufacturing or processing companies. Also the members of the Sub-Committee will appreciate for any suggestions or advices given on their way of future investigation.

11*	Mechanisms of Deterioration of Electrical Insulation Surfaces	William H. Middendorf	IEEE Transactions on Electrical Insulation	8/1984 Vol 19, pp 314-320

Performance tests during new product development are typically run on samples that have not been subjected to field environments. When failure of these products due to deterioration of insulation surface between metal parts of opposite polarity mounted on the insulation occurs, it is usually after many years of service and after the deposition of contaminants and moisture. This paper discusses the mechanism by which that deterioration occurs. The engineer designing insulating components should be able to use this information to avoid or at least greatly lessen the occurrence of the failure mode.

12*	Method for the Determination of the Proof and the Comparative Tracking Indices of Solid State Insulating materials	IEC 60112	IEC Specification	2003

This International standard specifies the method of test for the determination of the proof and comparative tracking indices of solid insulating materials on pieces taken from parts of equipment and on plaques of material using alternating voltages.
The standard provides for the determination of erosion when required.
Test results cannot be used directly for the evaluation of safe creepage distances when designing electrical apparatus.

13	Neural Networks to Analyze Surface Tracking on Solid Insulators	M. Ugur, et.al.	Transactions on Dielectrics and Electrical Insulation	19-Jun-05

Surface tracking on solid insulators is one of the most severe breakdown mechanisms associated with polymeric materials under long term service conditions. A wide range of relays can detect failure in a transmission line and prevent a total breakdown in the systems, but due to the non-healing characteristics of solid insulators, in most cases it might be too late to save the insulator after tracking initiation and growth. The method described here is employed mainly in detecting several conditions, such as discharges, leakage current, dry conditions, severe damage and tracking initiation. Initially a \BPN* type \NN* is trained with different signal types. Due to the nature of \NN, which always require similar values of input nodes, the system uses the \FFT* of the input signal, which might have high amplitude frequency components other than the fundamental frequency depending on the condition of the surface. The system works on a real time basis and warns the user with the first indication of severe damage on the surface and can protect the insulator from excessive damage.

14*	Plastics Testing	Victor Wigotsky	Plastics Engineering	1-Feb-02

Plastics testing has evolved, emphasizing precision and speed. Resin producers require data that more accurately reflect the actual operating conditions under which materials perform, so testing products with better performance and reliability are entering the market. In particular, the arc track measurements which is found to be difficult and inherently non-reproducible is presented. A new test which differentiates between materials is said to produce tracking failures with as few as five 12-volt batteries and better performers that resist tracking with as many as twelve batteries.

15*	Polymeric Materials – Short Term Property Evaluations	UL746A	UL Standard for Safety	Nov. 1, 2000

These requirements cover short-term test procedures to be used for the evaluation of materials used for parts intended for specific applications in electrical end products.

Together with the requirements mentioned in Supplementary Test Procedures, Section 4, these investigations provide data with respect to the physical, electrical, flammability, thermal, and other properties of the materials under consideration and are intended to provide guidance for the material manufacturer, the molder, the end-product manufacturer, safety engineers, and other interested parties.

16	Reducing Variability in Inclined-plane Tracking Test results	A.S.G. Alghamdi, et.al.	Transactions on Dielectrics and Electrical Insulation	18-Jun-05

Factors which cause variability in the results of inclined-plane tracking tests have been investigated. The effects of introducing shunt or stray capacitance across the test specimen, or of varying the contaminant flow rate, are measured. The discharge energy to the time of observation of initial damage shows less variability than the time-to-track criterion, and may be a more appropriate criterion for comparing the track resistance of materials.

17*	Report on Copper vs. Platinum Electrodes	William H. Middendorf	University of Cincinnati	

The CTI test measures one of the most important characteristics of electrical insulation; that is, whether or not it tracks in moist environments. The results of this investigation and other preceding it leave no doubt that the metal used for the electrodes influence the results. The CTI value using copper electrodes is less than that using platinum electrodes. However, the degree of difference varies widely. It would be unwise for a product designer to assume that the comparative Tracking Index based upon the use of platinum electrodes can be obtained by dividing CTI values by an estimate such as presented in this paper. Data needs to be accumulated on each kind of insulation using copper electrodes for insulation use where copper is to be used.

18*	Scaling Law for a Low-Pressure Gas Breakdown in a DC Electric Field in Oxygen	V.A. Lisovskiy, et. al.	Scientific Center of Physics and Technology, Kharkov, Ukraine	

Gas breakdown in oxygen in a DC electric field at various interelectrode gaps *L* is studied experimentally. A scaling law for a low-pressure gas breakdown is deduced. According to this scaling law, the breakdown voltage U_{dc} is a function not only of the product of the gas pressure *p* and the gap length *L,* but also of the ratio of the gap length *L* to the chamber radius *R.* his shown that, for any dimensions of the cylindrical discharge chamber (in the range of *LIR* under investigation), the ratio of the breakdown electric field to the gas pressure *p* at the minimum of the breakdown curve remains constant. A method for calculating the breakdown curve in a cylindrical discharge chamber with arbitrary values of *L* and *R* is proposed.

19*	Specifying Plastics for Electronics Design	Homi Ahmadi	Compliance Engineering	Nov./Dec. 2001

Although not always an easy task, selecting the right plastics can help ensure the safety and reliability of today's electronics.
Most electronic equipment uses some type of thermoplastic. It is important to understand the characteristics of plastics used in electronics equipment to determine which plastic is appropriate for a given application. These characteristics often affect the safety and reliability of the final product. This article examines many factors surrounding plastics selection that engineers should consider during a product's design stages.
Underwriters Laboratories (UL) has one of the most comprehensive materials databases available, and UL 94 ratings are widely accepted flammability performance standards for plastic materials. The UL 94 standard explains various flammability categories and describes the test methods used for each rating.

20*	Standard test method for Comparative Tracking Index of Electrical Insulating materials	ASTM D 3638	ASTM Specification	20-Jun-05

This test method evaluates in a short period of time the low-voltage (up to 600 V) track resistance or comparative tracking index (CTI) of materials in the presence of aqueous contaminants.

21*	Standard Test Method for Determining the Tracking Index of Electrical Insulating Materials Using Various Electrode Materials (Excluding Platinum)	ASTM D 5288	ASTM Specification	Sep. 1997

This test method was developed using copper electrodes to evaluate the low-voltage (up to 600 V) tracking resistance of materials in the presence of aqueous contaminants.
Other electrode materials may be considered for use with this test method depending upon the application of the insulating material.
This test method is similar to Test Method D 3638, which determines the comparative tracking index of materials using platinum electrodes to produce the tracking on the specimen surface.

22*	Summary report on Study in the Testing Method for Tracking Resistance of Plastic insulating Materials	The Japan Society of Plastics Technology		Dec. 1989

Among the several testing methods of tracking resistance for solid organic insulating materials under humid conditions, one method is specified in IEC Publ.112 for determining the comparative (racking index (CTI) or proof tracking index (PTI). It has been desired that the test results obtained by IEC Publ.112 method on various insulating materials should be in good agreement among the different testing parties in Japan as well as of the world. However due to the fact that CTI and PTI values obtained through experiences spread to wide varieties, many of the people involved in electric and electronic industry have been wanting this problem being solved at an early occasion.

In order to minimize the variation of test results and lessen the influence by the test apparatus used, Japan Society of Plastics Technology investigated on test apparatus and methods specified in IEC Publ.112 by carrying out round robin tests with identical samples. This effort has drawn that there are several ways for minimization of such variation. Based on these results, we have concluded to make proposals for the revision of IEC Publ.112 to IEC/SC 15A.

It will be a great pleasure for the members of this committee of electric and electronic *appliances* and their parts, and manufacturers of plastic insulating materials, as well as to the gentlemen who are interested in some problems with CTI and PTI.

23	Survey of Arc Tracking on Aerospace Cables and Wires	F. Dricot, H.J. Reher	Transactions on Dielectrics and Electrical Insulation	16-Jun-05

The paper gives a survey of the phenomenon ‘Arc Tracking of Wires’ which has been observed for the first time in wiring systems of aircraft and which recently has occurred also in spacecraft. Aircraft organizations are aware of this phenomenon and have tried to provide solutions to cope with this new wire failure, \ie\ modification of cable design and manufacture, avoiding pure polyimide insulation, and development of test methods. As regards space systems, the recognition of this phenomenon with its possible consequences has led to the development of test methods and to the introduction of new wire requirements within the framework of the Columbus Program. The available data do not establish with certainty a correlation between test results obtained for aircraft systems and the behavior expected on spacecraft. The untidy nature of arc tracking has been shown with the different kinds of events reported. In test laboratories, significant variations of results make this failure phenomenon even more difficult to define. From the data summarized in the survey it is apparent that the failure conditions vary with numerous conditions of electrical network, environment. cable design and aging parameters. Whereas the arcing phenomenon is essentially influenced by the environment and network conditions, the susceptibility to tracking is more dependent on the chemical nature of the insulation. Definitions are also presented in the survey to complete the understanding of the phenomenon.

24*	The Use of Copper Electrodes for the Comparative Tracking Index Test,	William H. Middendorf	IEEE Transactions on Electrical Insulation	1985 - Vol 20 pp 537-542

If failure of electrical insulation occurs after a product has been in service for a considerable time, the mechanism involved is usually that of a carbonaceous track which develops between electrodes under conditions of intermittent moisture. A number associated with specific insulations and designed to rank insulations in order of' their ability to avoid tracking is known as the comparative tracking Index (CTI). There is little doubt as to the importance of the test that establishes the CTI value but there is much concern about its accuracy.

This paper proposes modifications of the test equipment in an attempt to make the test more closely represent the conditions in the field and to make determination of the CTI value less subject to individual interpretation of the data. The proposed changes have been tested by Laboratories in this country and Europe

25*	The Chemistry of Insulation Tracking with Copper Electrodes	William H. Middendorf, et.al.	IEEE Transactions on Electrical Insulation	12/1/1988 Vol 23, pp 987-991

Continued research into the mechanism of insulation failure when copper electrodes are used for the Comparative Tracking Index test has led to the conclusion that exothermic reactions initiated by the scintillation increase the intensity of the microarcs. Futhermore, it is argued that this same mechanism is active in products using copper parts when subjected to moisture.

26*	A Study on the Investigation of Surface Tracking in Polyester Insulators	Ayten Kuntman, et.al.	www.eleco.emo.org.tr/SamplePaper03.doc	

In this study, the effects of longitudinal compressive and tensile stress, ultraviolet (UV) radiation and wind pressure from different positions with respect to the surface of the sample under test have been investigated in detail with the AS1M D2303 Inclined Plane Tracking Test method. The structure and topography of surface tracking patterns generated on the surface of polyester resin have been examined using fractal dimension model.

27*	The Occurrence of Tracking in Printed Circuit Boards Using Organic Insulating Materials	Yuichi Aoki, et. al.	ESPEC Technology Report	No. 11

The current heightened level of concern with respect to environmental problems has brought about a trend toward eliminating fire-retardants such as halogen materials and antimony from printed circuit boards (PCBs) used in electronic equipment As a result, we now face difficulties in product development concerning how to maintain/ire retardant properties and how to deal with tracking. Since the Japanese product liability law has gone into effect, there has been a heightened concern with safety. Accidents due to tracking can cause fire and examples of such accidents are continually occurring. Various test standards exist for evaluation, but complex factors are involved, and countermeasures cannot be obtained for all factors. We have investigated the effects of the basic factors related to the occurrence of tracking, and we shall present the results of our investigation in this report.

28*	The Use of Copper Electrodes for the Comparative Tracking Index Test	Toshio Suzuki, et. al.	Transactions on Dielectrics and Electrical Insulation	1986 - Vol 21 pp 677-680

Although the use of copper electrodes allows the CTI test to be performed in less time and, with a 5 mm spacing, at higher voltages, the most important reason to consider a change in electrode material is to simulate the insulation-conductor systems that are most likely to occur in practice. Only in that way can design engineers make correct decisions for safe products.

29*	VDE-Specification for Electrical Tests of Insulating Materials, Resistance to Tracking	DIN 53480	VDE Specification	Oct-76

English translation not available.

30*	Present Status of ASTM Tracking Test Methods	G.R. Mitchell	Journal of Testing and Evaluation	Vol. 2, No. 1 Jan - 74

Three standard tracking test methods have been developed, which are in active use im evaluating materials for medium voltage applications of electrical insulation. A fourth method intended for evaluation of materials for low voltage applications is in the interlaboratory development stage. A fifth method is being developed specifically for outdoor medium voltage insulation applications. Each of the test methods exhibits different advantages and disadvantages. Test methods must he selected based on testing objectives.

31*	New Look at ASTM Tracking Test Methods for Polymers	Salama, M. M. A.; Mansour, E. A. E.	Proceedings of the 15th Electrical/Electronics Insulation Conference	1981

The use of polymers as insulating materials has increased very rapidly in the last two decades. Different insulating materials track to different extents under the same operating conditions. The ASTM tracking test methods provide valuable tools for screening of materials. They permit the trackable materials to track in a similar manner to that experienced in service, but at a much faster rate. The authors present a useful comparison between the ASTM tracking test methods, taking into consideration the different viewpoints of the polymer suppliers, testers and users.

32*	Evaluation of Gases Generated by Heating and Burning of Cables	Gandhi, P.; Wagner, R. et. al.	Electric Power Research Institute report prepared by UL	Aug-96

Smokers, fires, and explosions in underground cable distribution systems are not common events, but they occur persistently. In this study, the first phase of a research project intended to mitigate these problems, the conditions under which low voltage arcing and elevated currents can decompose insulation were investigated and the gases generated from decomposing cable insulating materials were characterized. The flammability limits and explosive potential of gases generated from arcing and overheating were determined. A risk assessment methodology was developed to analyze the factors that influence the occurrence of smoke, fire, and explosions in secondary distribution systems.

APPENDIX B - TEST RESULTS

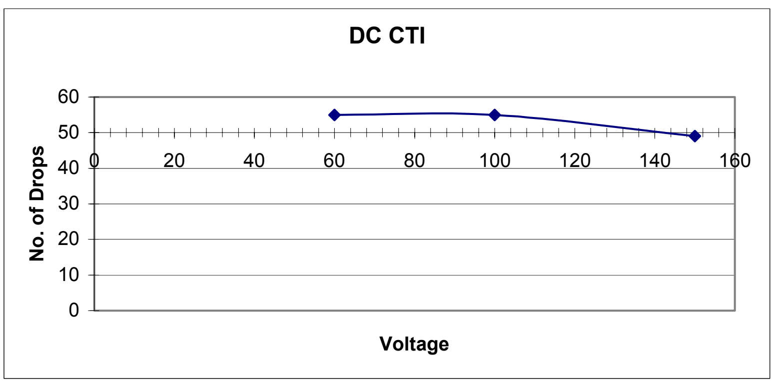
The results of the testing performed are documented in the following test record pages. Unless otherwise specified, testing was performed using a 5% NaCl reagent solution and a maximum of 55 drops.

Material Designation
1

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.17	3.19	3.19	3.18	3.17	3.17	3.19	3.19	3.18				3.18
150	55+	55+	38										49+
Notes:	[-]a,c,d	[16]a,c,d	[-]a,c,d										
100				55+	55+	55+							55+
Notes:				[51]a,c,d	[-]a	[-]a							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	49
100	55
60	55
50	
42	
12	



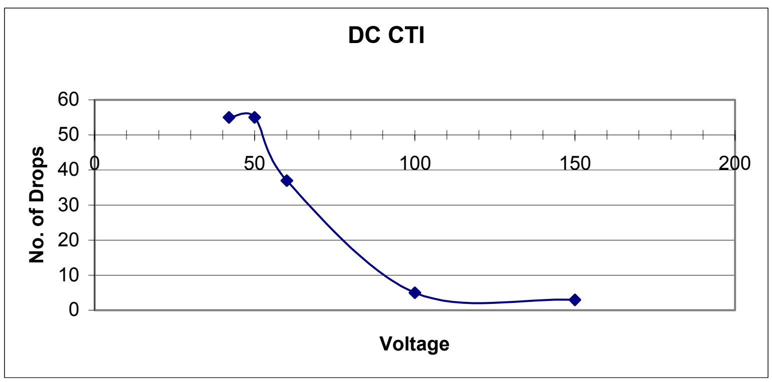
Material Designation
2

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.15	3.15	3.14	3.14	3.14	3.14	3.15	3.14	3.14	3.12	3.12	3.12	3.14
150	2	3	3										3
Notes:	[1]a,c,d	[2]a,c,d	[2]a,c,d										
100				4	5	5							5
Notes:				[4]e	[4]e	[4]e							
60							33	48	29				37
Notes:							[32]e	[48]e	[-]e				
50										55	55	55	55
Notes:										[-]a	[-]a	[-]a	
42	55+	55+	55+										55+
Notes:	[-]a	[-]a	[-]a										
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
e	Test terminated. Excessive flaming interefered with the dropping of reagent.
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	3
100	5
60	37
50	55
42	55
12	



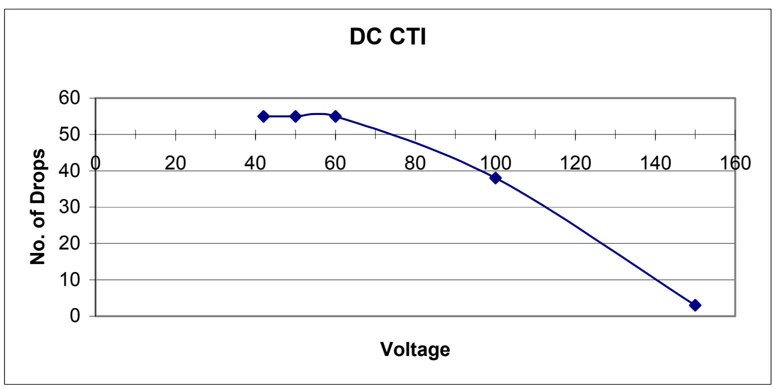
Material Designation
3

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.14	3.20	3.21	3.19	3.18	3.19	3.17	3.14	3.18	3.15	3.25	3.31	3.18
150	2	4	4										3
Notes:	[-]b,c	[-]b,c	[-]b,c										
100				45	40	30							38
Notes:				[-]c,d	[-]c,d	[-]b,c							
60					~~14~~		55+	55+	55+				55+
Notes:					~~[-]b,c~~		[-]	[-]a	[-]a				
50			55+								55+	55+	55+
Notes:			[-]a								[-]a	[-]a	
42	55+	55+								55+			55+
Notes:	[-]a	[-]a								[-]a			

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	3
100	38
60	55
50	55
42	55
12	



Material Designation
4

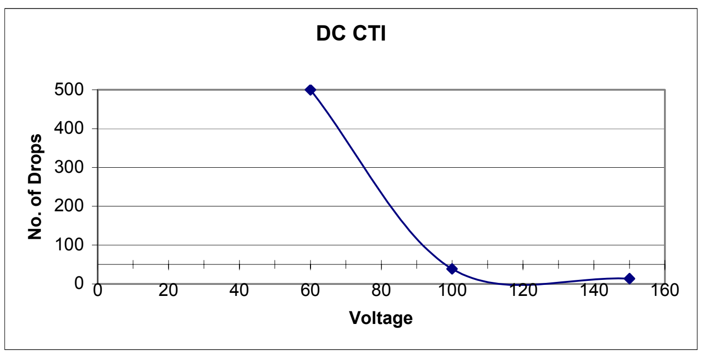
DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.06	3.08	3.08	3.09	3.08	3.08	3.1	3.08	3.08	3.08			3.08
150	5	26	12	5	~~55+~~								14
Notes:	[-]a	[19]c	[-]a	[-]a	~~[-]a~~								
100					40	54	23						39
Notes:					[39]a	[-]a	[-]a						
60								55+	55+	55+			55+
Notes:								[-]a	[-]a	[-]a			

500 DROP TEST													
60		500+											
Notes:		[99]d											

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	14
100	39
60	500
50	
42	
12	



Material Designation
5

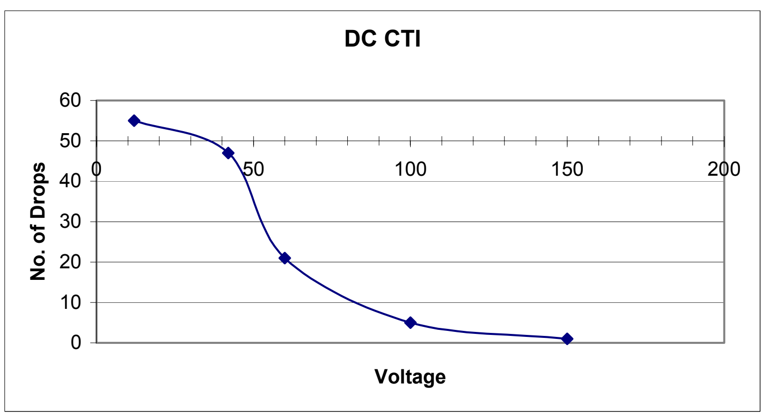
DC TEST VOLTAGE	Number of Drops to Track											
	Specimen Number											
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.12	3.11	3.11	3.12	3.12	3.11	3.13	3.11	3.13	3.11			3.12
150	2	1	1										1
Notes:	[-]a	[-]a	[-]a										
100				7	4	4							5
Notes:				[-]a	[-]a	[-]a							
60							17	25	20				21
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42	54	48	37	52	55+	33	51	55+	55+	26			47
Notes:	[-]a	[-]a	[-]a	[51]a	[-]a	[31]a	[50]a	[-]a	[-]a	[25]a			
12				*									
Notes:				[-]e									

ADDITIONAL TESTING					
	Reagent	% Solution	Resistivity (ohm-cm.)	Max. No. of Drops	Actual No. of Drops
42	NaCl	5	15	500	77
42	NH4Cl	35	15	500	32

Notes:

- a Eroded
- b Melted
- c Flamed
- d Melted Through
- e Test terminated. No scintillation.
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	1
100	5
60	21
42	47
12	55



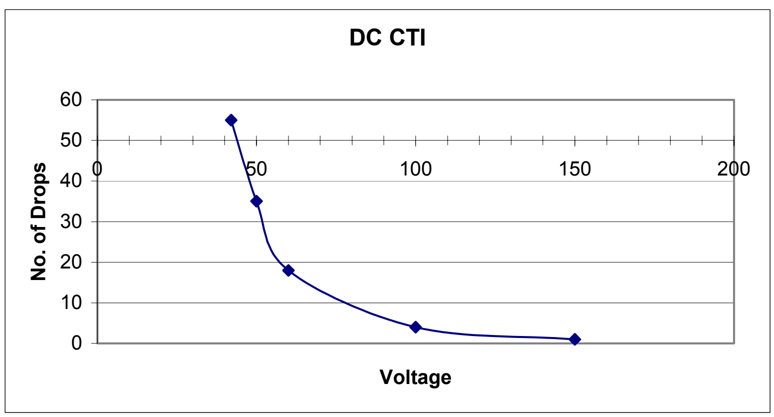
Material Designation
6

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.09	3.08	3.08	3.07	3.07	3.09	3.10	3.11	3.11	3.13	3.12		3.09
150	1	1	1										1
Notes:	[-]a,b,c	[-]a,b,c	[-]a,b,c										
100				4	4	4							4
Notes:				[-]a,b,c	[-]a,b,c	[-]a,b,c							
60							26	17	10				18
Notes:							[-]a	[-]a	[-]a				
50	22						52				32		35
Notes:	[30]c,d						[21]a,c				[41]a,c		
42	55+	55+								55+			55+
Notes:	[-]a	[-]a								[-]a			
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	1
100	4
60	18
50	35
42	55
12	

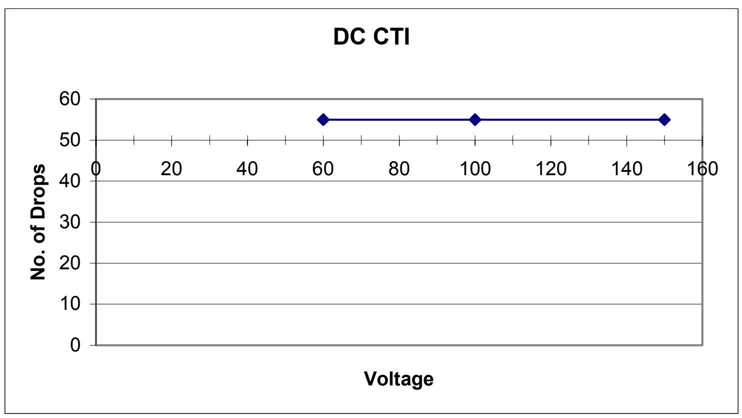


Material Designation
7

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.04	3	2.98	3.04	3.05	3.05	3.01	3.01	3				3.02
150	55+	55+	55+										55+
Notes:	[-]a,c	[-]a,c	[-]a,c										
100				55+	55+	55+							55+
Notes:				[-]a	[-]a	[-]a							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	55
100	55
60	55
50	
42	
12	



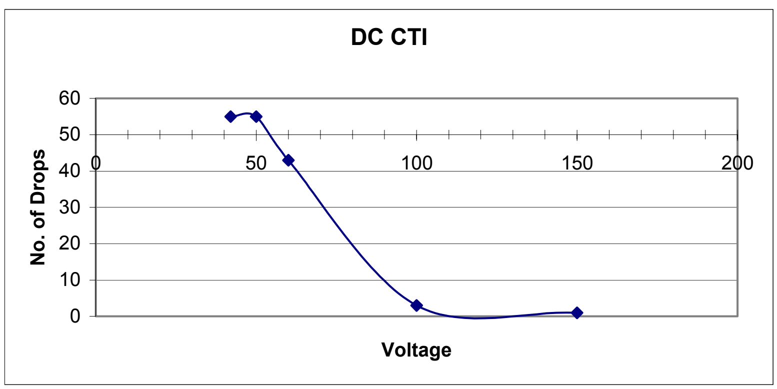
Material Designation
8

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.05	3.05	3.05	3.07	3.10	3.09	3.07	3.07	3.07	3.15	3.06	3.19	3.08
150	1	1	1										1
Notes:	[-]a	[-]a	[-]a										
100				3	4	3							3
Notes:				[-]a	[-]a	[-]a							
60							32	42	55+				43+
Notes:							[-]a	[-]a	[-]a				
50										55+	55+	55+	55+
Notes:										[-]a	[-]a	[-]a	
42	55+	55+								55+			55+
Notes:	[-]a	[-]a								[-]a			
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	1
100	3
60	43
50	55
42	55
12	

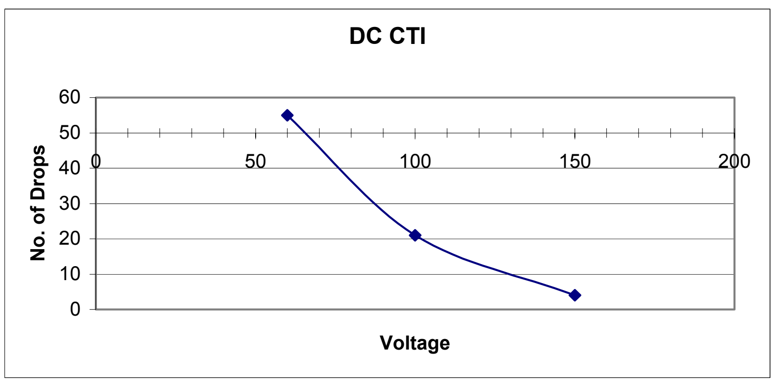


Material Designation
9

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.26	3.2	3.07	3.24	3.11	3.3	3.02	3.06	3.07				3.15
150	5	5	2										4
Notes:	[-]a,b,c	[-]a,b,c	[-]a,b,c										
100				7	32	23							21
Notes:				[-]a,b,c	[-]a,b,c	[-]a,b,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	4
100	21
60	55
50	
42	
12	



Material Designation

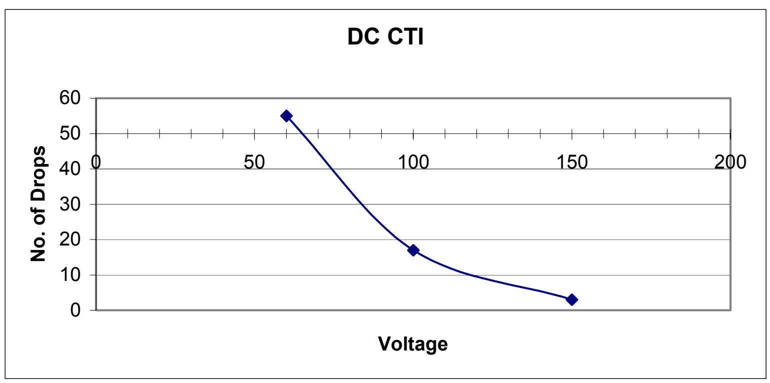
10

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.31	3.30	3.28	3.22	3.25	3.27	3.13	3.19	3.13				3.23
150	5	3	1										3
Notes:	[-]a,b,c	[-]a,b,c	[-]a,b,c										
100				21	15	16							17
Notes:				[-]a,b,c	[12]c	[-]a,b,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	3
100	17
60	55
50	
42	
12	



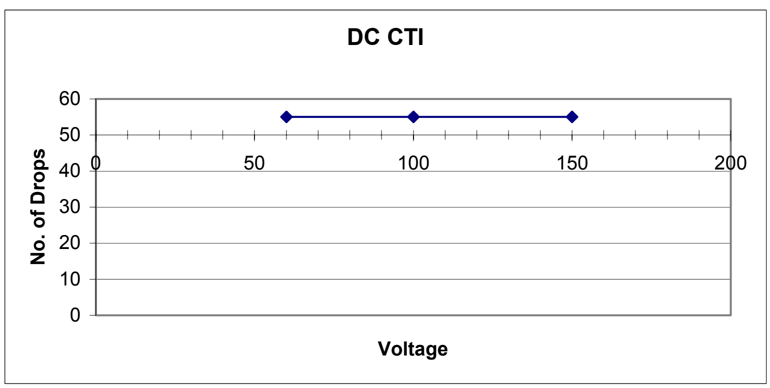
Material Designation
11

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.21	3.2	3.2	3.16	3.2	3.19	3.3	3.33	3.36				3.24
150	55+	55+	55+		~~27~~								55+
Notes:	[-]a,d	[-]a,d	[-]a,d		~~[-]a,c~~								
100				55+	55+	55+							55+
Notes:				[-]a,c	[-]a,d	[-]a,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	55
100	55
60	55
50	
42	
12	

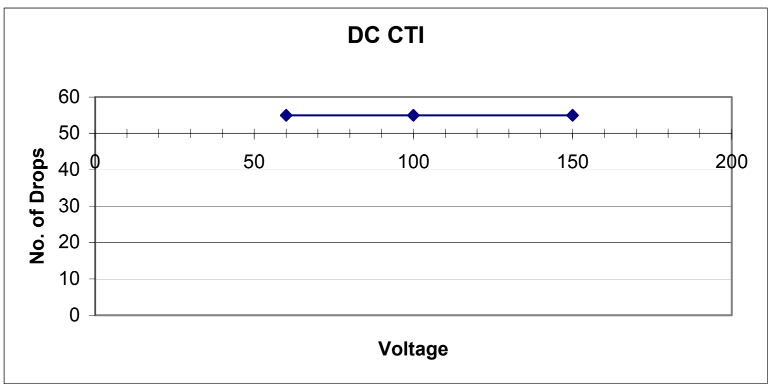


Material Designation
12

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	4.01	4	4.08	1.92	1.9	1.9	1.93	1.95	1.93				2.62
150	55+	55+	55+										55+
Notes:	[-]a	[-]a	[-]a										
100				55+	55+	55+							55+
Notes:				[-]a	[-]a	[-]a							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	55
100	55
60	55
50	
42	
12	



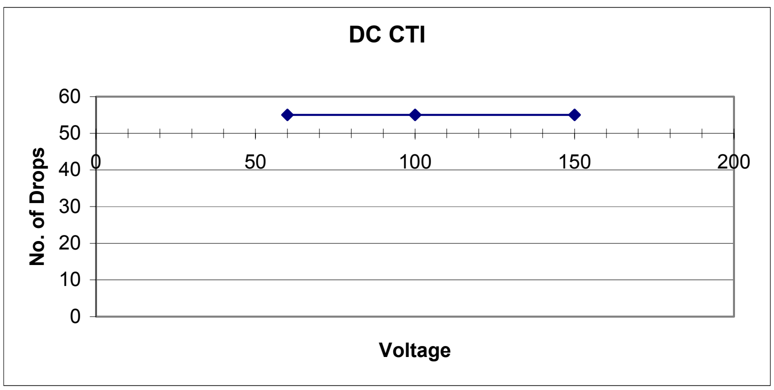
Material Designation
13

DC TEST VOLTAGE	Number of Drops to Track											
	Specimen Number											
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	4.08	4.11	3.87	1.77	1.79	1.77	2.03	2.04	2.07				2.61
150	55+	55+	55+										55+
Notes:	[-]a	[-]a	[-]a										
100				55+	55+	55+							55+
Notes:				[-]a	[-]a	[-]a							
60							55	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	55
100	55
60	55
50	
42	
12	



Material Designation
14

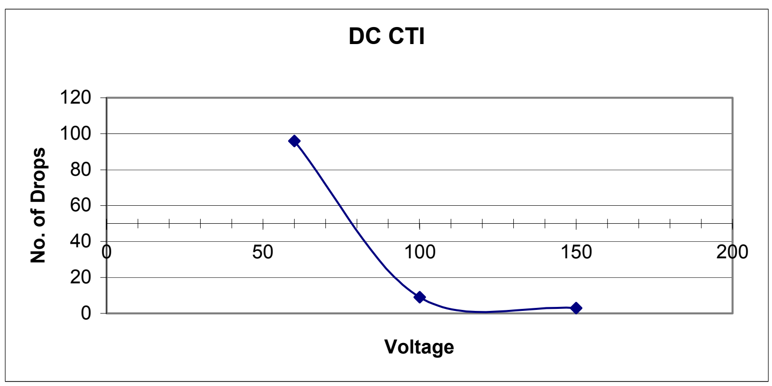
DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.10	3.10	3.07	3.1	3.08	3.11	3.07	3.09	3.13				3.09
150	2	2	4										3
Notes:	[1]a,b	[-]a,b	[3]a,b										
100				12	6	9							9
Notes:				[10]a,b	[-]a,b	[-]a,b							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				

500 DROP TEST													
60		96											
Notes:		[-]d											

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	3
100	9
60	96
50	
42	
12	



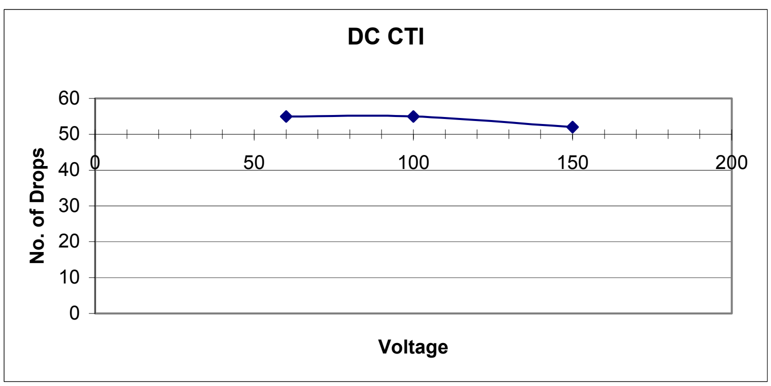
Material Designation
15

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.07	3.07	3.07	3.08	3.08	3.07	3.05	3.09	3.09				3.07
150	45	55+	55+										52+
Notes:	[-]a	[-]a	[-]a										
100				55+	55+	55+							55+
Notes:				[-]a	[-]a	[-]a							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	52
100	55
60	55
50	
42	
12	



Material Designation
16

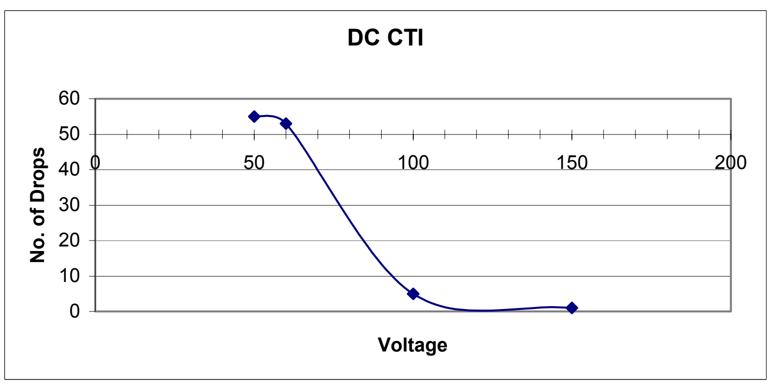
DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.14	3.11	3.05	3.10	3.11	3.12	3.09	3.12	3.09	3.10	3.11	3.12	3.1
150	1	1	1										1
Notes:	[-]a	[-]a	[-]a										
100	6	5	4	5	3	6	7			3	6	3	5
Notes:	[-]a	[-]a	[-]a	[-]a,c	[-]a,c	[-]a,c	[-]a			[-]a	[-]a	[-]a	
60							55+	55+	50				53
Notes:							[-]a	[-]a	[-]a				
50						55+	55+				55+		55+
Notes:						[34]a,c	[-]a				[51]a,c		

VARIATION IN REAGENT CONDUCTIVITY					
	Reagent % Solution	1	2	3	AVERAGE
		(min. thickness 3 mm)			
100	NaCl	3	3	3	3
Notes:	15%	[2]a,c	[2]a,c	[2]a,c	
100	NaCl	5	3	6	5
Notes:	5%	[-]a,c	[-]a,c	[-]a,c	
100	NaCl	21	20	11	17
Notes:	1%	[20]a,c	[-]a	[-]a	
100	NaCl	55+	55+	55+	55+
Notes:	0.15%	[-]a	[-]a	[-]a	
100	NH_4Cl	55+	55+	55+	55+
Notes:	0.1%	[-]a	[-]a	[-]a	

Notes:

a	Eroded	b	Melted
c	Flamed	d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)		

Voltage	Drops
150	1
100	5
60	53
50	55
42	
12	



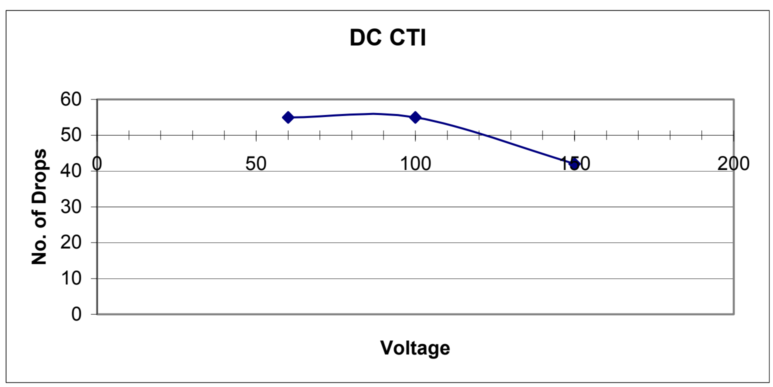
Material Designation
17

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.13	3.15	3.13	3.17	3.16	3.17	3.14	3.16	3.15	3.18	3.18	3.18	3.15
150	26	55+	55+					25		55+	55+	20	42+
Notes:	[-]a,c	[-]a,c	[-]a,c					[-]a,c		[-]a,c	[-]a,c	[-]a	
100				55+	55+	55+							55+
Notes:				[-]a,c	[-]a,c	[-]a,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	42
100	55
60	55
50	
42	
12	



Material Designation
18

Material Deleted by Request

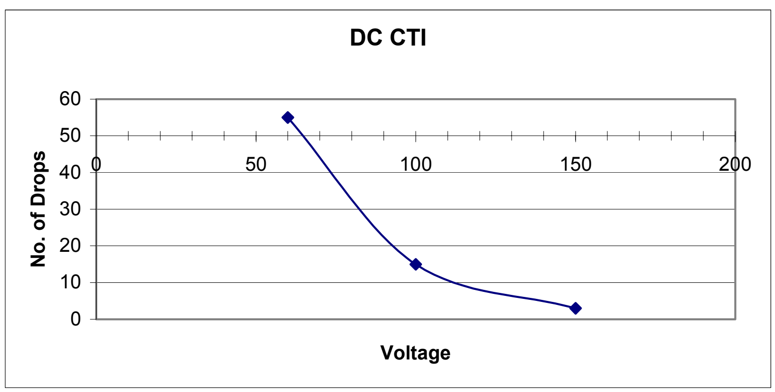
Material Designation
19

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.09	3.09	3.09	3.09	3.07	3.1	3.05	3.09	3.05				3.08
150	3	3	4										3
Notes:	[-]a	[-]a	[-]a										
100				21	6	18							15
Notes:				[-]a,c	[-]a,c	[-]a,c							
60							55	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
60													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	3
100	15
60	55
50	
42	
12	



Material Designation

20

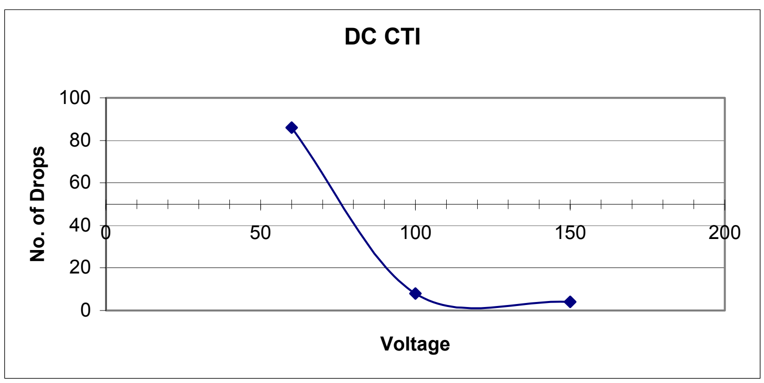
DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.1	3.1	3.05	3.07	3.07	3.09	3.05	3.08	3.09				3.08
150	4	4	4										4
Notes:	[-]a	[-]a	[-]a										
100				8	8	9							8
Notes:				[-]a,c	[-]a,c	[-]a,c							
60							55+	55	55+				55+
Notes:							[-]a	[-]a	[-]a				

500 DROP TEST													
60			86										
Notes:			[-]a										

Notes:

- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	4
100	8
60	86
50	
42	
12	



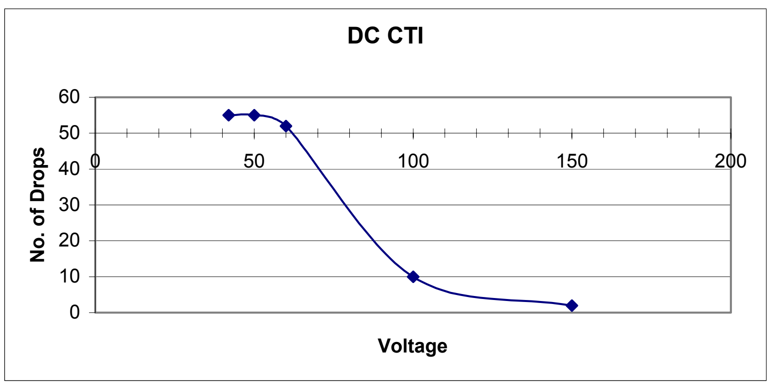
Material Designation
21

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.05	3.06	3.05	3.09	3.09	3.10	3.04	3.10	3.03	3.11	3.08	3.12	3.08
150	2	3	1										2
Notes:	[-]a	[-]a	[-]a										
100				10	7	12							10
Notes:				[-]a,c	[-]a,c	[-]a,c							
60			55+			55+	55+	42	46	55+	55+	55+	52+
Notes:			[27]a,c			[50]a,c	[-] (a)	[-]a,c	[-]a,c	[-] (a)	[-] (a)	[-] (a)	
50					55+	55+				55+			55+
Notes:					[-]a	[-]a				[-]a			
42	55+	55+								55+			55+
Notes:	[-]a	[-]a								[-]a			

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	2
100	10
60	52
50	55
42	55
12	

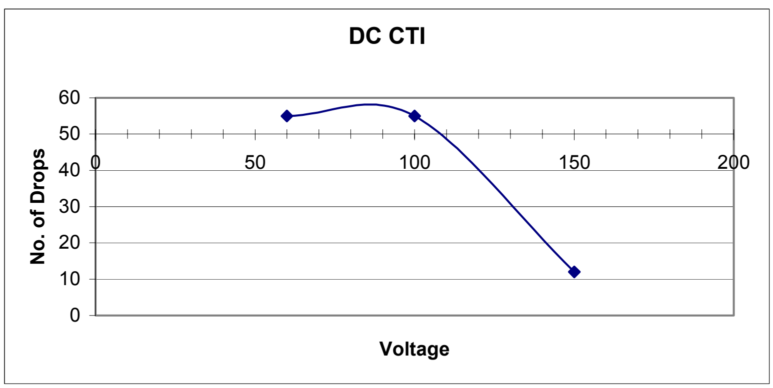


Material Designation
22

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.13	3.13	3.16	3.14	3.16	3.13	3.1	3.13	3.15				3.14
150	15	9	11										12
Notes:	[10]a,c	[-]a,c	[10]a,c										
100				55+	55+	55+							55+
Notes:				[-]a,c	[-]a,c	[-]a,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:
- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	12
100	55
60	55
50	
42	
12	



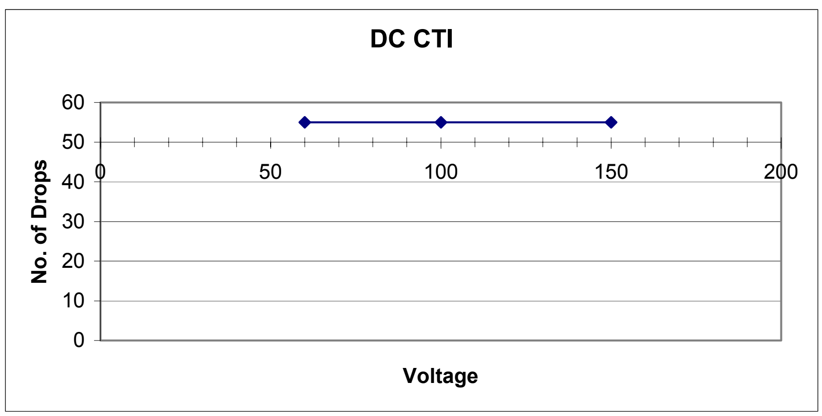
Material Designation
23

DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.14	3.12	3.11	3.17	3.12	3.17	3.09	3.15	3.13				3.13
150	55+	55+	55+										55+
Notes:	[-]a	[16]a,c	[-]a										
100				55+	55+	55+							55+
Notes:				[-]a	[-]a	[-]a							
60							55	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				
50													
Notes:													
42													
Notes:													
12													
Notes:													

Notes:

- a Eroded
- b Melted
- c Flamed
- d Melted Through
- [x] Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	55
100	55
60	55
50	
42	
12	



Material Designation
24

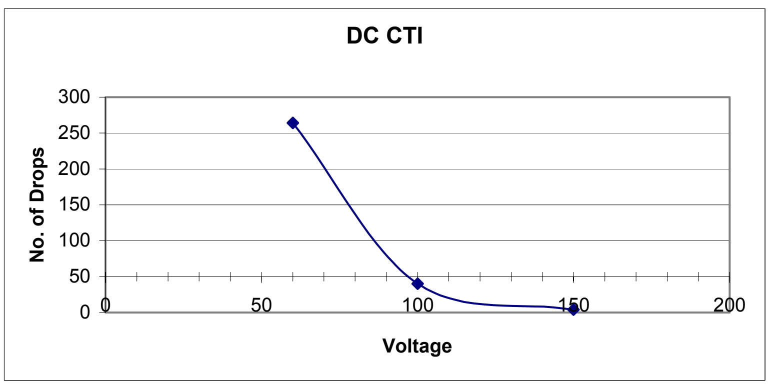
DC TEST VOLTAGE	Number of Drops to Track												
	Specimen Number												
	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Thickness (mm)	3.11	3.14	3.17	3.13	3.14	3.15	3.11	3.14	3.16	3.12			3.14
150	7	3	3										4
Notes:	[3]a,c	[-]a	[2]a,c										
100				49	39	31							40
Notes:				[31]a,c	[26]a,c	[18]a,c							
60							55+	55+	55+				55+
Notes:							[-]a	[-]a	[-]a				

500 DROP TEST													
60										264			
Notes:										[-]d			

Notes:

a	Eroded
b	Melted
c	Flamed
d	Melted Through
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)

Voltage	Drops
150	4
100	40
60	264
50	
42	
12	



Material Designation

25

DC TEST VOLTAGE	Number of Drops to Track									
	Specimen Number									
	1	2	3	4	5	6	7	8	9	AVERAGE
Thickness (mm)	3.08	3.08	3.07	3.13	3.08	3.11	3.06	3.09	3.11	3.09
150	1	1	1							1
Notes:	[-]a,b	[-]a,b	[-]a,b							
100				3	6	6				5
Notes:				[2]a,b,c	[4]a,b,c	[5]a,b,c				
60							55+	55+	55+	55+
Notes:							[-]a	[-]a	[-]a	

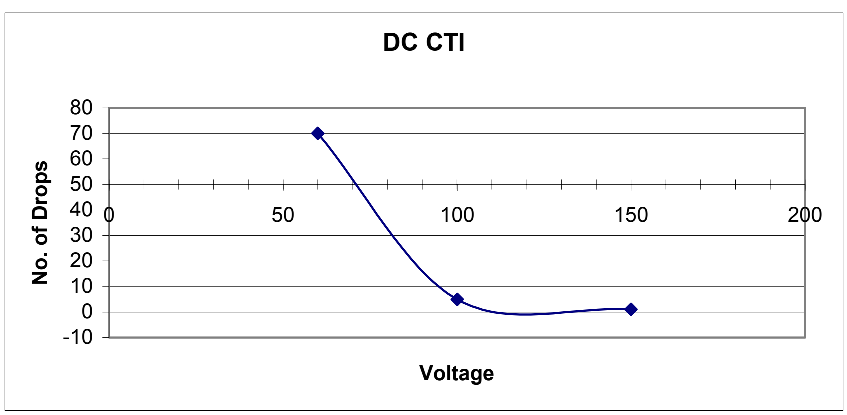
500 DROP TEST										
60				70						
Notes:				[-]d						

VARIATION IN REAGENT CONDUCTIVITY					
	Reagent % Solution	1	2	3	AVERAGE
		(min. thickness 3 mm)			
60	NaCl	22	54	35	37
Notes:	15%	[22]a,b,c	[46]a,b,c	[35]a,b,c	
60	NaCl	55+	55+	55+	55+
Notes:	5%	[-]a	[-]a	[-]a	
60	NaCl	55+	55+	55+	55+
Notes:	1%	[-]a	[-]a	[-]a	
60	NaCl	--			
Notes:	0.15%	[-]e			
60	NH_4Cl	--			
Notes:	0.1%	[-]f			

Notes:

a	Eroded	b	Melted	c	Flamed	d	Melted Through
e	No scintillation, test terminated after 3 drops						
f	No scintillation, test terminated after 6 drops						
[x]	Indicates number of drops to observe continuous flaming (minimum of 2 S)						

Voltage	Drops
150	1
100	5
60	70
50	
42	
12	

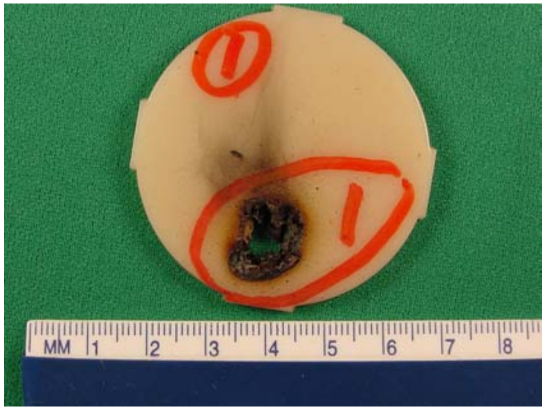


APPENDIX C - PHOTOS OF TEST SPECIMENS

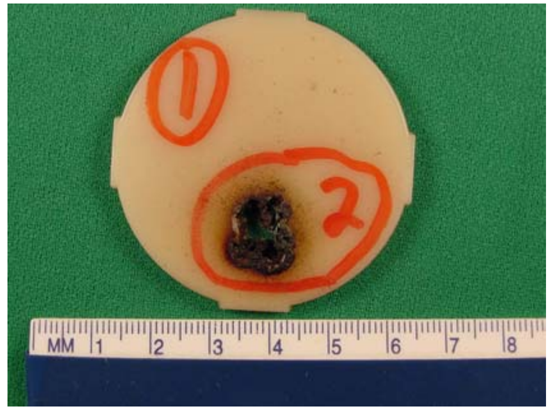
Photos of representative test specimens follow. Unless otherwise indicated, testing was performed using a 5% NaCl reagent solution.

The number appearing in the lower left corner below each photo corresponds to the JPG image saved to CD-ROM.

Material #1 - 150 Volts



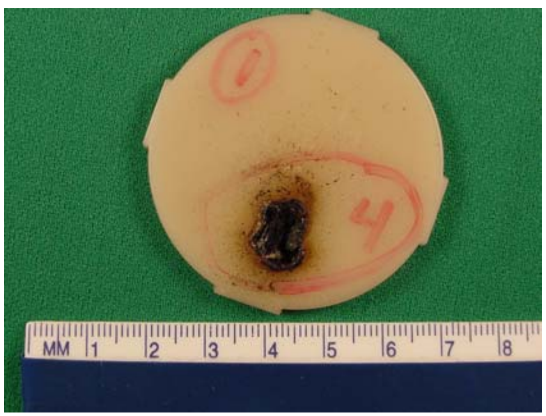
1



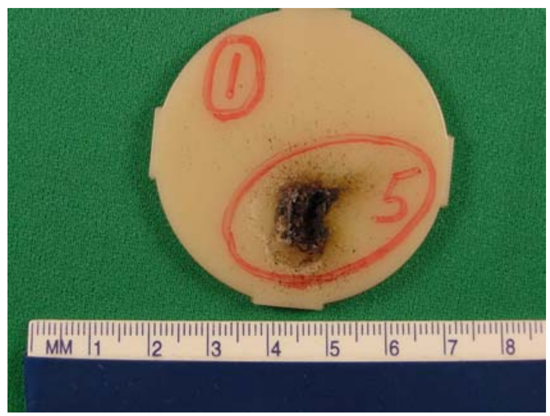
2

3

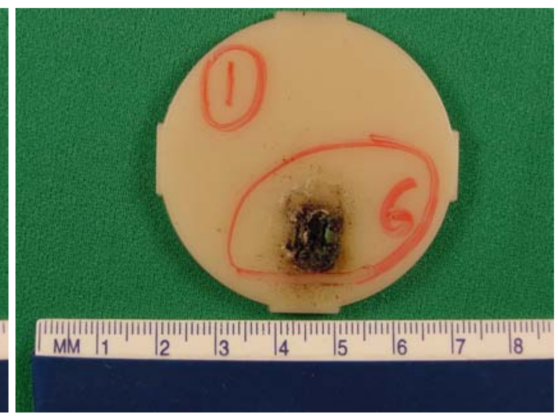
Material #1 - 100 Volts



4



5



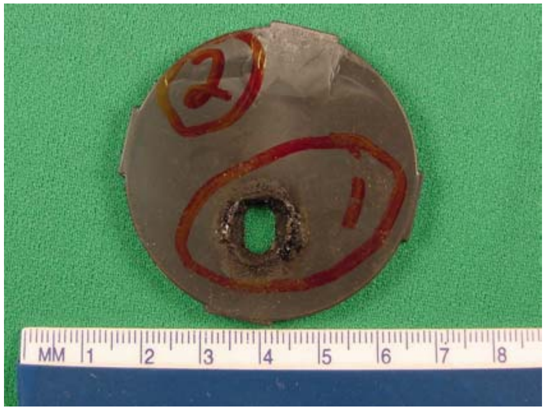
6

Material #1 - 60 Volts

7

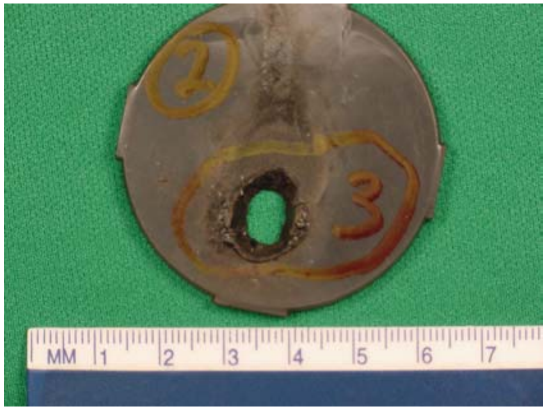
8

Material #2 - 150 Volts



9

10



11

Material #2 - 100 Volts

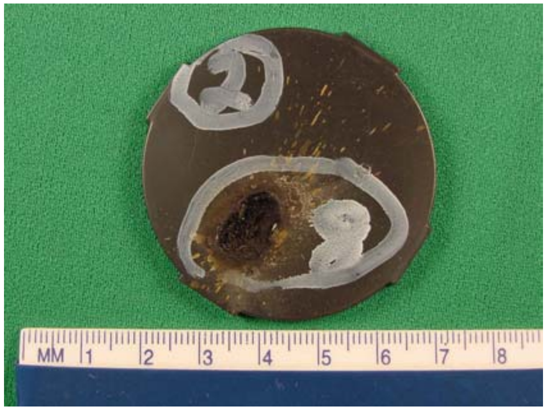
12

13

14

Material #2 - 60 Volts

15



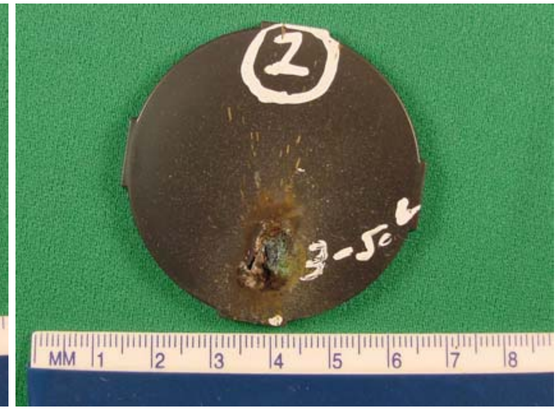
16

17

Material #2 - 50 Volts

18

19



20

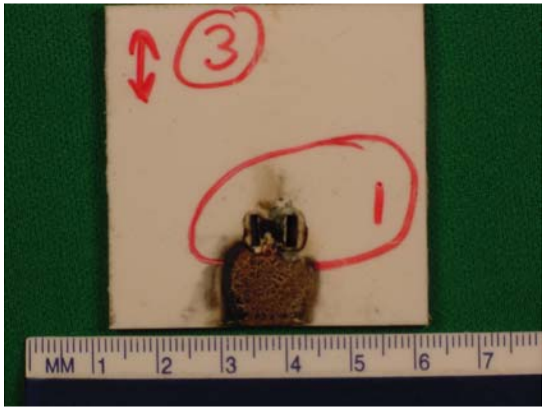
Material #2 - 42 Volts

21

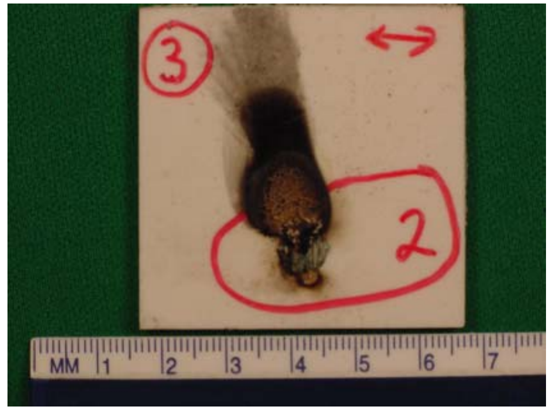
22

23

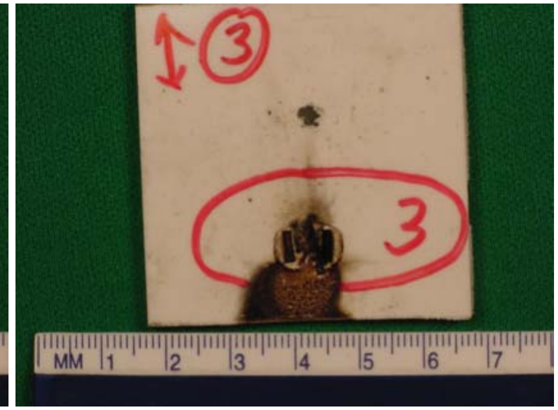
Material #3 - 150 Volts



24

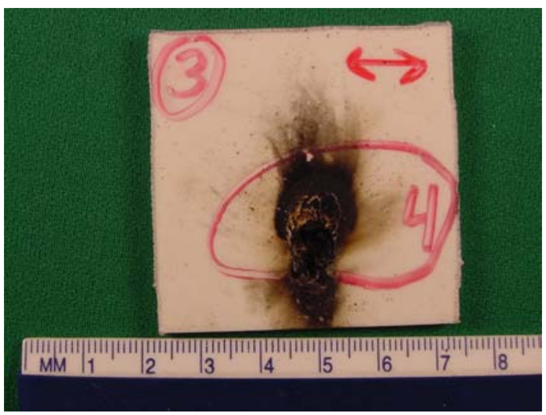


25

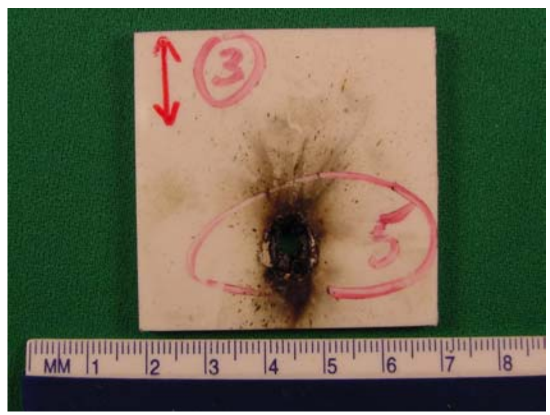


26

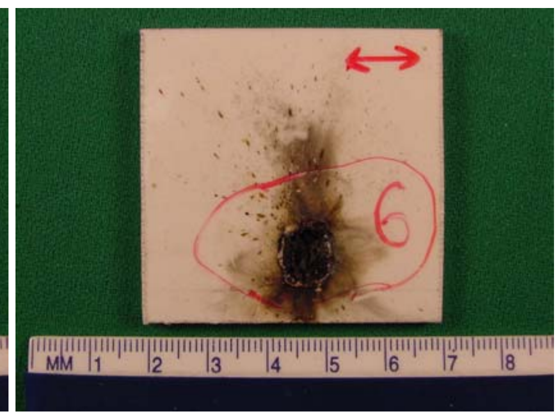
Material #3 - 100 Volts



27

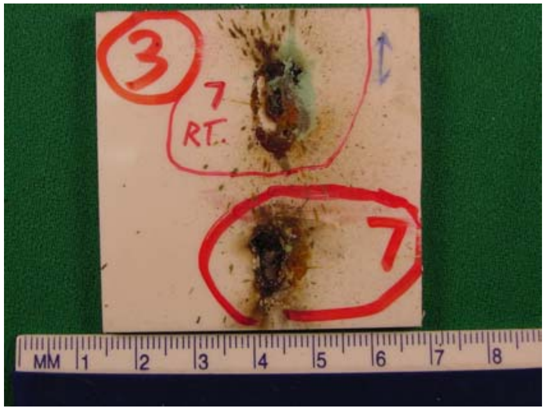


28

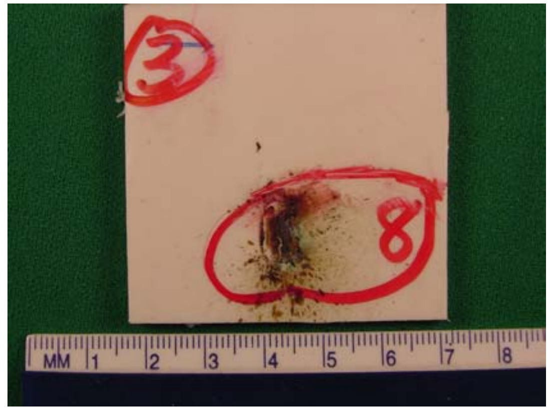


29

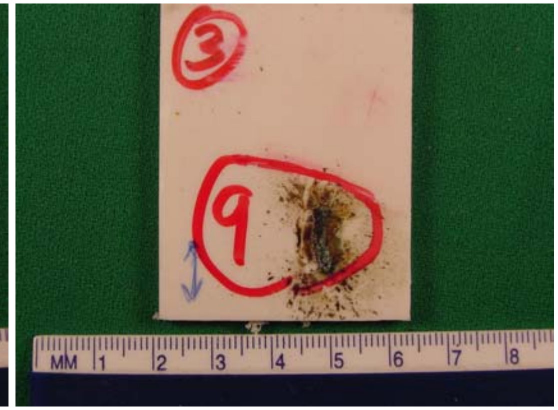
Material #3 - 60 Volts



30

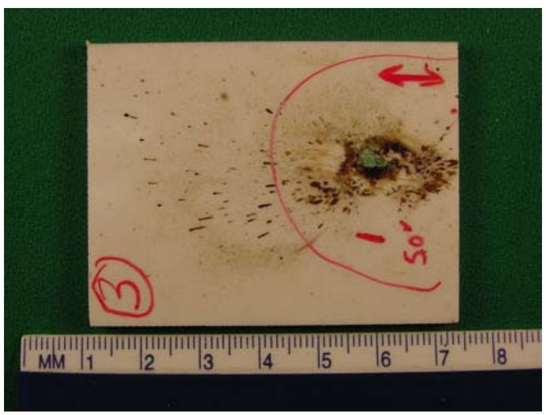


31

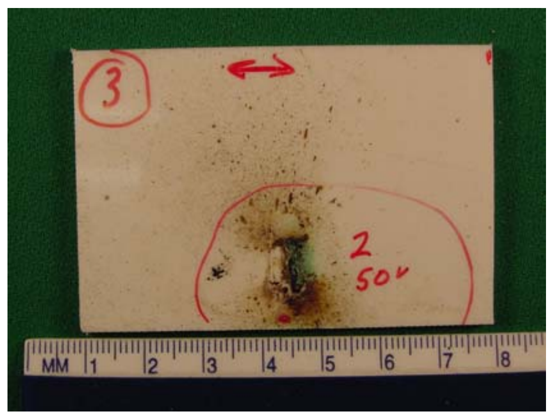


32

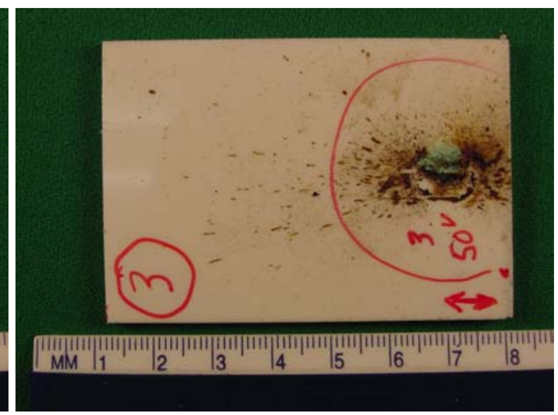
Material #3 - 50 Volts



33

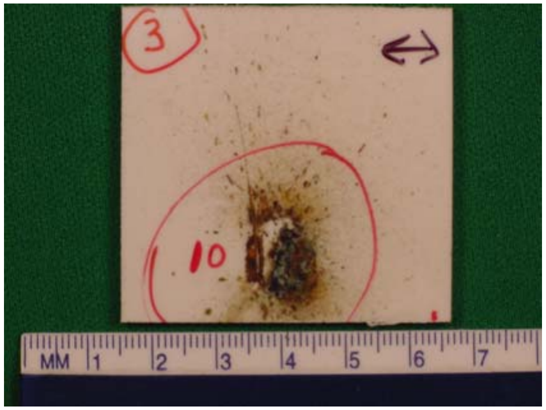


34

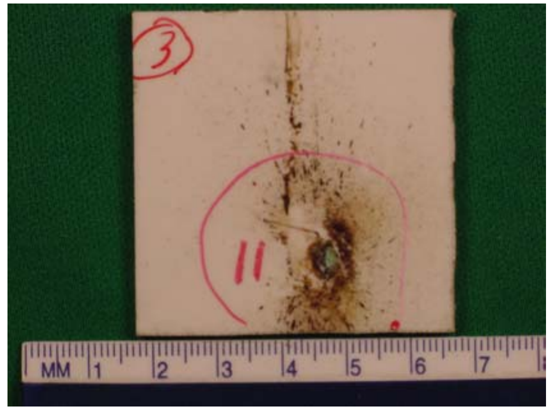


35

Material #3 - 42 Volts



36



37

38

Material #4 - 150 Volts

39

40

41

Material #4 - 150 Volts

42

Material #4 - 100 Volts

43

44

Material #4 - 60 Volts

45

46

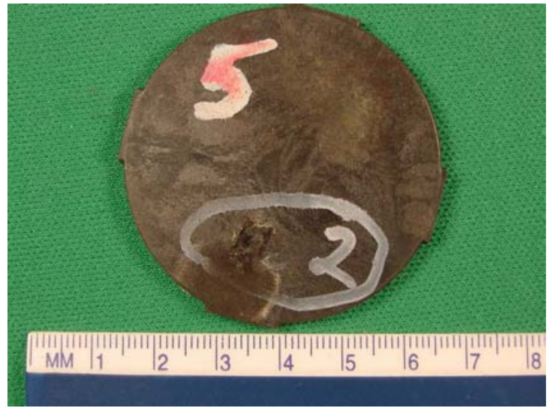
47

Material #4 - 60 Volts

48 **500 Drop Test**

Material #5 - 150 Volts

49



50

51

Material #5 - 100 Volts

52

53

Material #5 - 60 Volts

54

55

56

Material #5 - 42 Volts

57

58

59

Material #5 - 42 Volts

60

61

62

Material #5 - 42 Volts

63

64

65

Material #5 - 42 Volts

66

67 **500 drops**

68 **500 drops (35% NH_4Cl)**

Material #6 - 150 Volts

69

70

71

Material #6 - 100 Volts


72


73

Material #6 - 60 Volts


74


75


76

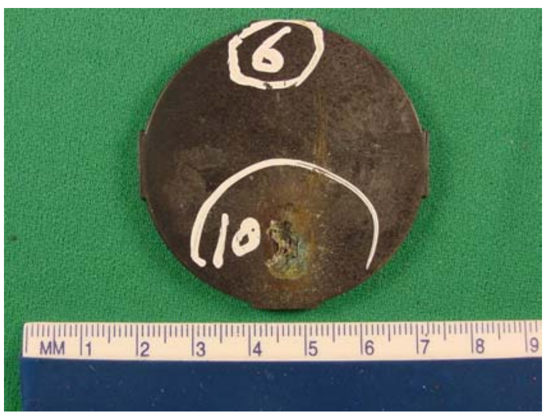
Material #6 - 50 Volts

77

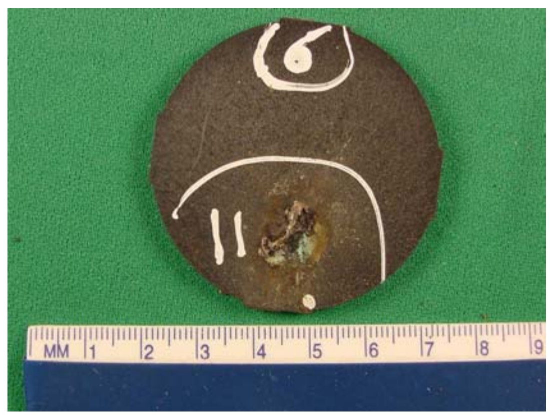
78

79

Material #6 - 42 Volts



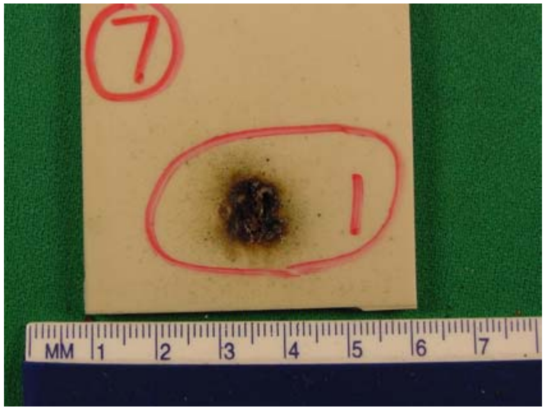
80



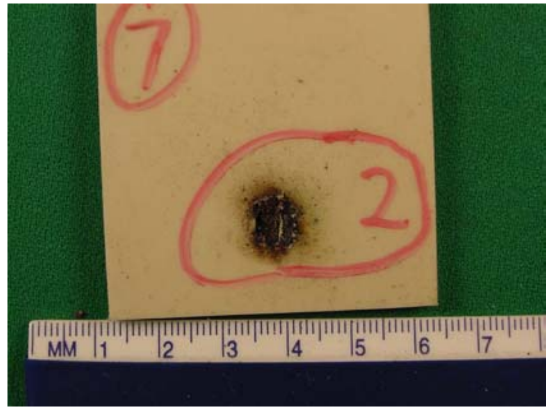
81

82

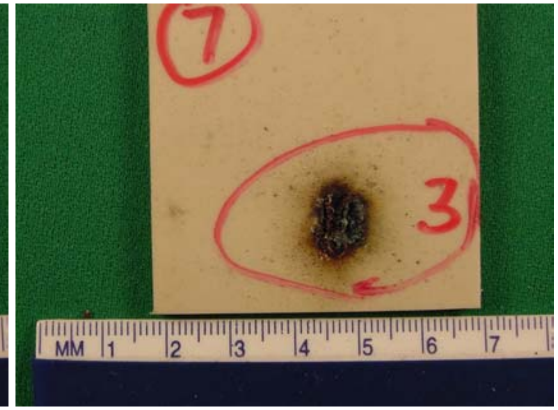
Material #7 - 150 Volts



83

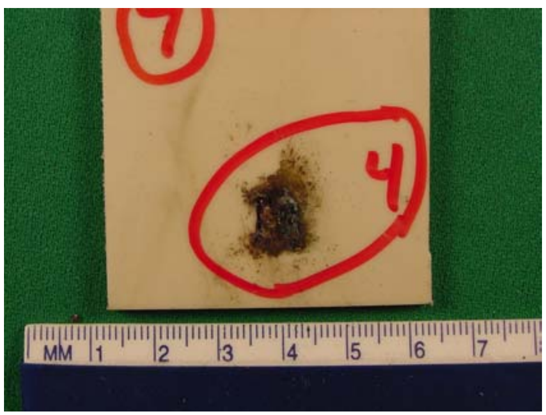


84

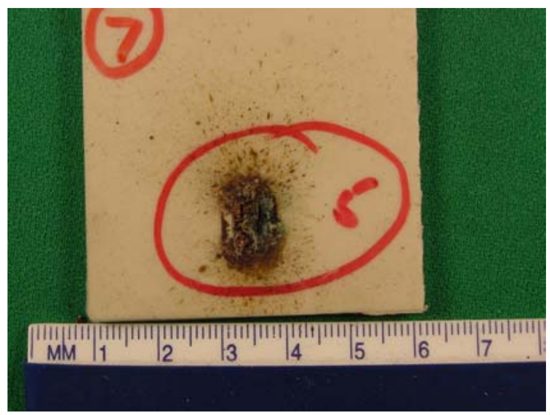


85

Material #7 - 100 Volts



86



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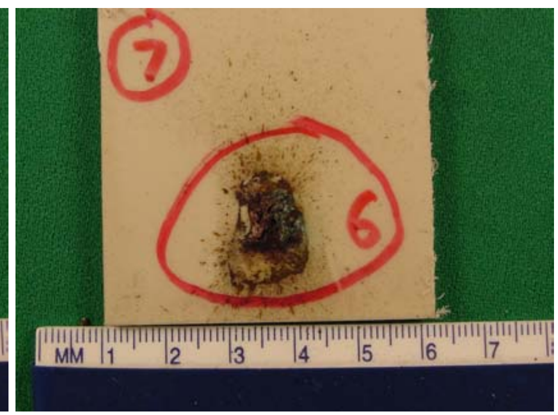
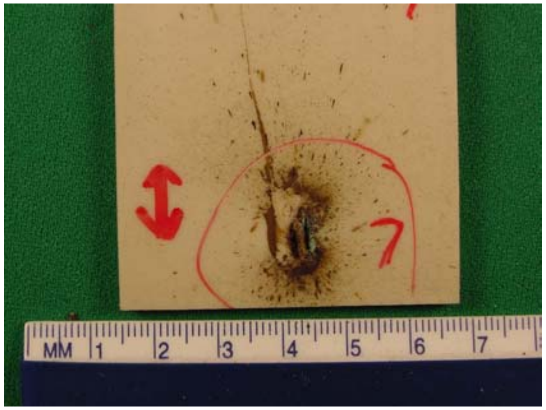


88

Material #7 - 60 Volts



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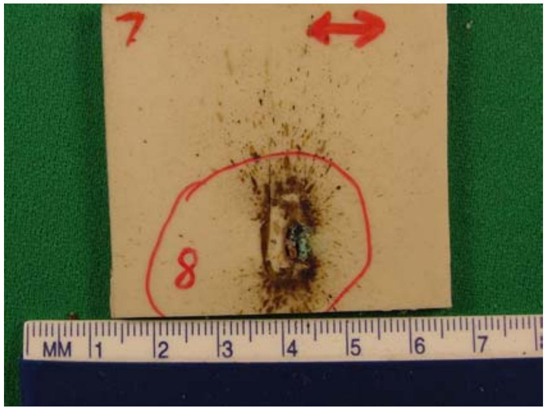

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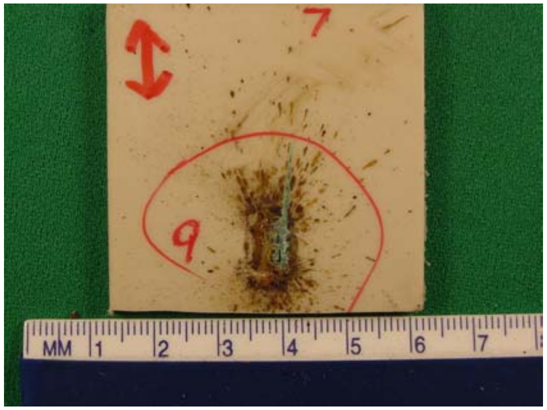
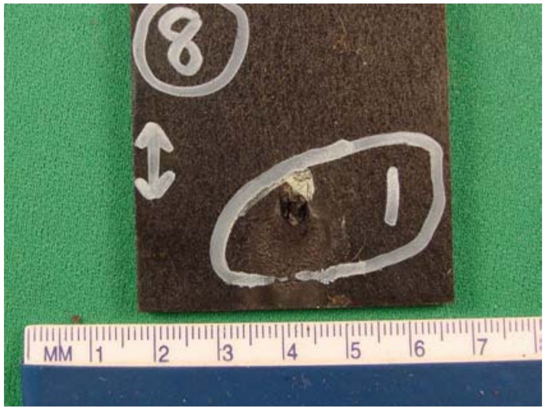


91

Material #8 - 150 Volts



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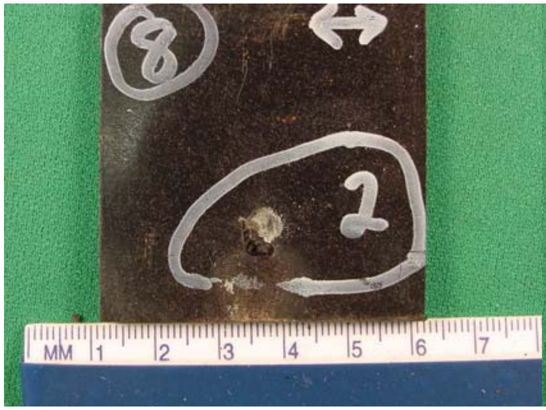

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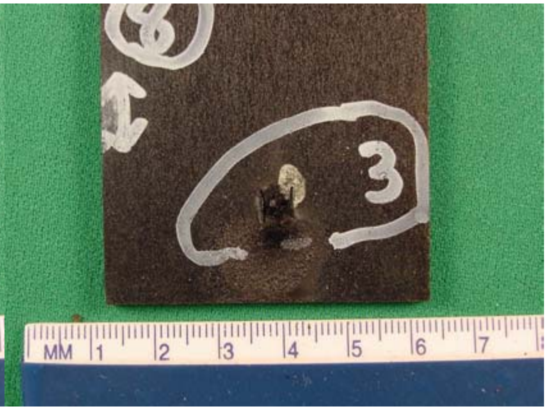
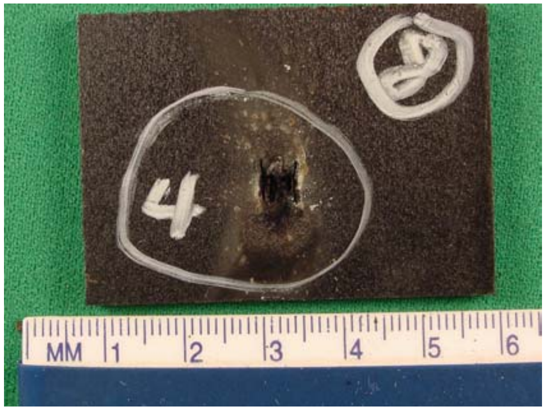


94

Material #8 - 100 Volts



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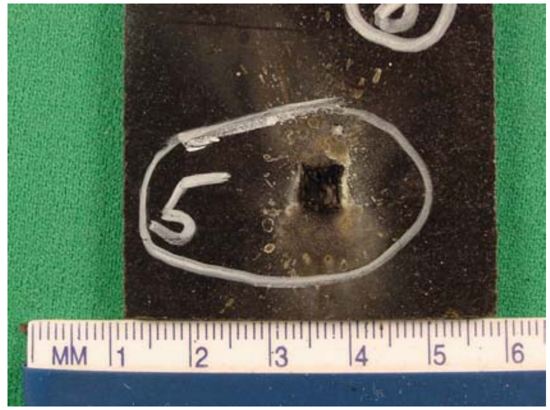

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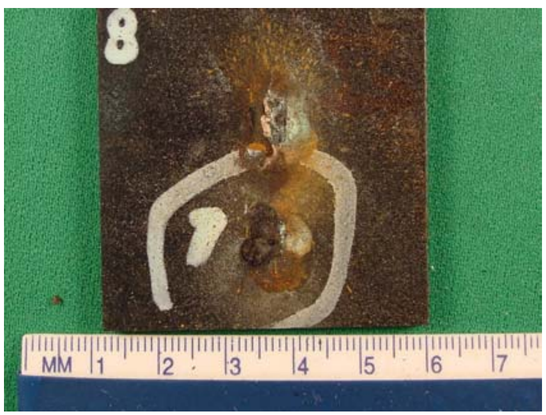
97

Material #8 - 60 Volts

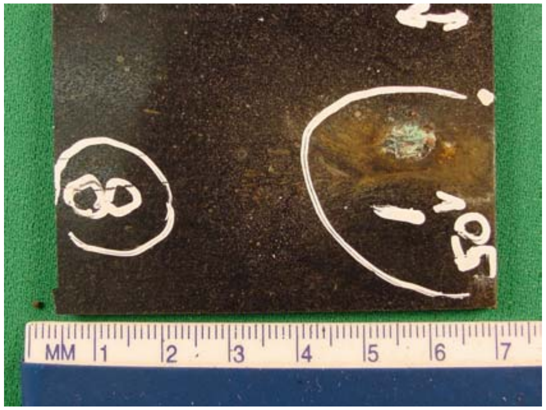


98

99

100

Material #8 - 50 Volts



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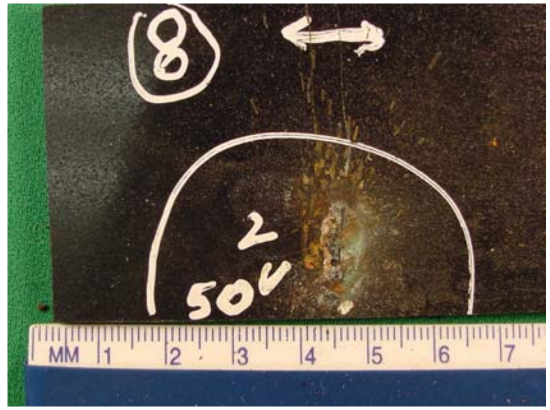

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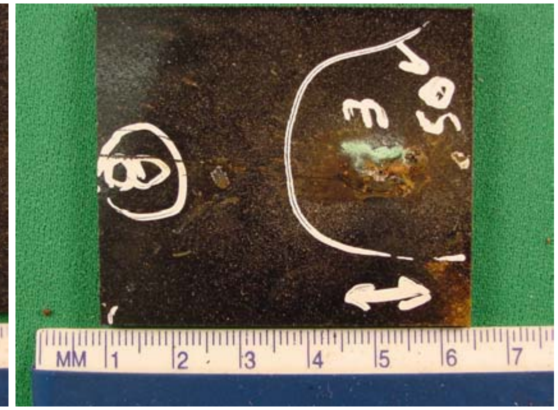
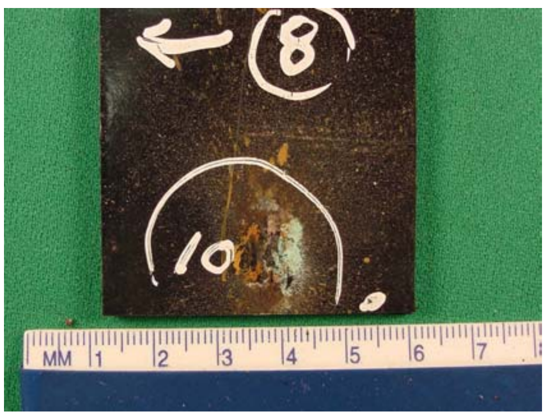


103

Material #8 - 42 Volts



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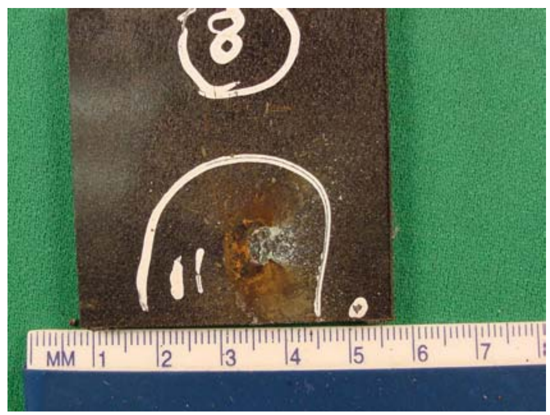

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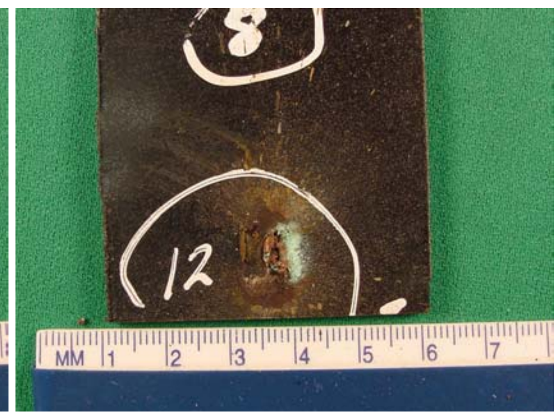
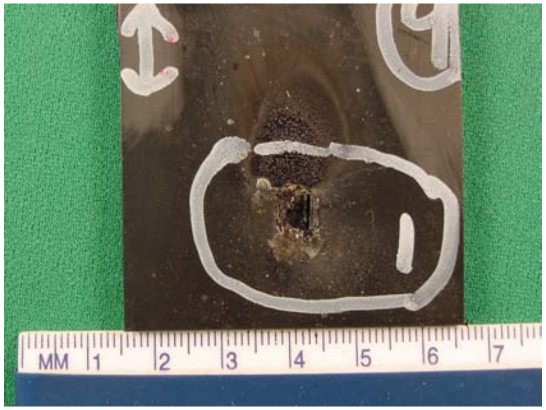


106

Material #9 - 150 Volts



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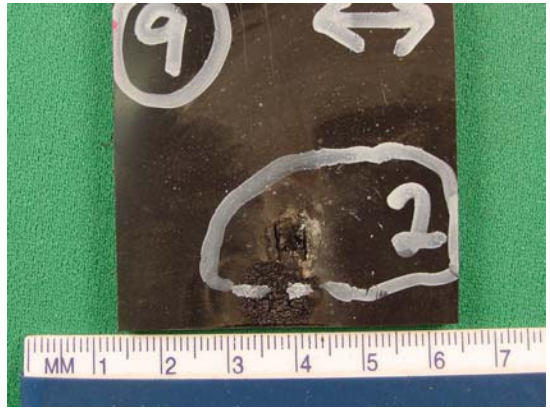
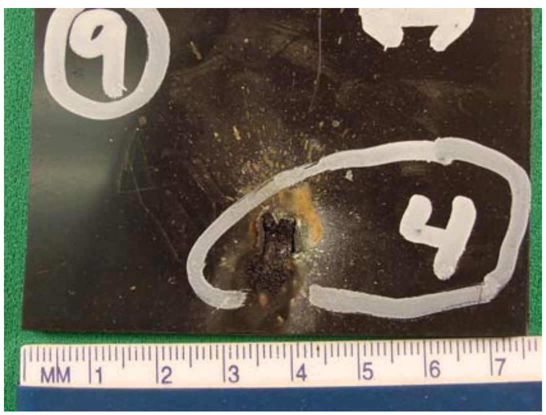


108

109

Material #9 - 100 Volts



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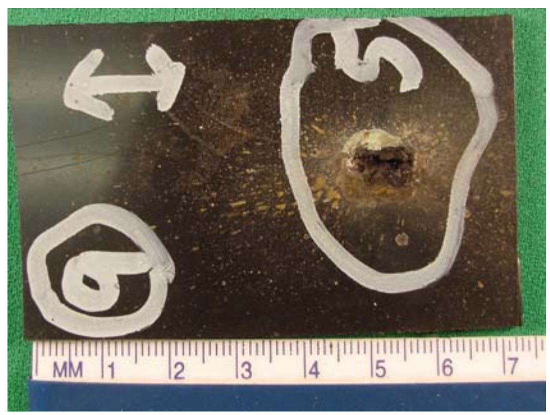

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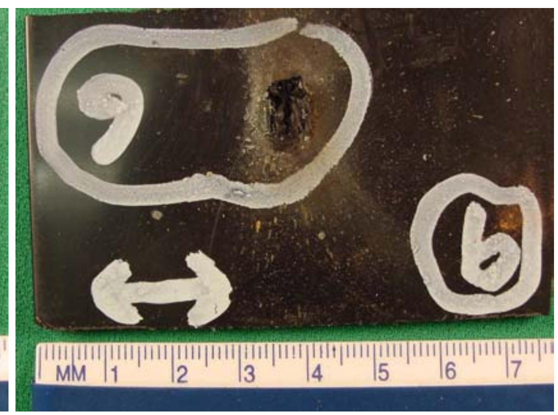
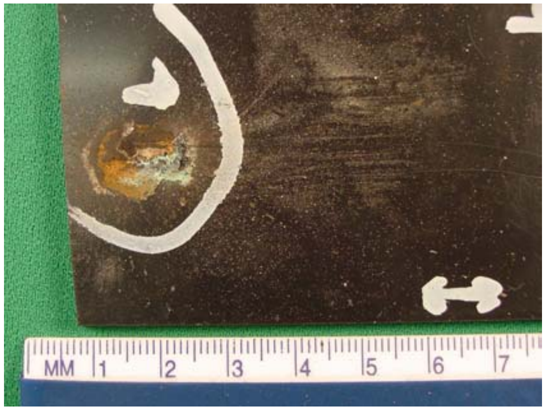


112

Material #9 - 60 Volts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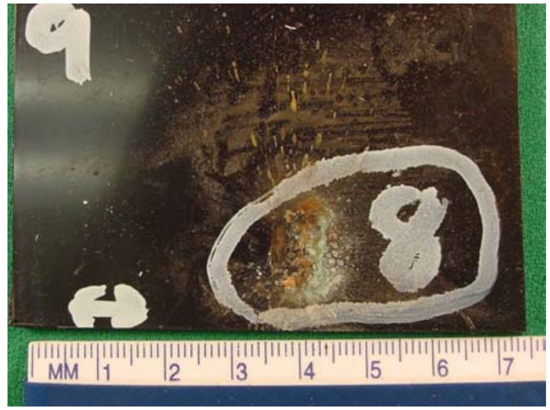
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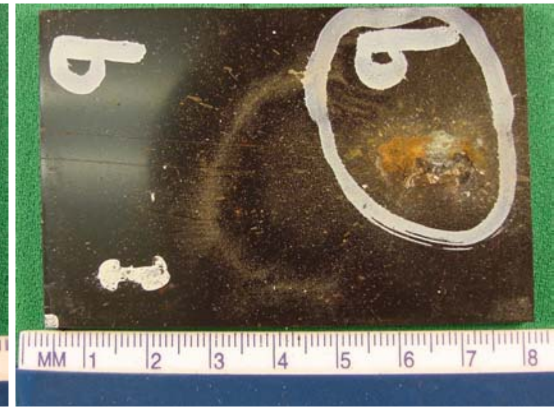
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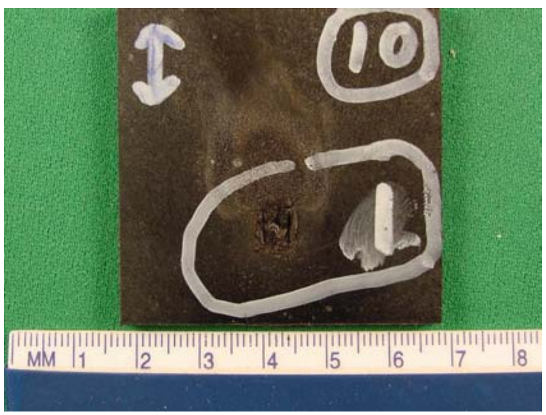
Material #10 - 150 Volts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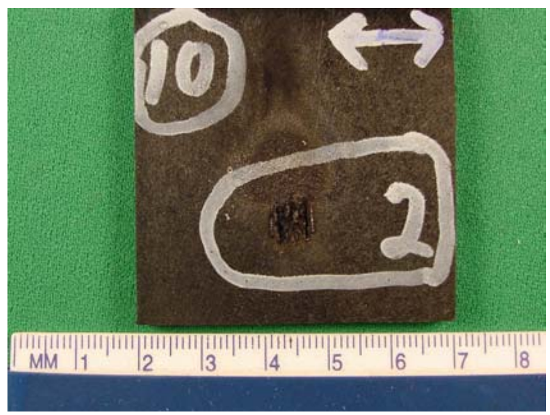
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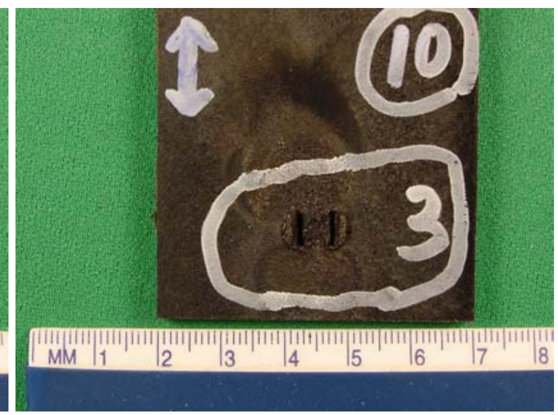
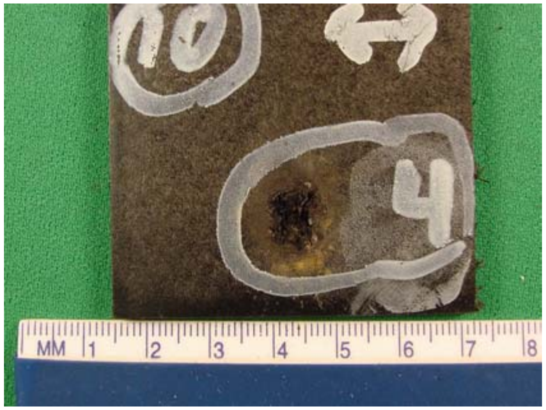

118

Material #10 - 100 Volts



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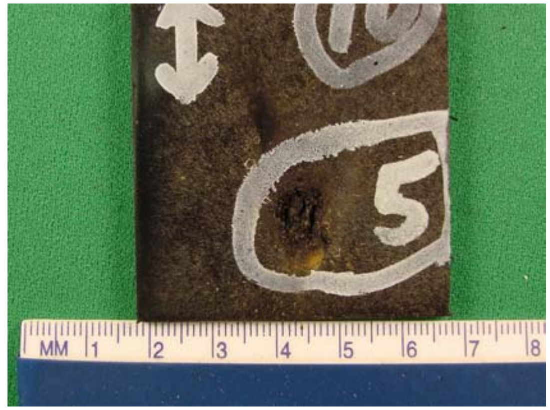

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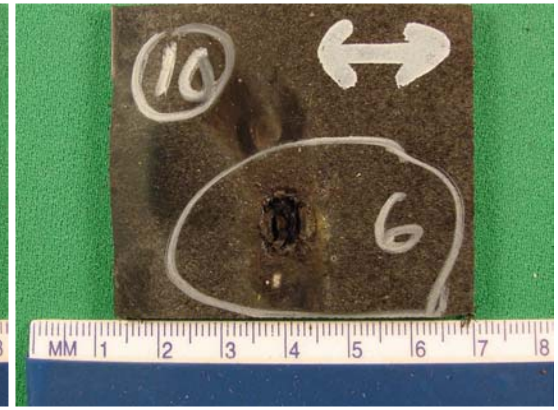

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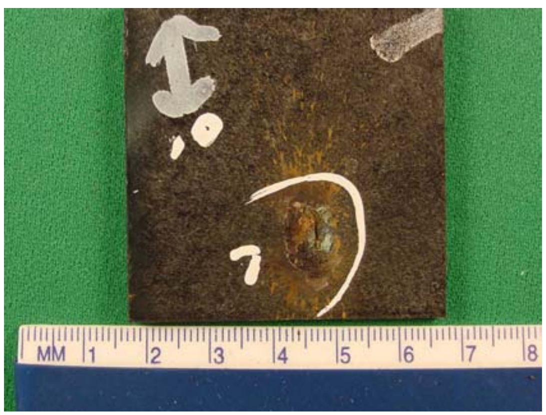
Material #10 - 60 Volts



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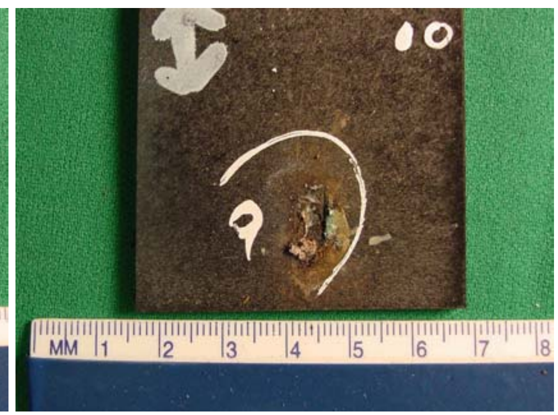
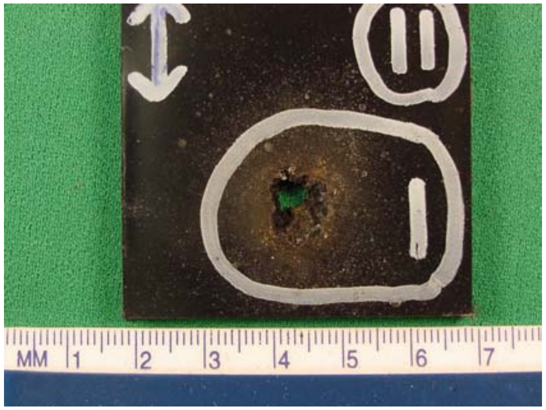
123



124

Material #11 - 150 Volts

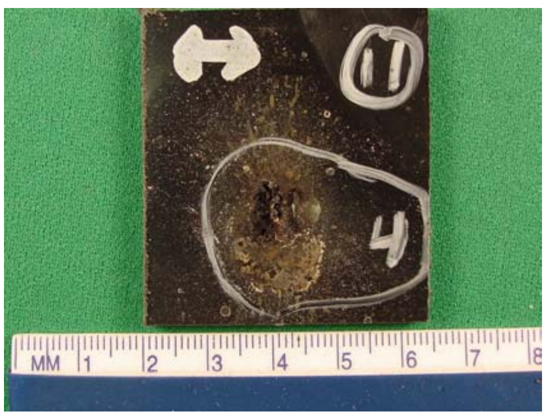


125

126

127

Material #11 - 100 Volts



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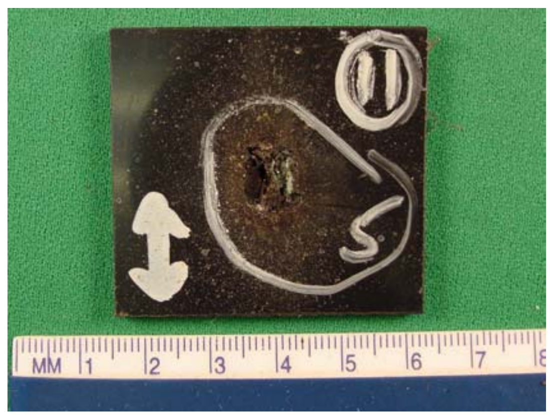

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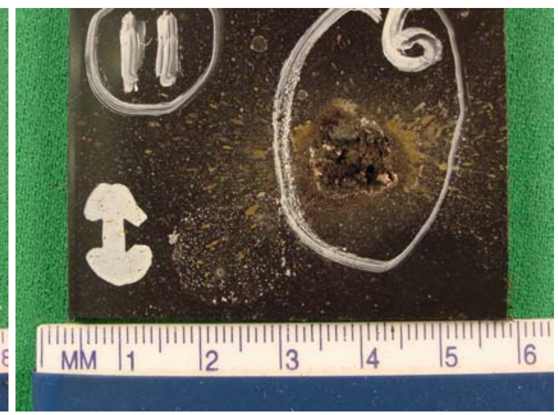

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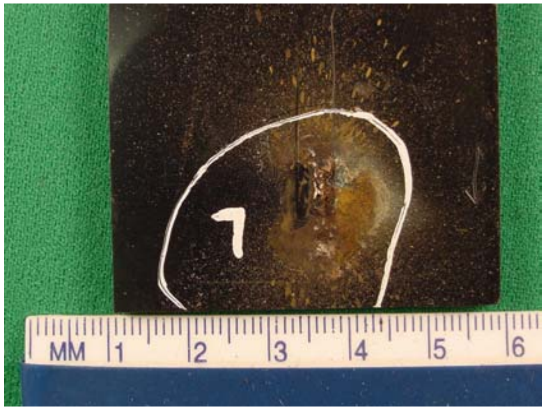
Material #11 - 60 Volts



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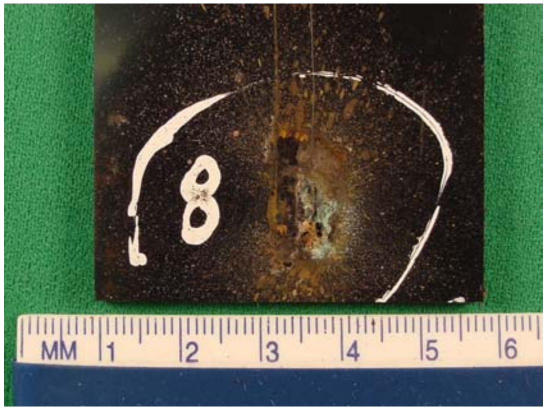

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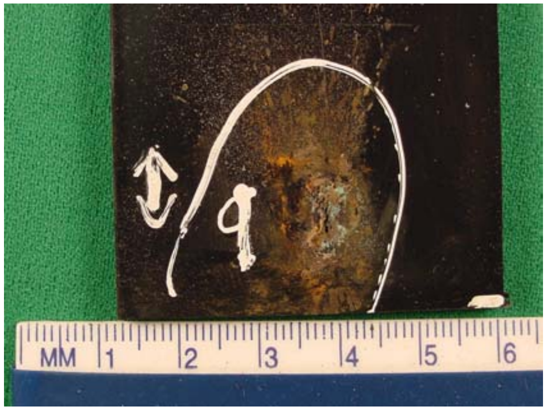
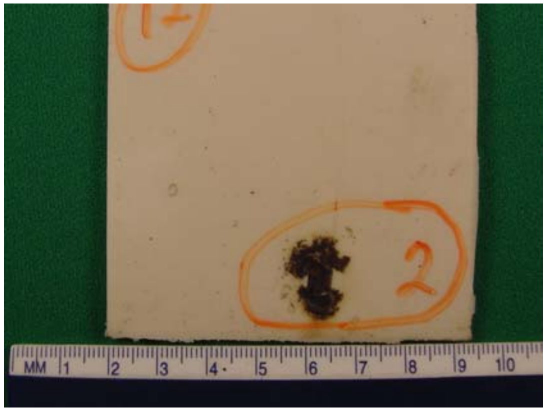


133

Material #12 - 150 Volts

134



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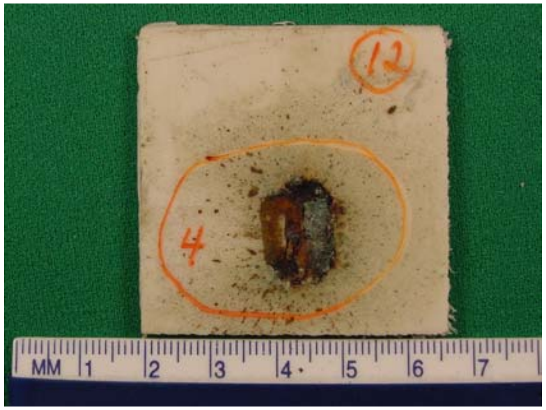
136

Material #12 - 100 Volts



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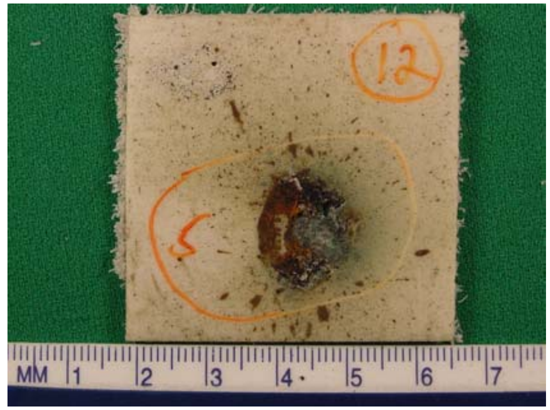

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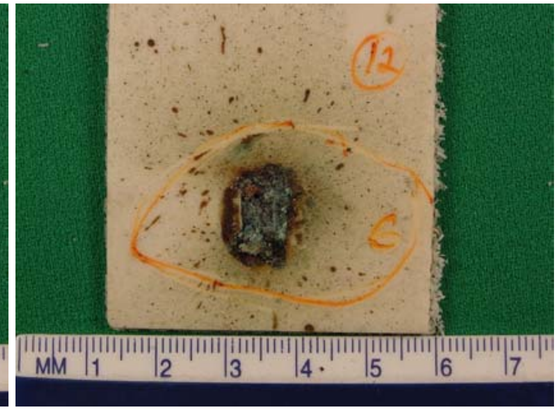

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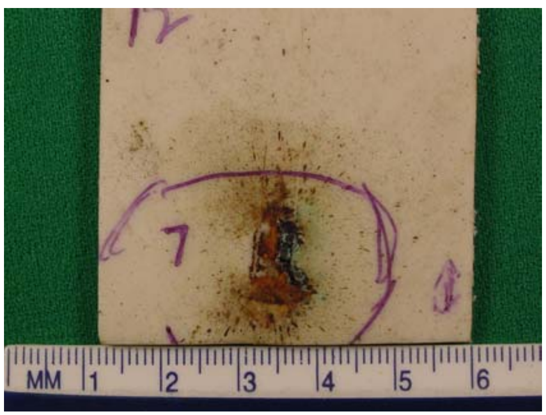
Material #12 - 60 Volts



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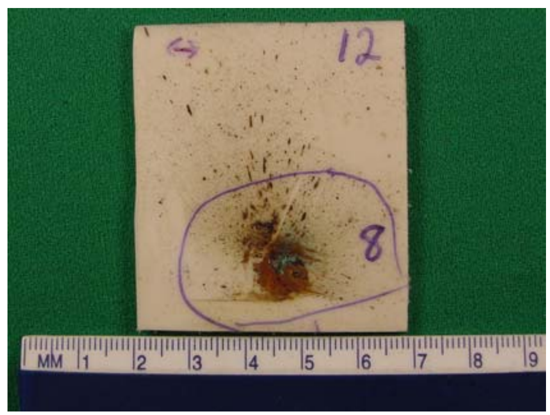

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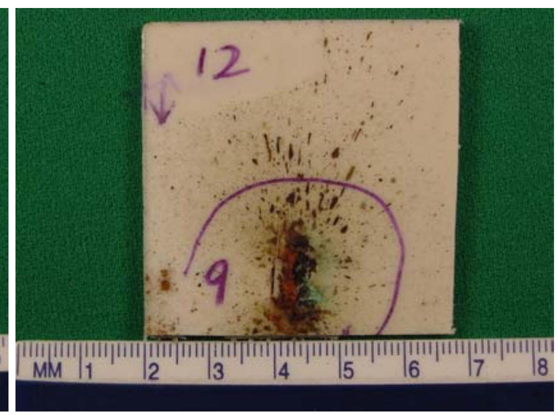

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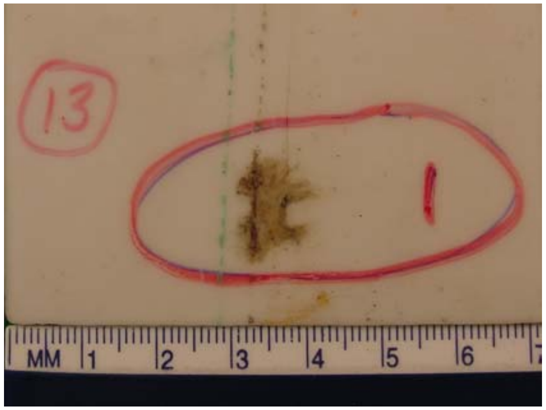
Material #13 - 150 Volts



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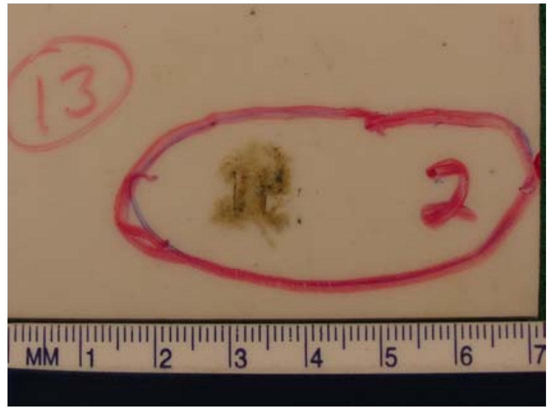

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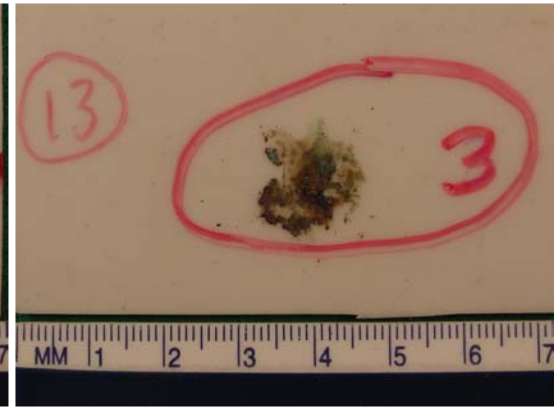
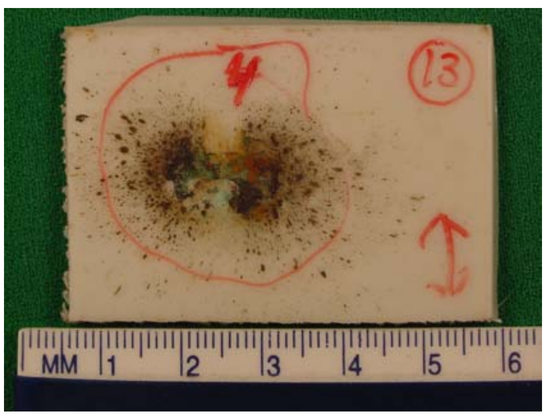


145

Material #13 - 100 Volts



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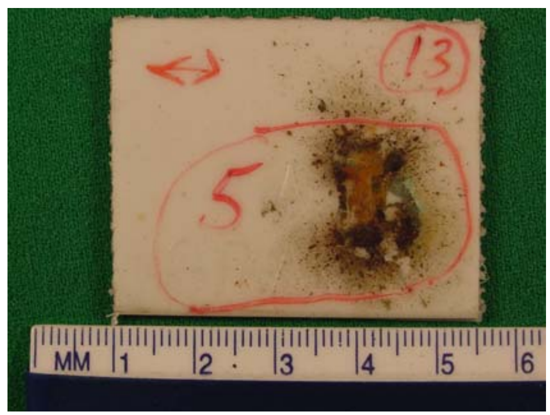

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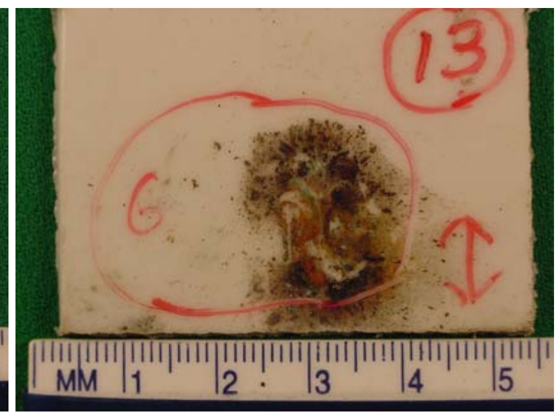
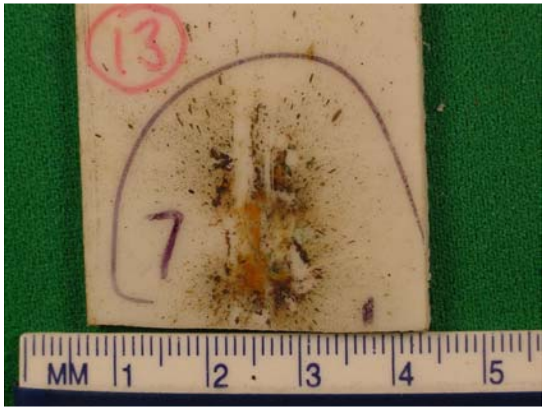


148

Material #13 - 60 Volts



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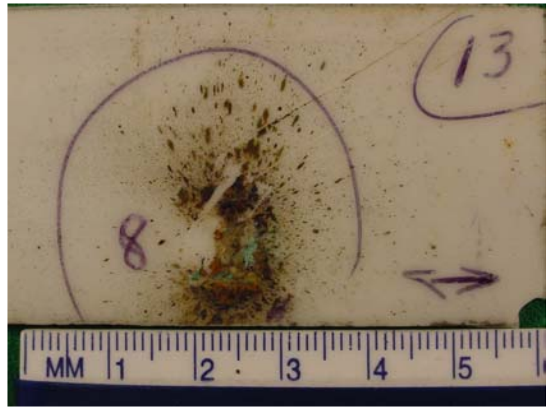

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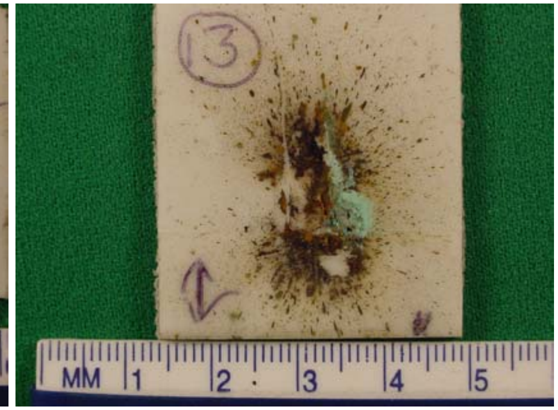
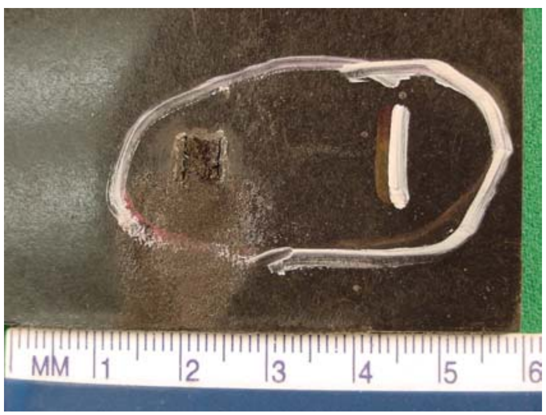


151

Material #14 - 150 Volts



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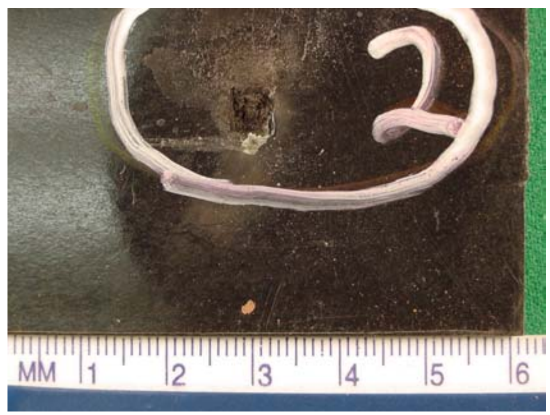


153

154

Material #14 - 100 Volts

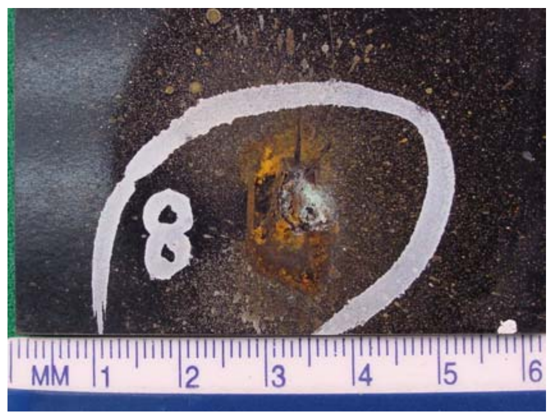
155

156

157

Material #14 - 60 Volts

158



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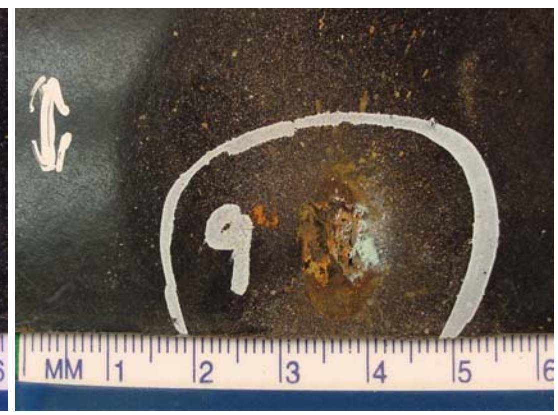
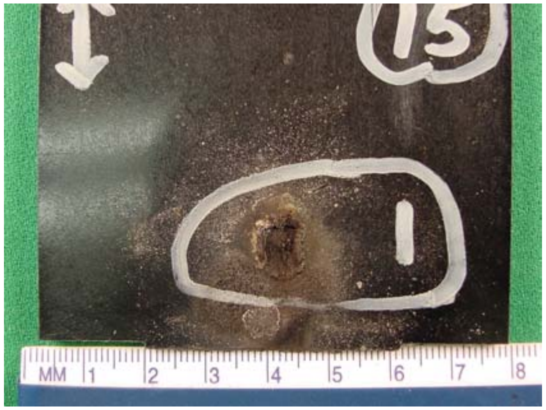


160

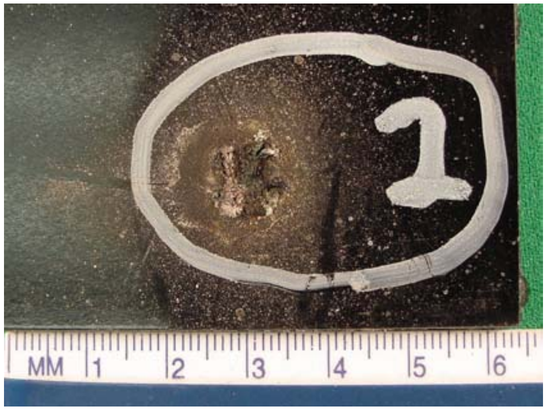
Material #14 - 60 Volts

161 **500 Drop Test**

Material #15 - 150 Volts



162



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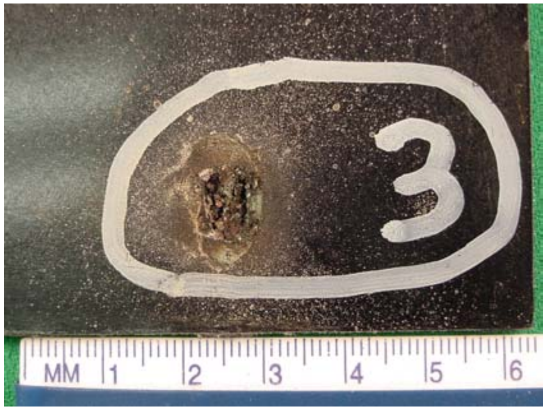
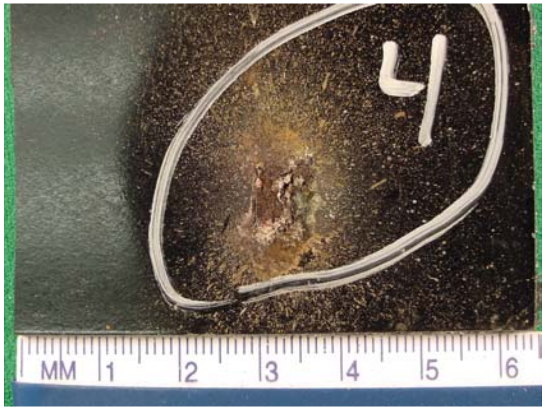
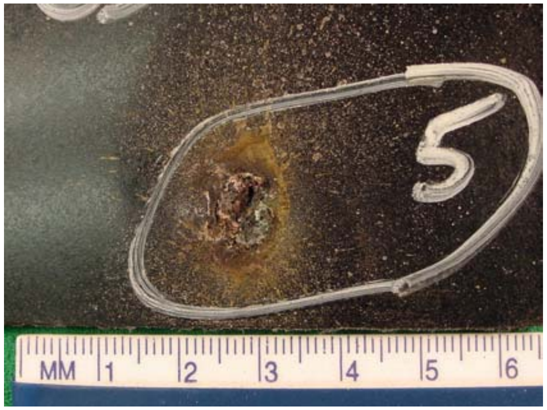


164

Material #15 - 100 Volts



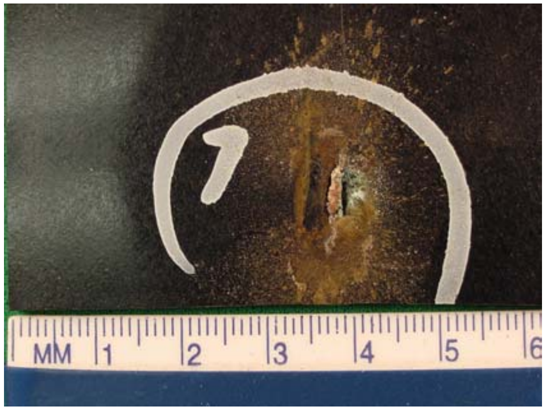
165



166

167

Material #15 - 60 Volts



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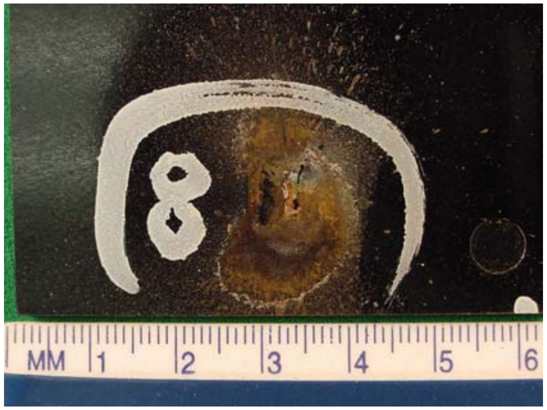

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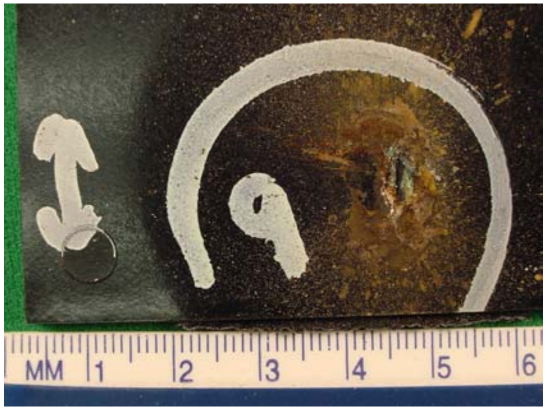
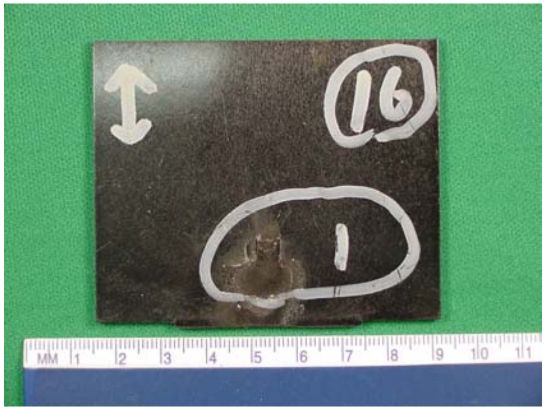
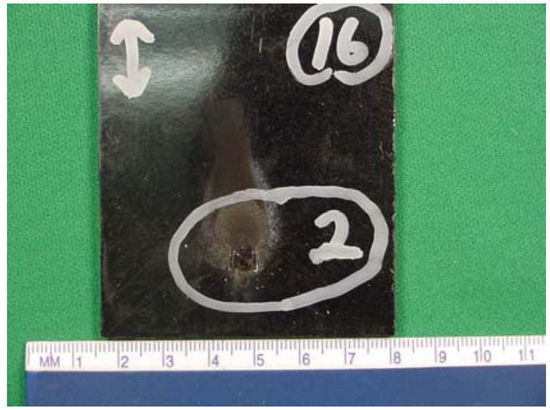


170

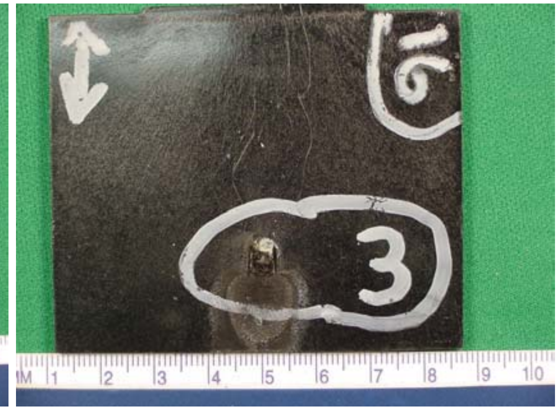
Material #16 - 150 Volts



171

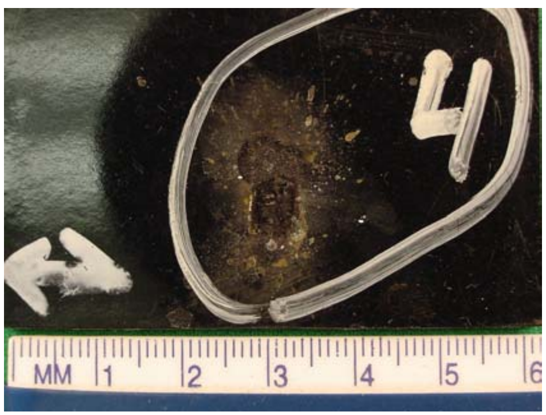


172



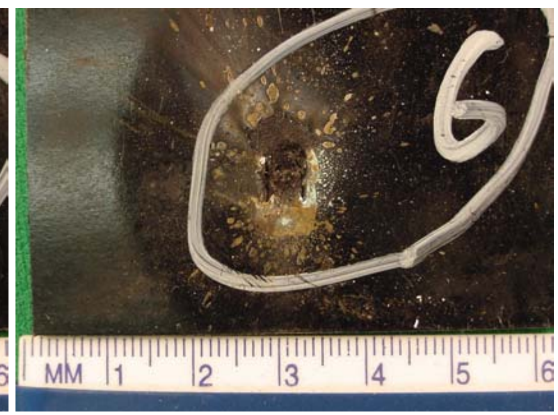
173

Material #16 - 100 Volts



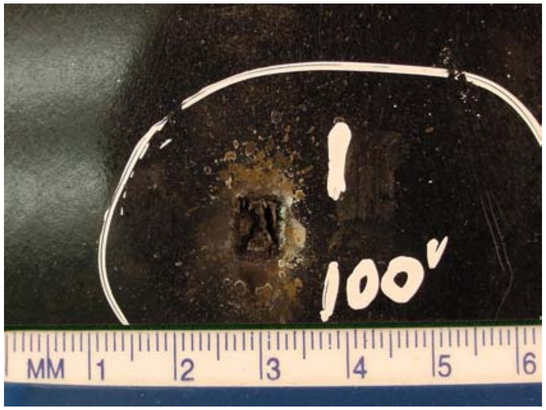
174

175

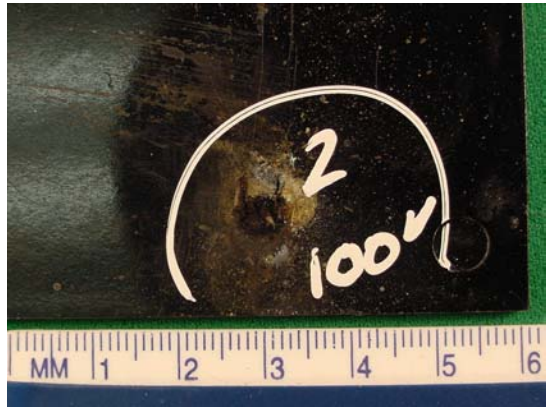


176

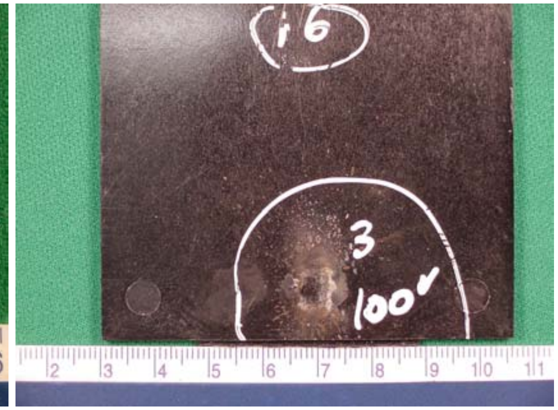
Material #16 - 100 Volts



177

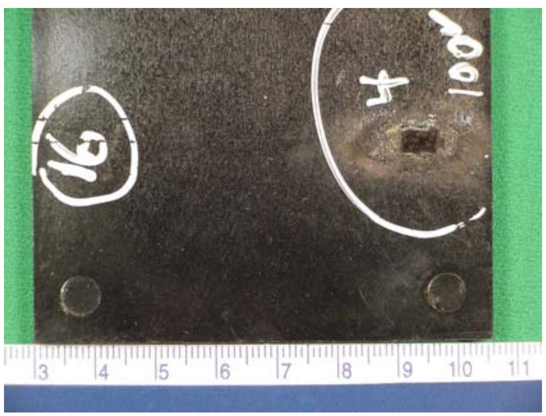


178



179

Material #16 - 100 Volts

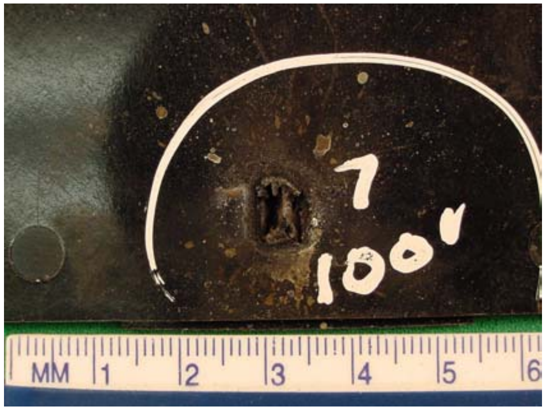


180

181

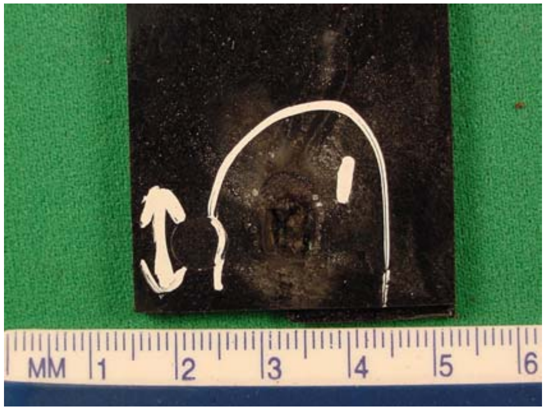
182

Material #16 - 100 Volts

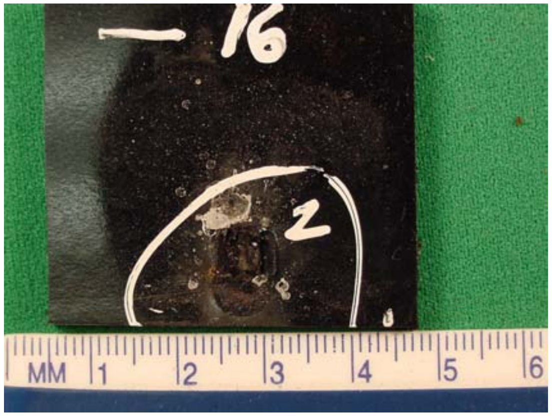


183

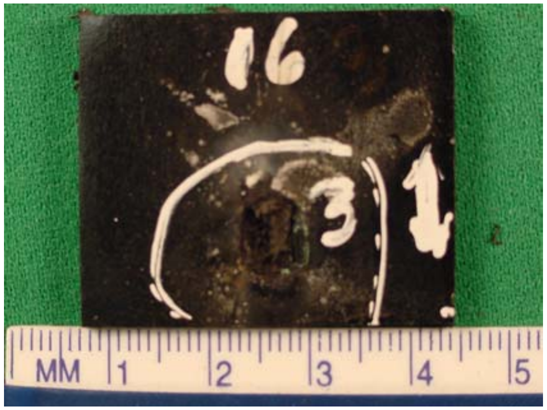
Material #16 - 100 Volts



184 **15% NaCl**

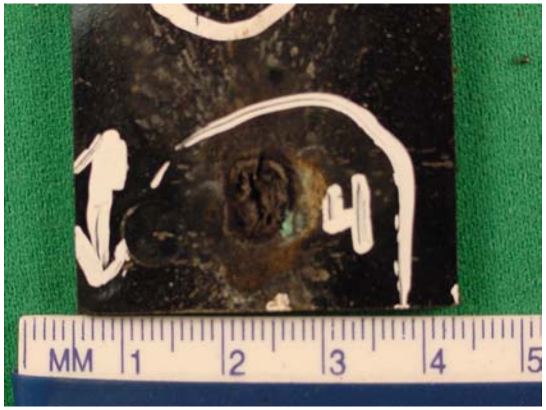


185 **15% NaCl**

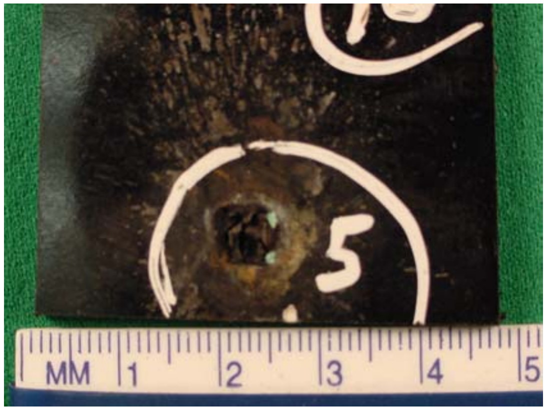


186 **15% NaCl**

Material #16 - 100 Volts

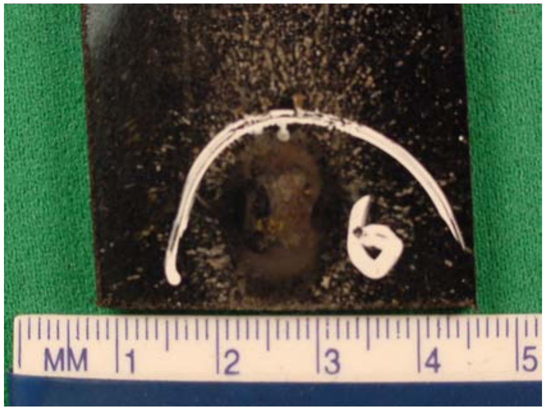


187 1% NaCl



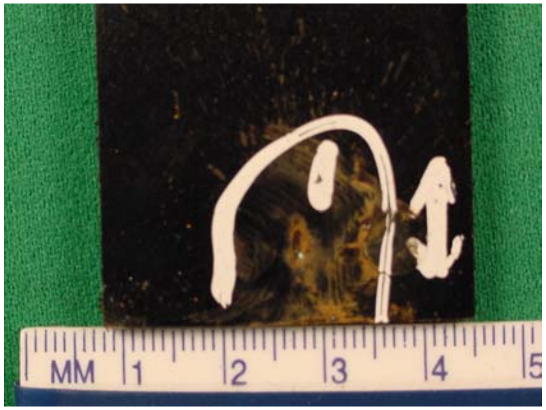
188 1% NaCl

Material #16 - 100 Volts

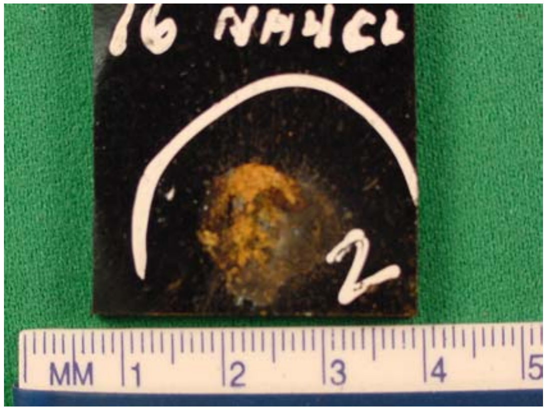


189 **0.2% NaCl**

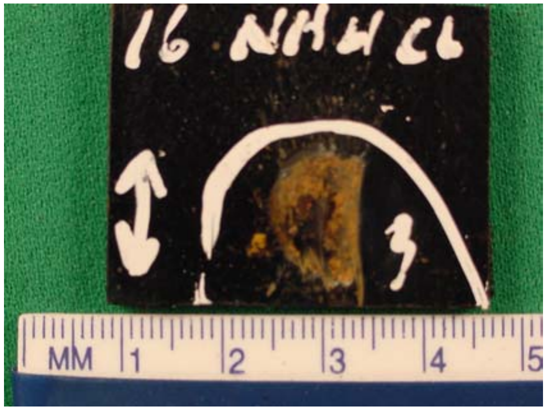
Material #16 - 100 Volts



190 **0.1% NH4Cl**

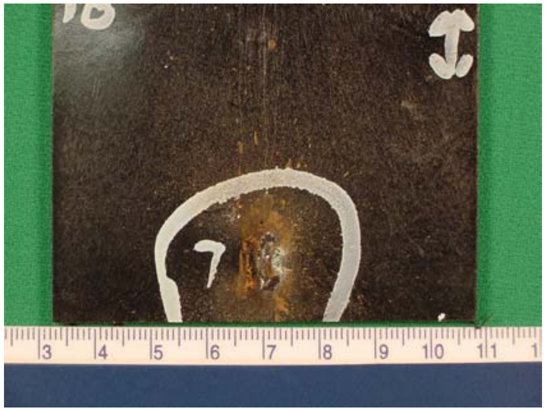


191 **0.1% NH4Cl**

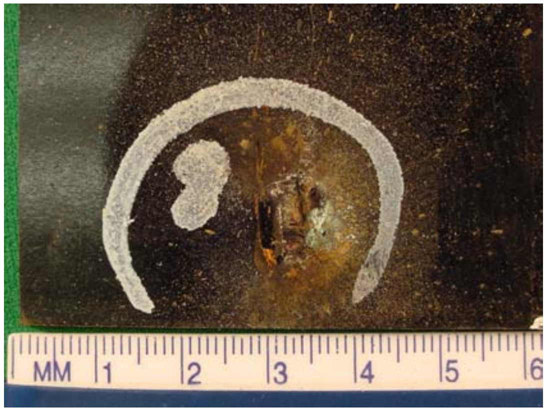


192 **0.1% NH4Cl**

Material #16 - 60 Volts



193



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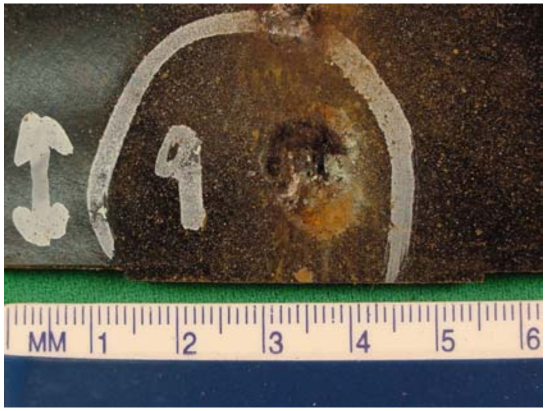
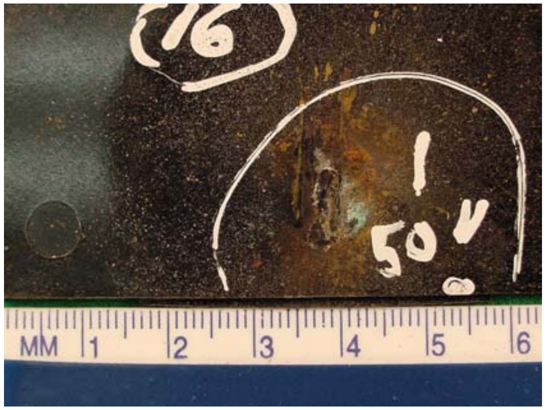
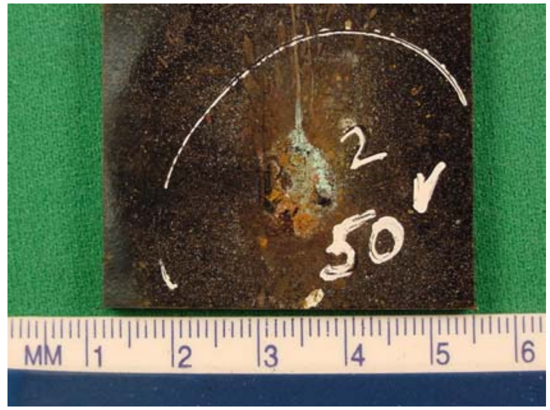


195

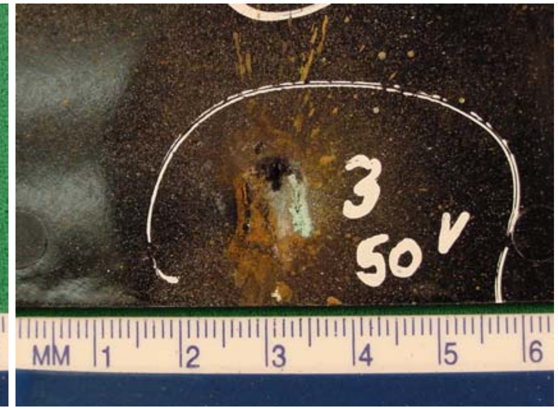
Material #16 - 50 Volts



196

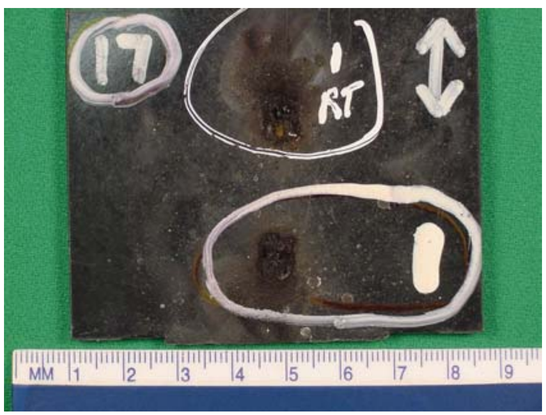


197

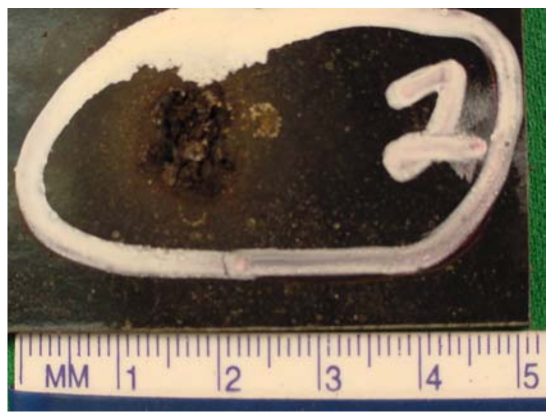


198

Material #17 - 150 Volts



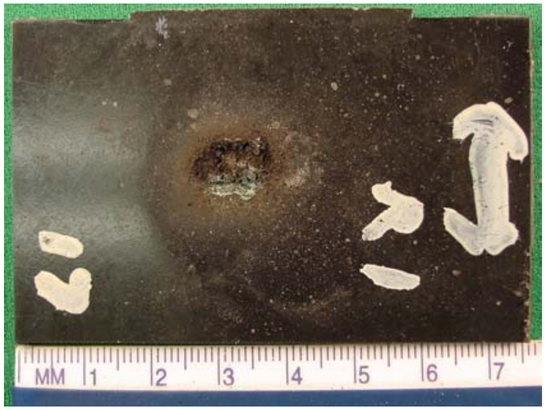
199



200

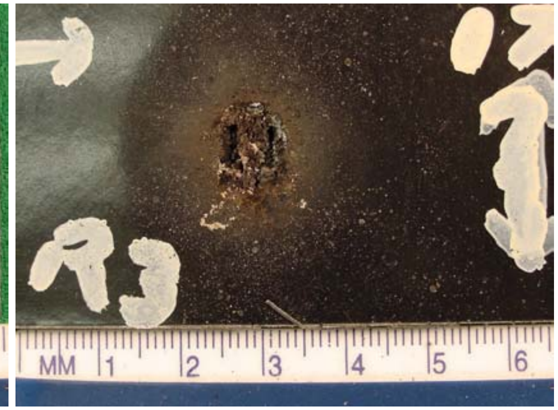
201

Material #17 - 150 Volts



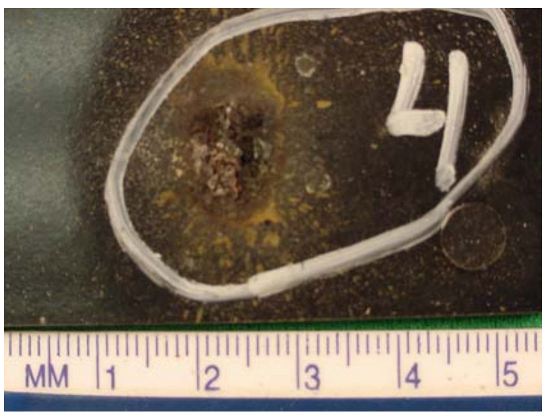
202

203

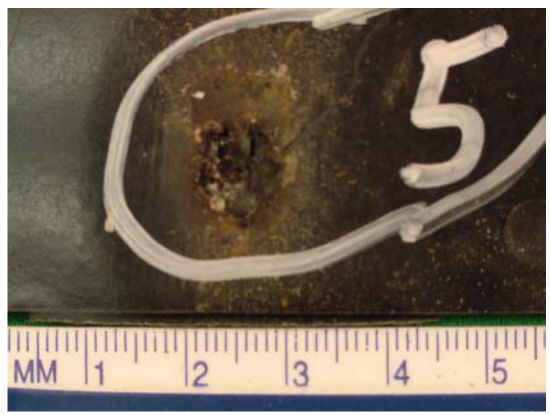


204

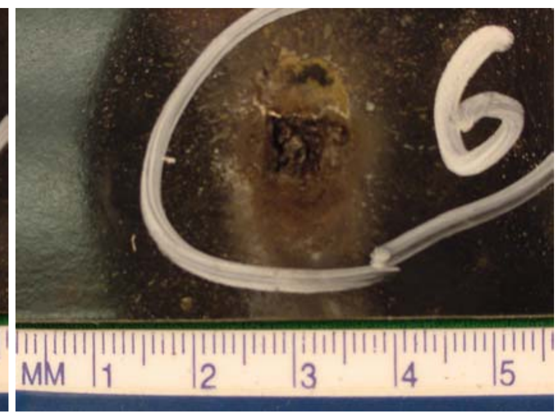
Material #17 - 100 Volts



205

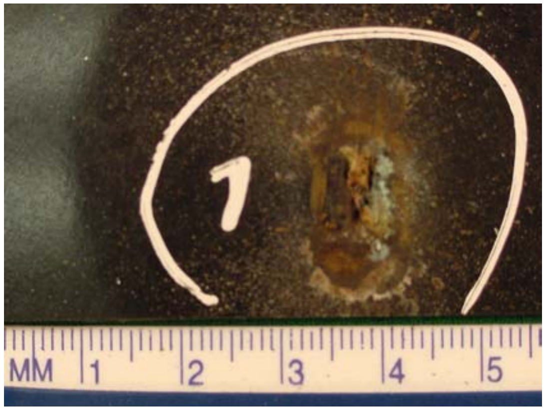


206

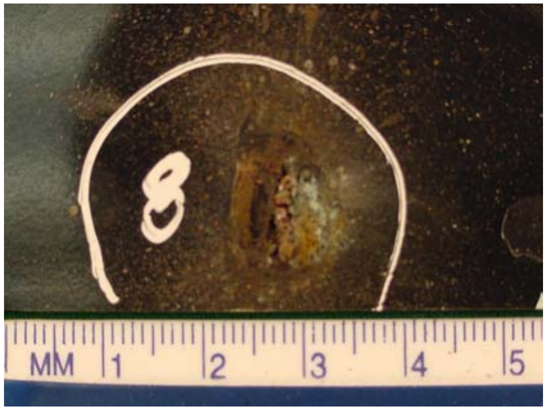


207

Material #17 - 60 Volts



208



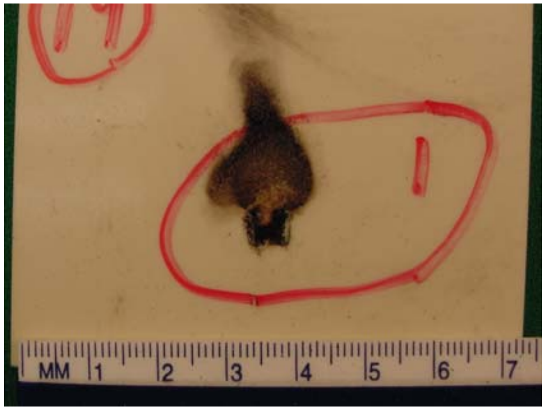
209

210

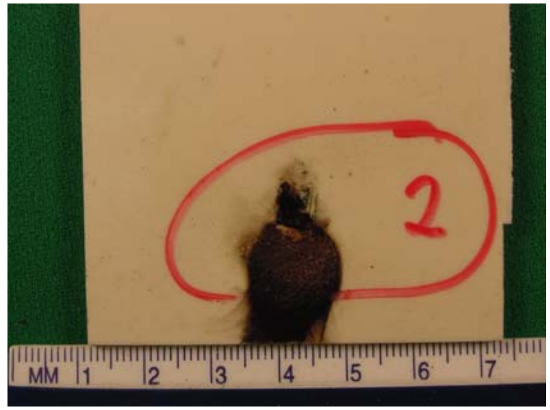
Material #18 -

Deleted by Request

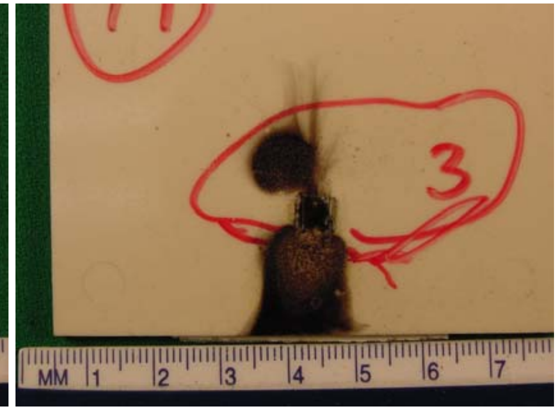
Material #19 - 150 Volts



211

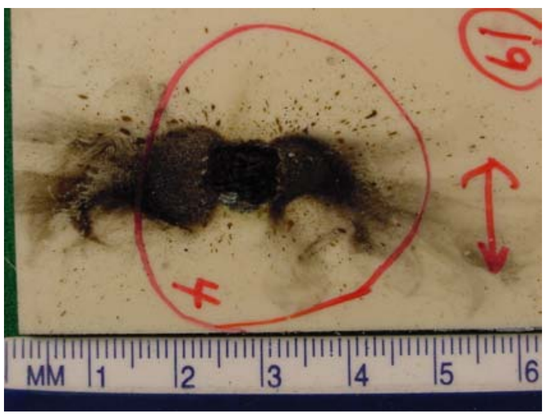


212

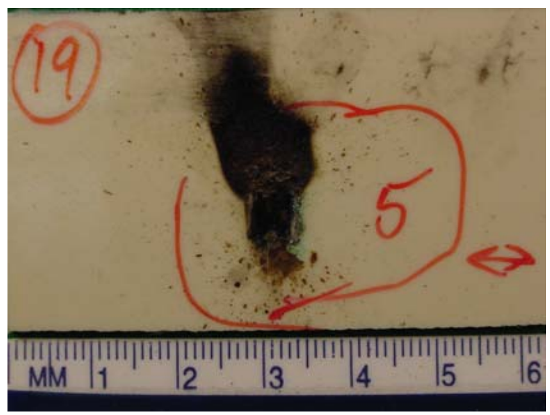


213

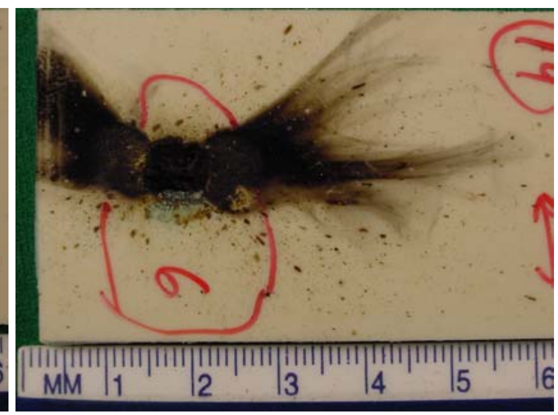
Material #19 - 100 Volts



214

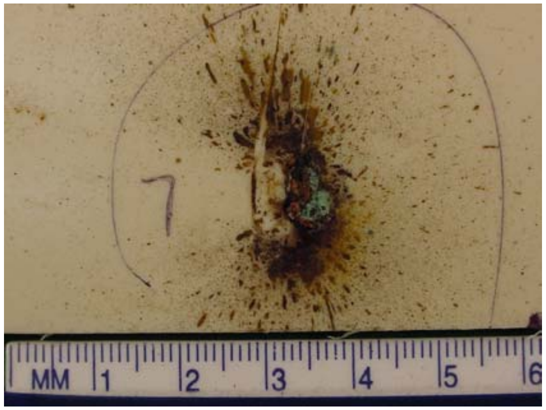


215

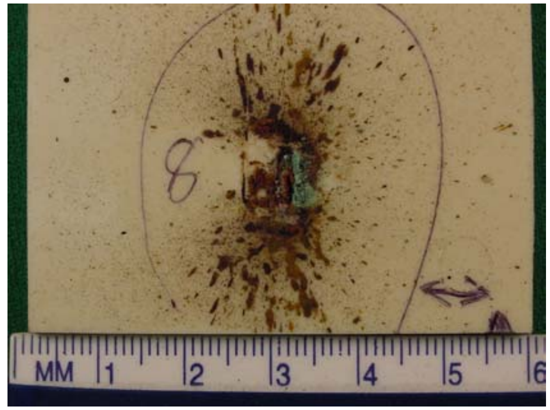


216

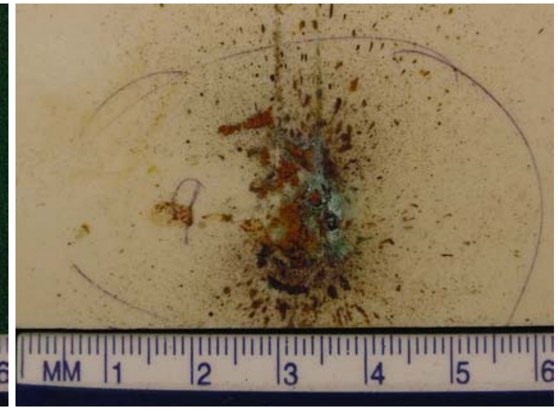
Material #19 - 60 Volts



217

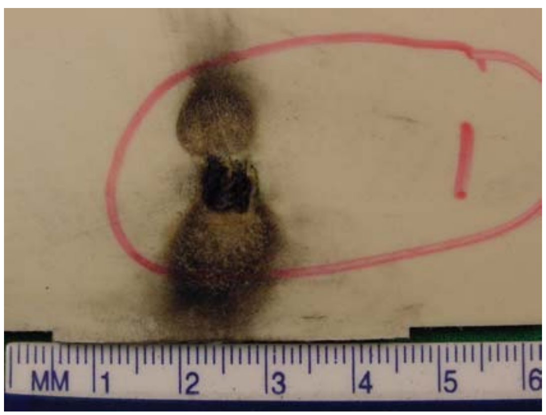


218

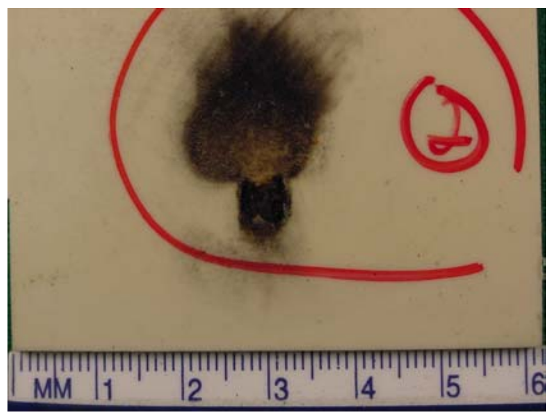


219

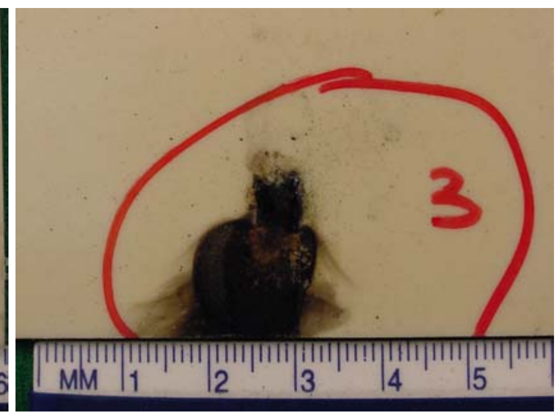
Material #20 - 150 Volts



220

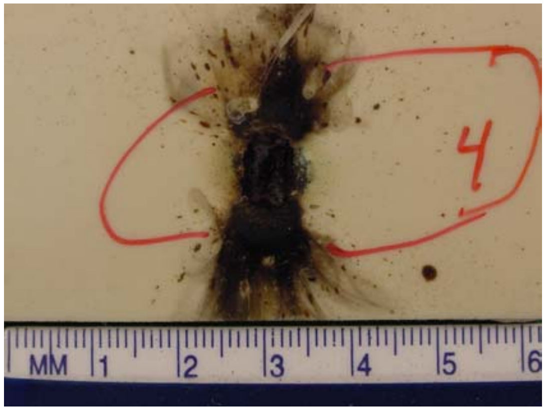


221

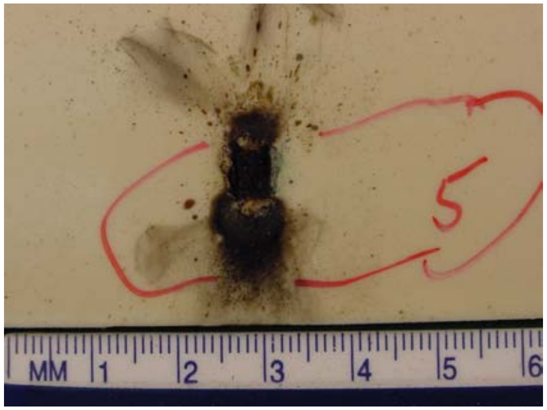


222

Material #20 - 100 Volts

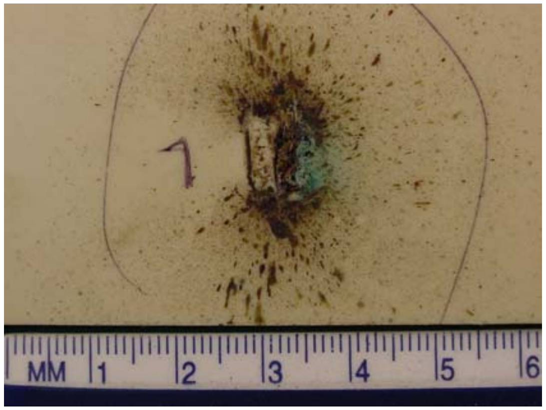


223

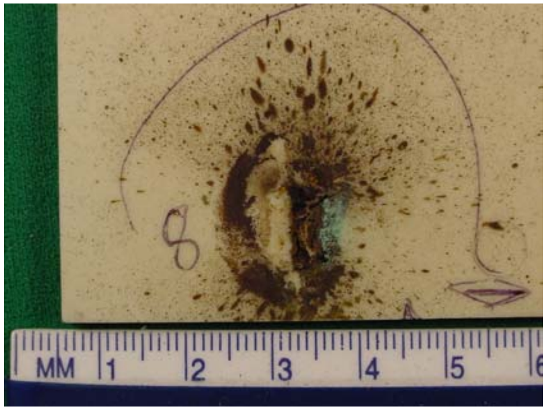


224

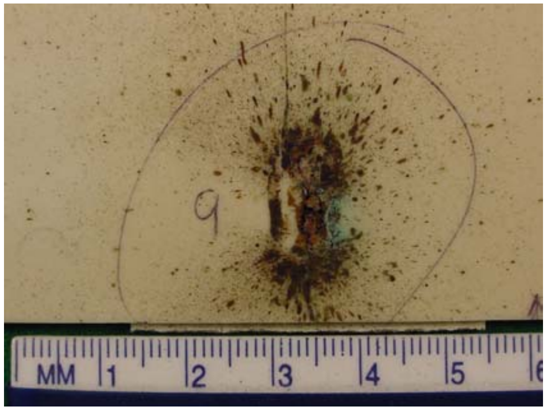
Material #20 - 60 Volts



225

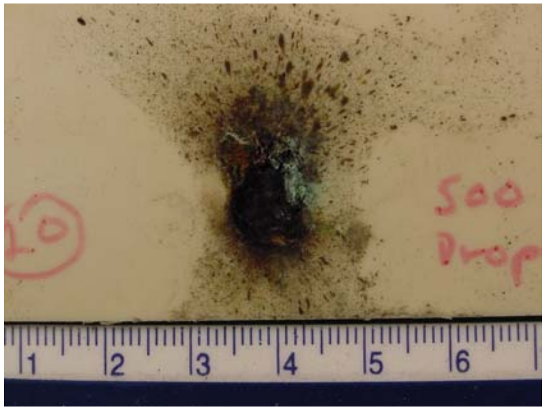


226



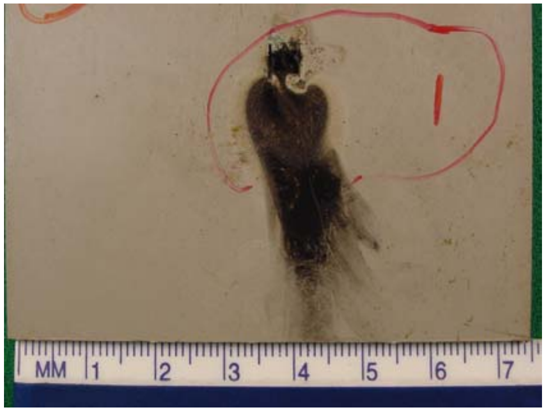
227

Material #20 - 60 Volts

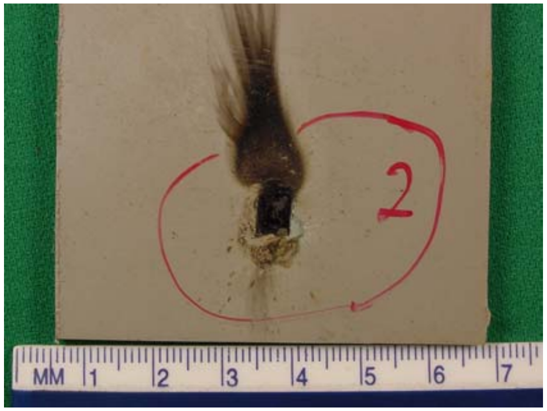


228 **500 Drop Test**

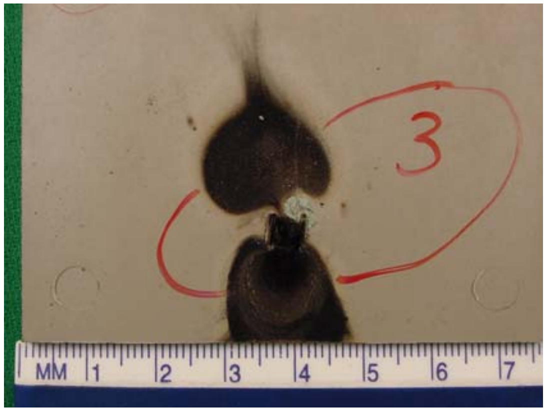
Material #21 - 150 Volts



229

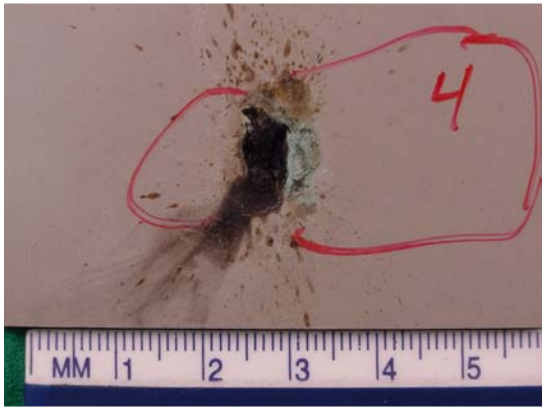


230

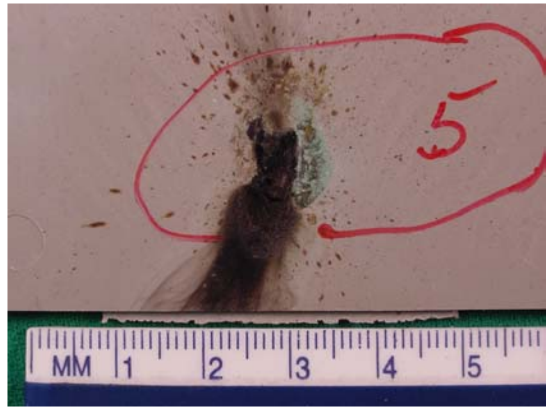


231

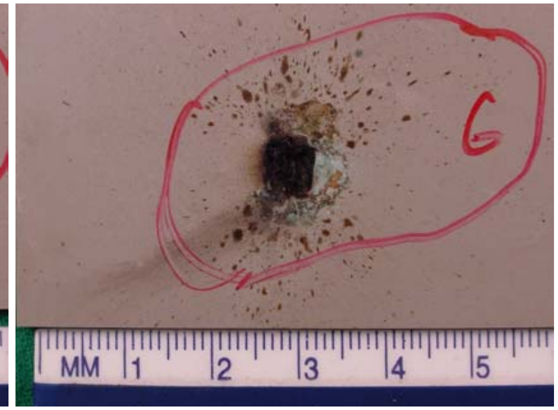
Material #21 - 100 Volts



232

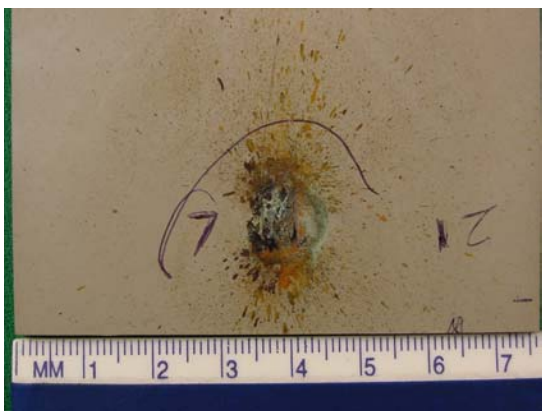


233



234

Material #21 - 60 Volts



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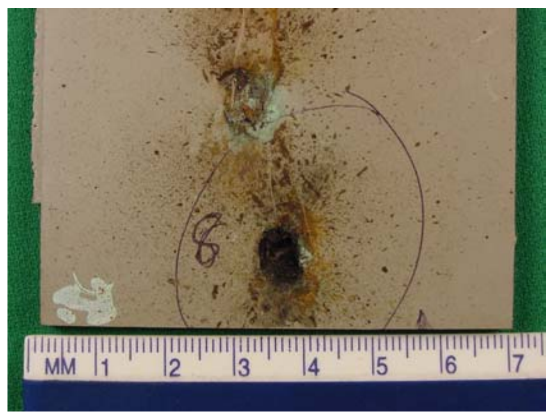
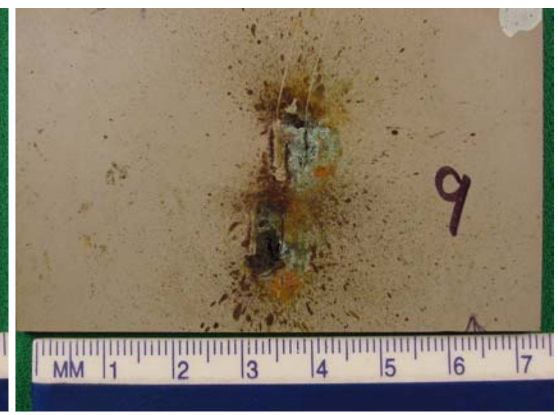
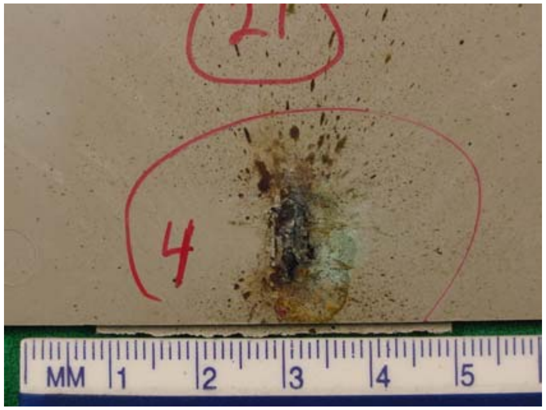


236

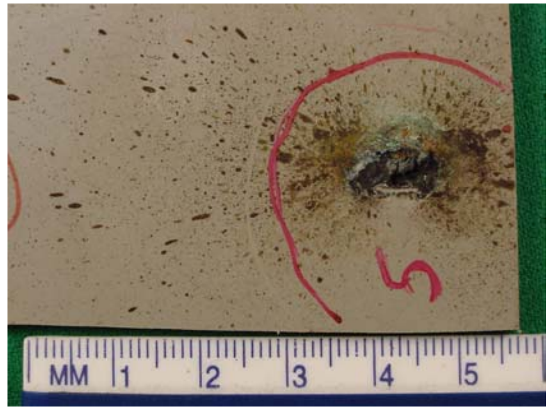


237

Material #21 - 60 Volts



238



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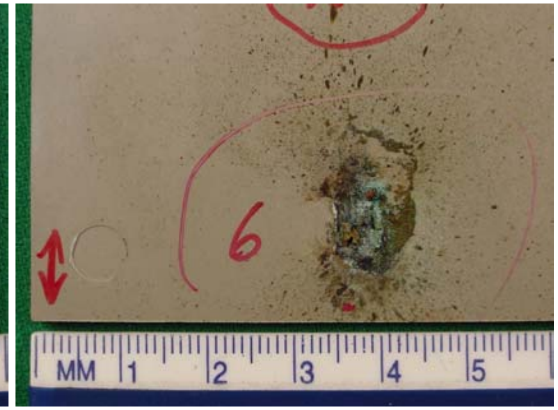
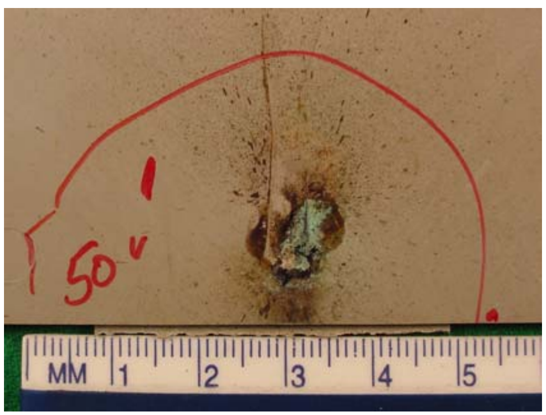
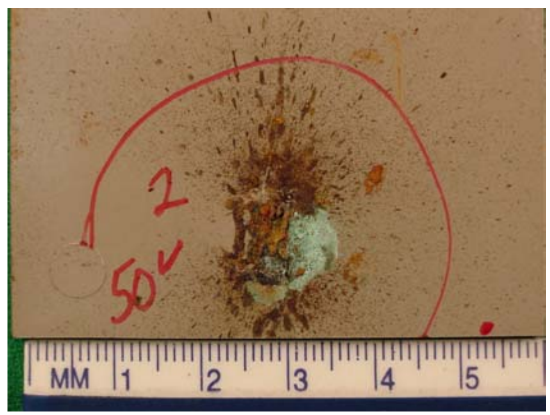


240

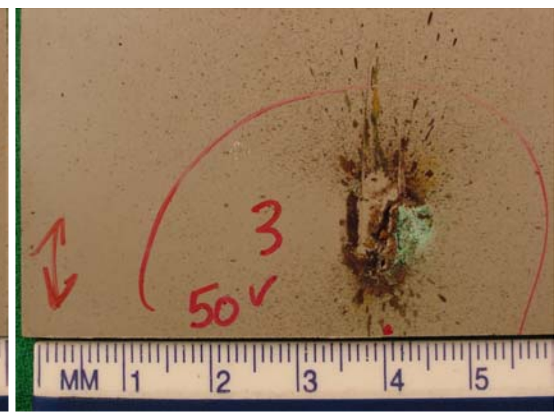
Material #21 - 50 Volts



241

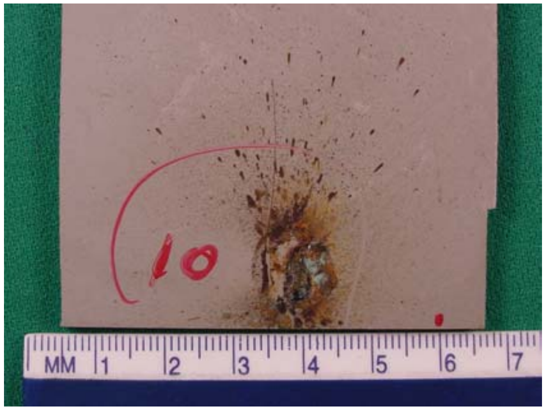


242

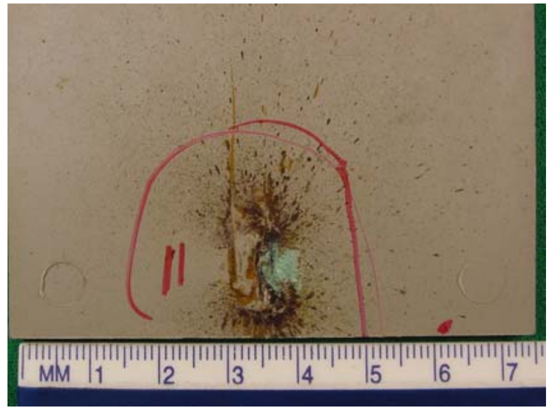


243

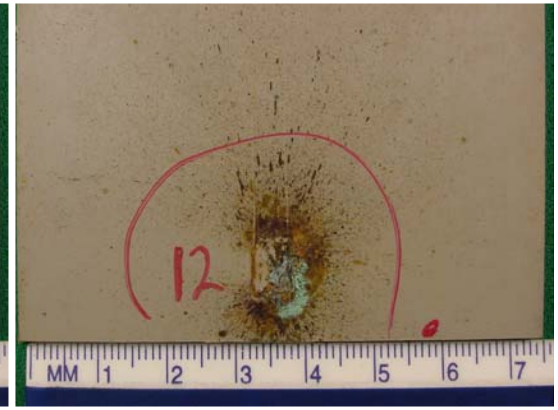
Material #21 - 42 Volts



244

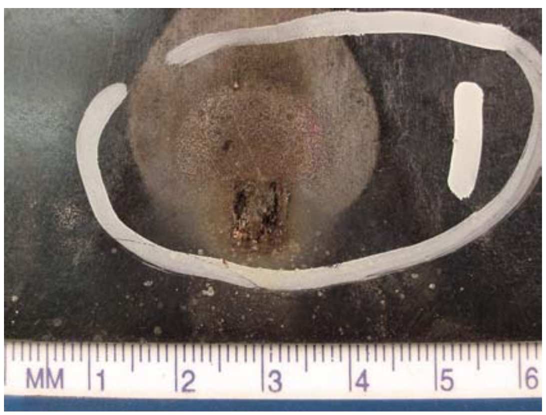


245

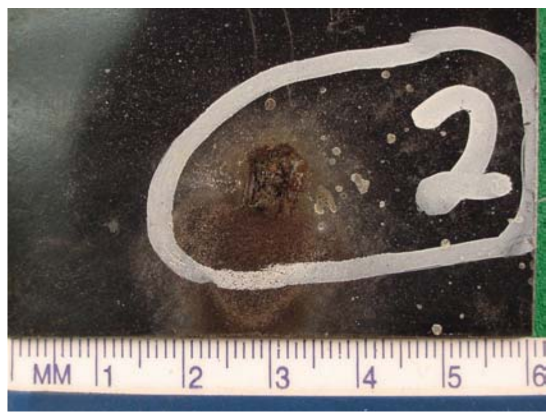


246

Material #22 - 150 Volts



247

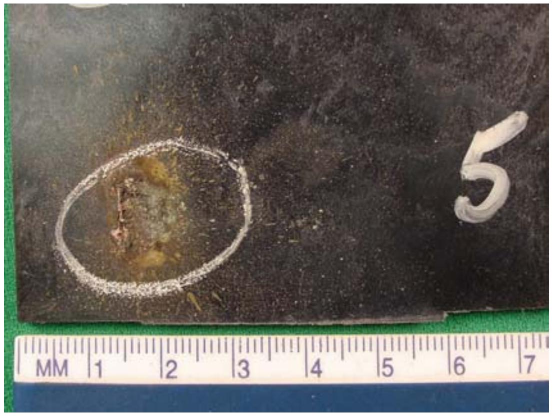


248

249

Material #22 - 100 Volts

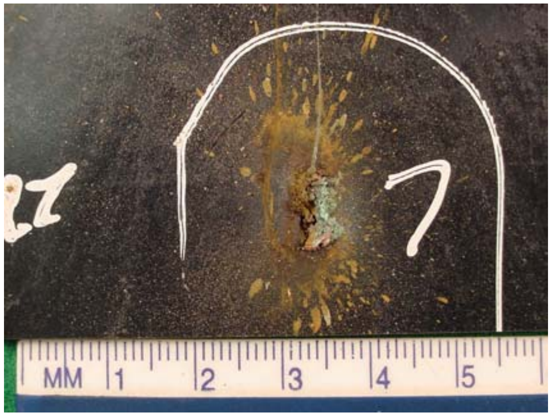
250



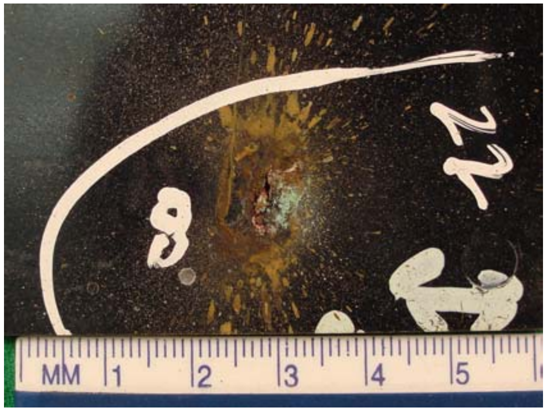
251

252

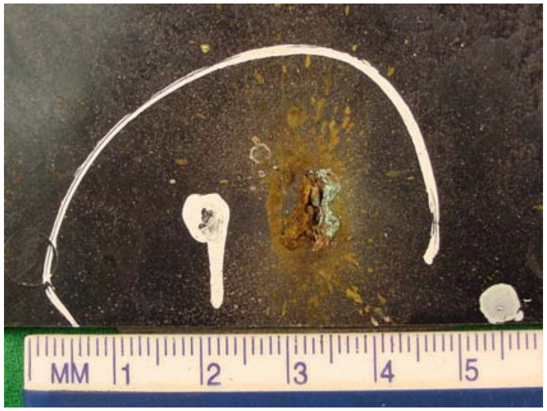
Material #22 - 60 Volts



253



254

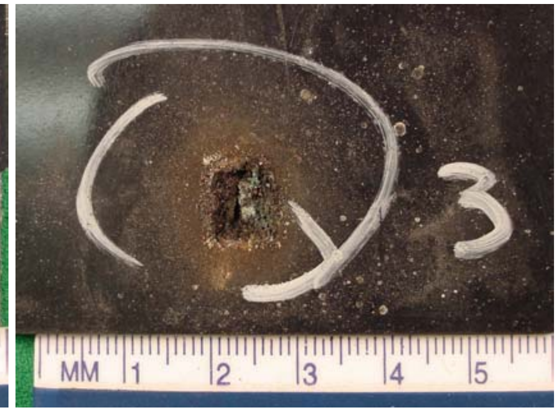


255

Material #23 - 150 Volts

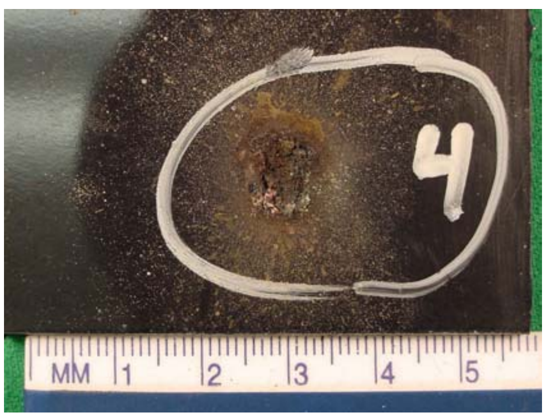
256

257

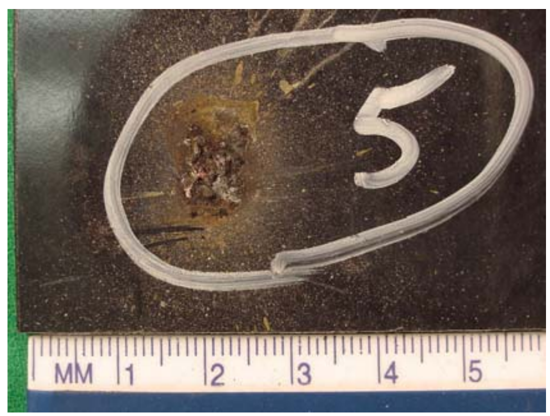


258

Material #23 - 100 Volts



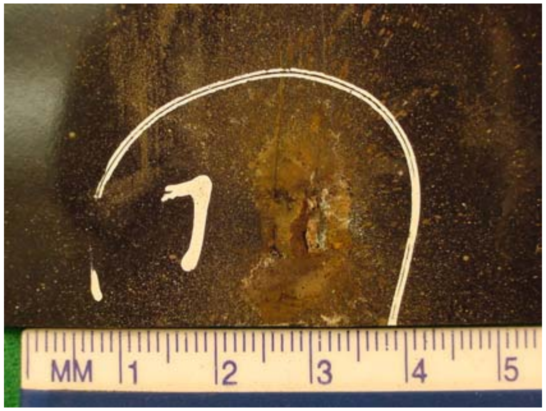
259



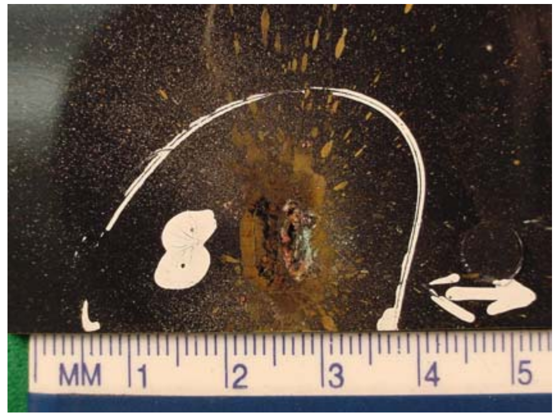
260

261

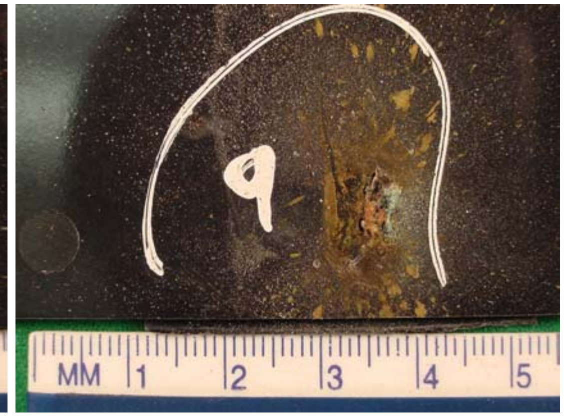
Material #23 - 60 Volts



262

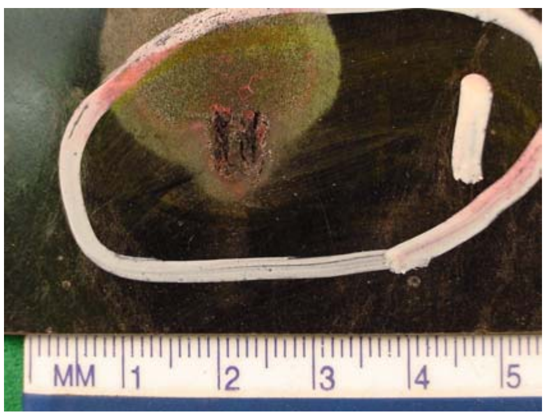


263

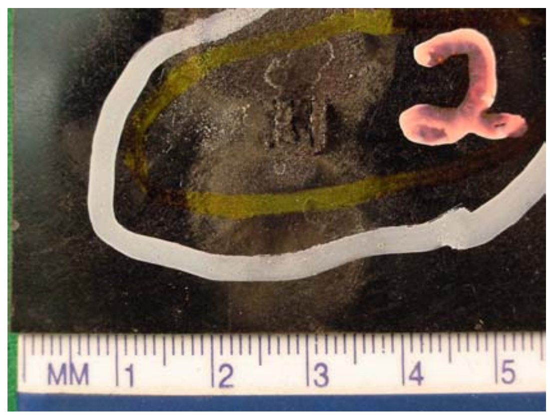


264

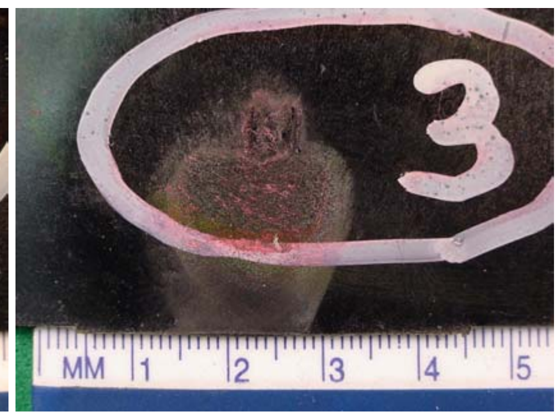
Material #24 - 150 Volts



265



266

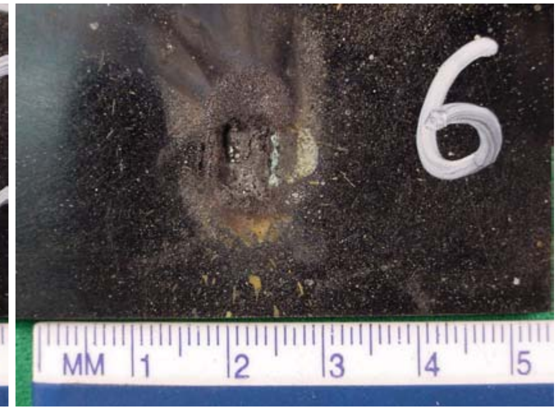


267

Material #24 - 100 Volts

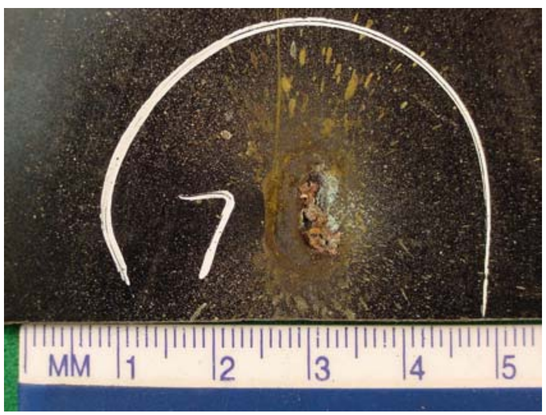
268

269

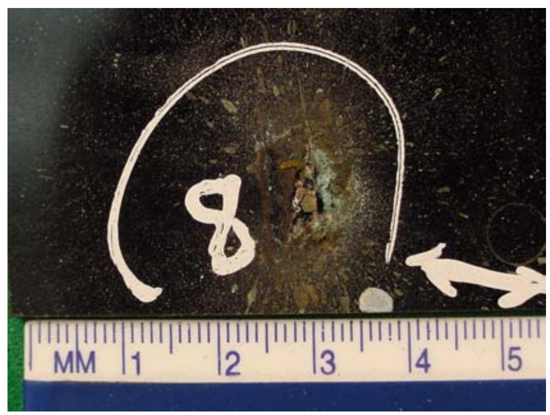


270

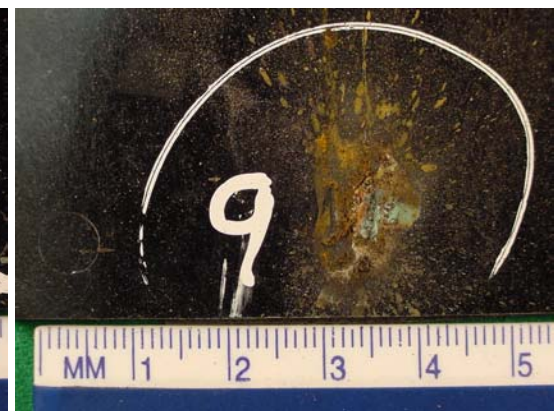
Material #24 - 60 Volts



271

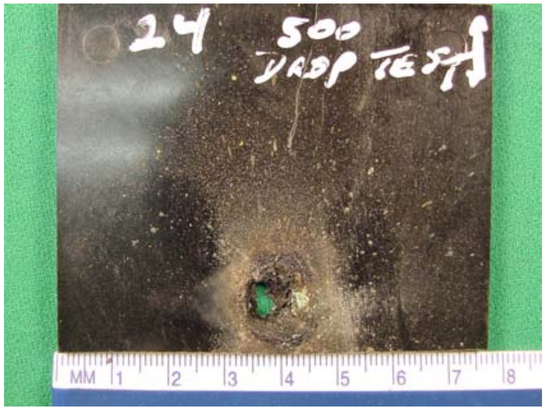


272



273

Material #24 - 60 Volts



274 **500 Drop Test**

Material #25 - 150 Volts

275

276

277

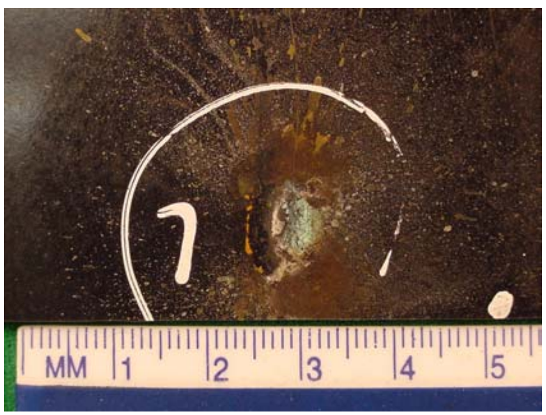
Material #25 - 100 Volts

278

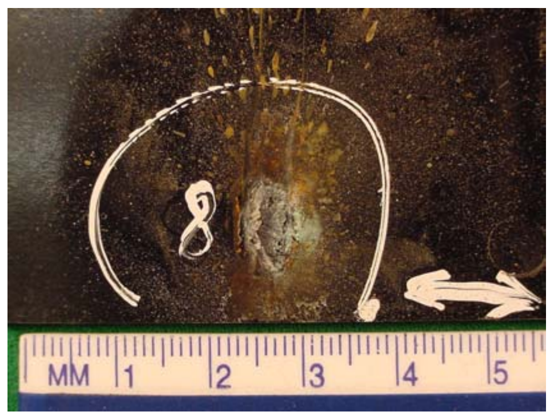
279

280

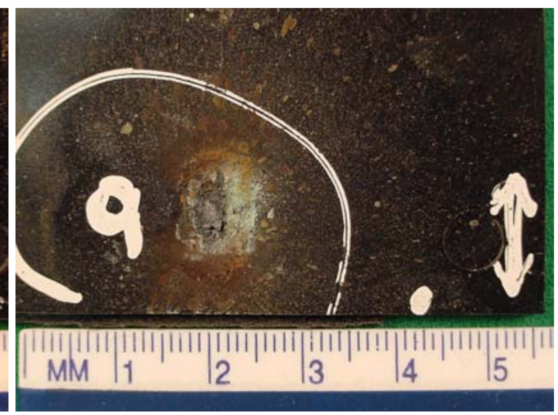
Material #25 - 60 Volts



281

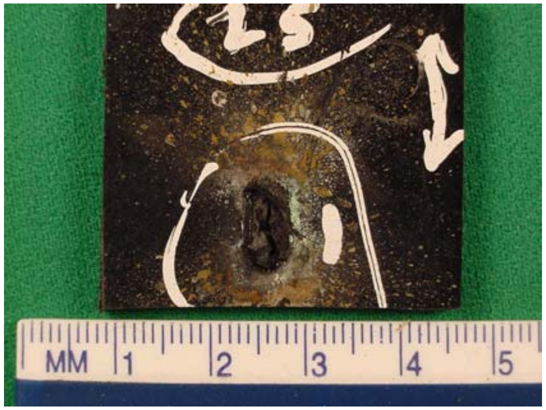


282

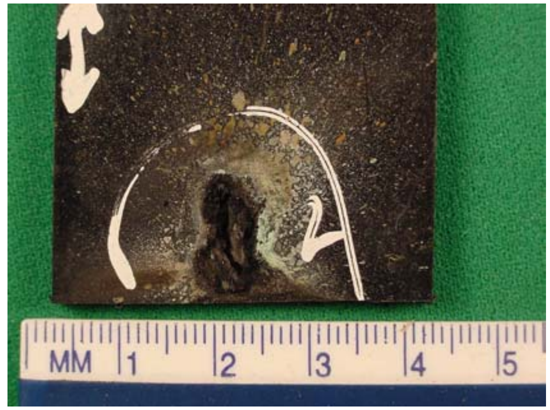


283

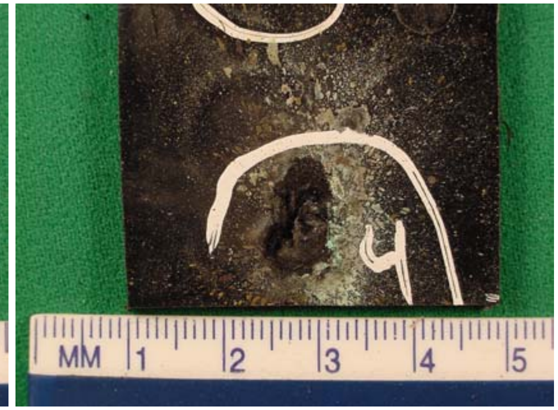
Material #25 - 60 Volts



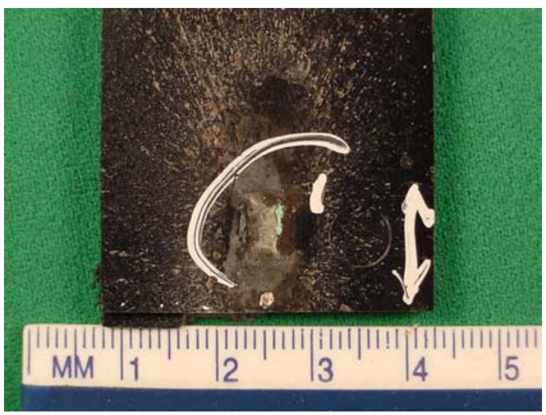
284 **15% NaCl**



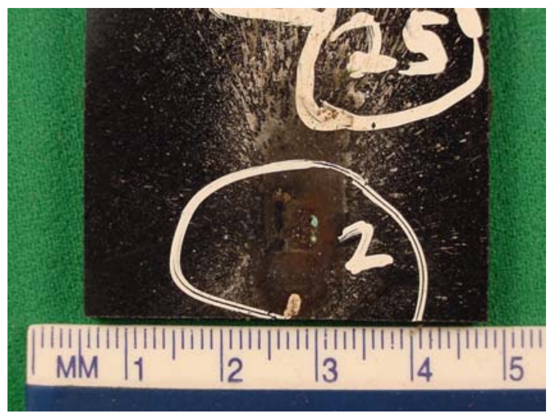
285 **15% NaCl**



286 **15% NaCl**



287 **1% NaCl**



288 **1% NaCl**

289 **1% NaCl**

Material #25 - 60 Volts

290 **500 Drop Test**

291 **0.1% NH_4Cl**